Form-Finding, Force and Function:
A thin shell concrete trolley barn for Seattle's waterfront

Michael W. Weller

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Contents

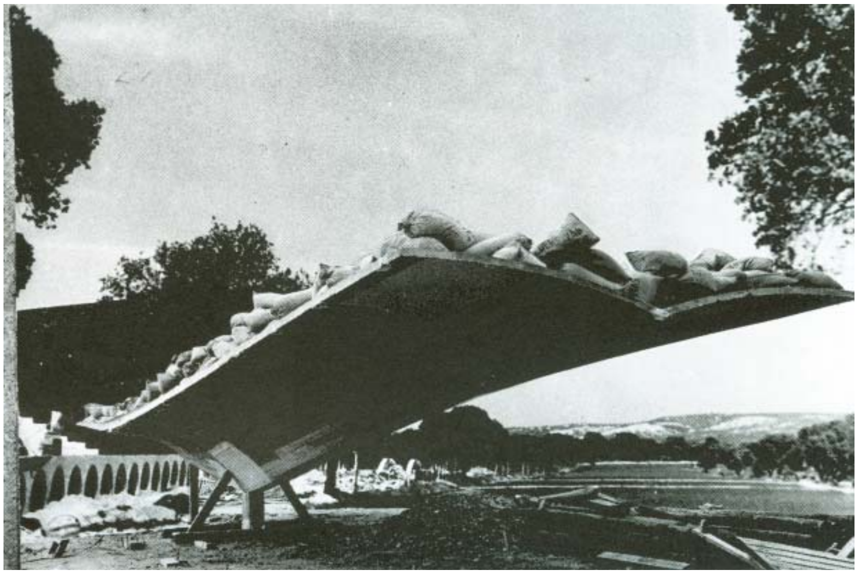

Figure 1. Thin shell's dramatic ability to cantilever is seen in this load test on a full-scale mockup of the Zarzuela racetrack, c. 1935. Photo: Bechthold, p. 37.

Problem Statement

In the early twentieth century reinforced concrete was a new building technology. Its novelty inspired experimentation, both from architects, such as Le Corbusier, and from engineers, who dreamed up different applications for the new ferroconcrete. One application for reinforced concrete that developed rapidly was its use in thin shells. These shells spanned great distances or stretched out in dramatic cantilevers, their thinness seemingly impossible for the distance they extended. This technology quickly grew ever more common, especially in long-span utilitarian settings, where thin shell concrete was able to cover large areas economically.

By the 1970s the use of thin shell concrete had all but disappeared, however. This change was due to a combination of factors, including price changes such as increased labor costs, the falling price of concrete, and the mass production of open-web steel trusses. This disappearance was also caused by the design challenges offered by thin shell concrete. Shell structures, because of their thinness, must be shaped to conform to the forces present in the structure. Until recently this shell form-finding could only be done by someone with specialized computer expertise, or through the slow process of physical model testing and measurement. These arcane processes forced thin shell into the realm of specialists, and drastically limited a designer's ability to consider multiple design options for a thin shell concrete structure.

Due to these methodological challenges thin shell concrete buildings were used chiefly on greenfield sites, where site and program introduced little irregularity. This allowed the designer to identify a single simple shell condition and to analyze it rapidly. Unfortunately, it also led to a proliferation of thin shell buildings that stood as high-tech objects in a flat, open field. There was little opportunity for a dialog with the building's context, and each building sent the implicit message that thin shell concrete could work only under conditions of perfect geometric regularity.

Figure 2. This garden center near Paris epitomizes the tendency for shell buildings to be designed as objects in a flat, empty field. Photo: Chilton, p. 81.

In recent years computational tools have become available that eliminate this constraint of regularity from thin shell form-finding. Simple computational models, originally developed for computer graphics, have been adopted by architectural researchers to explore rapid form-finding in a shell's early design phase. This thesis will demonstrate that digital schematic form-finding tools allow thin shell concrete structures to be used on sites and for programs requiring shell forms that would previously have been prohibitively difficult to analyze, let alone for a designer to test multiple options early in design.

This thesis will model a design process that adapts these new digital tools in order to design a thin shell concrete building on a constrained urban site. The selected program, a maintenance building for Seattle's waterfront streetcar, requires an open, utilitarian space to which thin shell concrete is well suited. It also requires a site in close proximity to the existing streetcar line, providing the constraints of an urban site. These factors create a laboratory in which a schematic form-finding tool can be tested. Because no available tool fits this project the author will incorporate available open-source code into an *ad hoc* tool. This computer program will develop as the building design develops, allowing for a chance to explore both the interaction of a custom digital tool with a design workflow, as well as the suitability of thin shell concrete for this particular design. The final result will be a design that must balance the influences of program, site and structural form-finding to create a public building in very public part of Seattle. Doing so will require the use of digital form-finding tools and design judgment, the right combination of which this thesis will be constantly negotiating.

Theoretical framework

The theoretical motivations for this exercise coalesce around the theme of constraint. Thin shell concrete is a construction type where a designer's desire to shape space through structural force is taken to the extreme. This impulse is pushed even further by the thesis' focus on tool-making, an activity that itself is highly influenced by the means-ends relationship of tool and purpose. Together this combines into a design exercise that is laden with questions of where externally-imposed constraint ends, and where design begins. This, ultimately, is the largest question posed by this thesis.

Tectonics

Thin shell structures are a type of funicular structure. Funicular, derived from the Latin word for "rope", means that a structure takes its shape in response to the magnitude and location of the forces acting upon it. For example, a rope suspended from two level points will form a catenary when under self-weight, and a "V" when a single point load is added at midpoint.[1] While a suspended rope is a purely tensile system, if inverted and made rigid that same form will change into a system that is in pure compression. This was first postulated (and wonderfully expressed) by the English scientist Robert Hooke, who in 1675 wrote, "(a)s hangs the flexible line, so but inverted will stand the rigid arch" (see Figure 3).[2] Thin concrete shells are an example of this type of inverted compression structure.

While funicular structures are an engineering novelty, and recommend themselves pragmatically by their efficient use of material, they appeal to the theoretical position of architectural tectonics by

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[1] For a clear and through introduction to funicular structures see Shodek, pp. 185-230.

[2] Allen, p. 219.

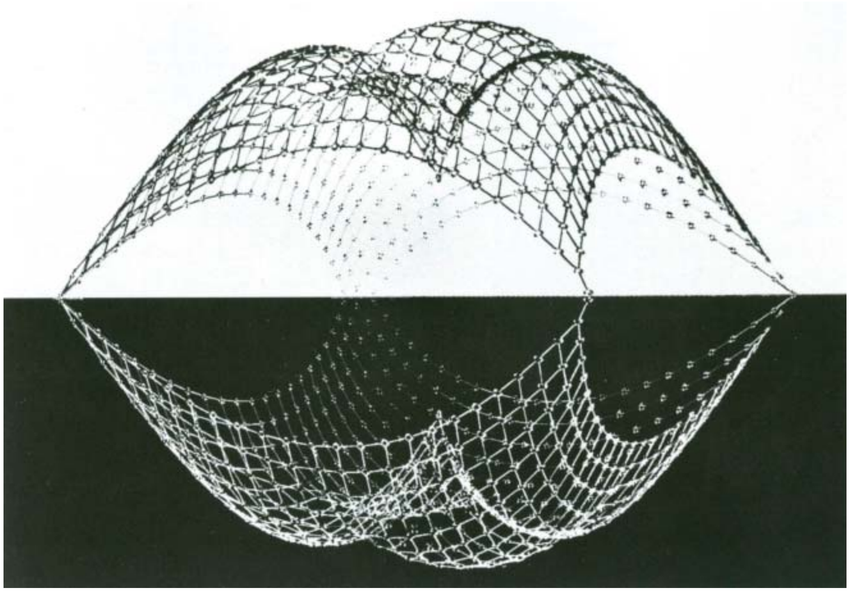

Figure 3. A form-finding experiment by Frei Otto illustrates Hooke's principle of inversion. Photo: Schanz, ed., p. 43.

their very nature. The tectonic in architecture is that quality of a building that stems from its very builtness. Kenneth Frampton, one of the clearest contemporary proponents of tectonics, writes of "crucial qualities that arise almost spontaneously from the nature of the construction" as well as of "a *poetic of construction.*"[3] Frampton stresses that an intensely expressive architecture can be created out of the physical material that makes up a building, as well as the ways that this material is assembled—no applied narrative or imagery is needed to make architecture.

From the tectonic perspective the appeal of a funicular structure, such as one of thin shell concrete, is clear. Forces present in the structure shape thin shell concrete. Areas of uniform load present smooth, catenary curvatures, while areas of concentrated force express themselves as sharp bends or spikes in the surface form. This transparency between force and structure resonates with the tectonic interest in the building as an expressive constructed object. A thin shell concrete structure is a strong statement of a building's inherent nature as a series of forces, and when well designed uses this to create an architectural space. This appeal is certainly present in the author's decision to investigate thin shell concrete design.

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[3] Frampton, pp. 353 & 356.

Sustainability Note

While thin shell's material efficiency may not be a key point in its importance to a theory of architectural tectonics, it is not something to be dismissed out of hand. Architecture's recent interest in the environmental impacts of its buildings has caused a reevaluation of all building techniques, thin shell included. By their very nature all funicular structures, including thin shell, use significantly less material than traditional construction. By designing only for pure tension or compression these structures experience very little bending force. These pure forces require less material to resist, therefore funicular structures can be extremely frugal in their use of material. One only needs to see a photograph of Heinz Isler's work to realize that material is being used much more effectively in a funicular structure than it is in a typical trabeated construction (see figure 4). Less material means less embodied energy and natural resource extraction, i.e. a smaller environmental impact.

Figure 4. Isler's Dietlingen Süd Service Station, 1968. Photo: Chilton, p. 92.

While embodied energy is a concern in sustainability, building operation typically far outweighs construction in terms of a building's total life-time energy consumption. Uninsulated thin shell concrete is a poor candidate for long-term energy efficiency. However, by virtue of their curvilinear forms thin shell buildings present a lower surface-to-volume ratio than traditional construction. Should this form be well-insulated a thin shell building would benefit from its low surface area in a heating-dominated climate such as Seattle's.

Sustainability may not be at the center of this thesis' theoretical interest, but it cannot be overlooked in any part of architecture today. While part of thin shell concrete's appeal is the opportunity it offers for tectonic expression, its virtue as an efficient mode of building should not be understated. Especially on Seattle's waterfront, within sight of Puget Sound's stressed ecosystem, architecture must address its impact on the environment as much as it strives for theoretical cohesiveness.

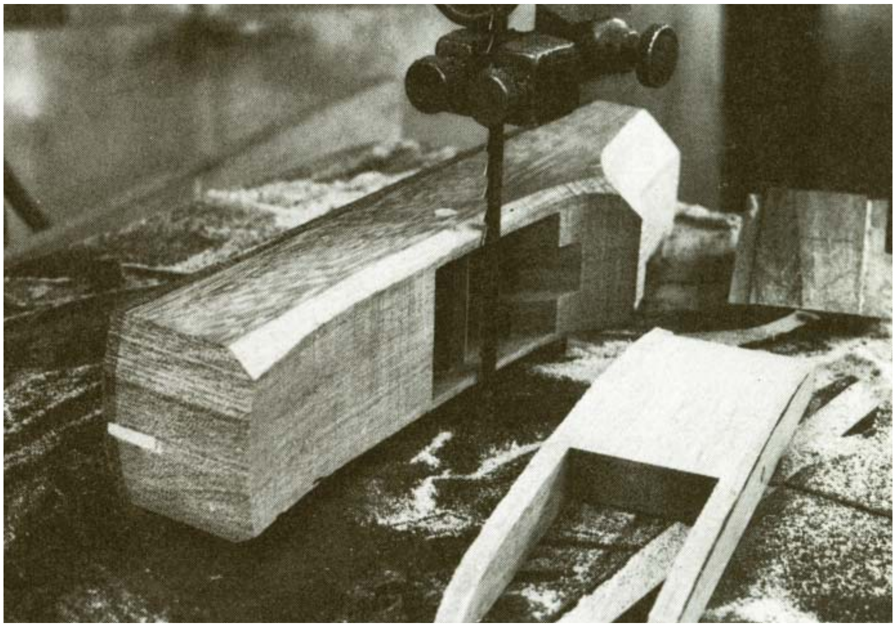

Figure 5. Tool making. Photo: Krenov, p. 91.

Tool Making

In part a tool making exercise, this thesis reflect a theoretical interest in the role of tool-making and tool-use in design. Simply put, a tool is a device that carries out a particular function. It allows the user to perform an act better than he can without the tool—perhaps faster, or more accurately, or some combination of these. Tool users also have the ability to become tool makers. When someone is familiar with a tool it is natural for that user to begin to think of ways to customize the tool to do tasks that it could not do before. A custom-shaped cutter head for a router is an example of this kind of tool making. Customizing tools is a way for the user to unlock more potential from a given tool.

On the other hand, there is the threat that a tool, as a specialization, will diminish the potential sphere of actions that its user will chose to engage in. The proverb "if all you have is a hammer, everything looks like a nail" is an expression of this fear. The tool can liberate potential, but it inevitably alters the work done, often losing some nuance that a less efficient way of doing work imparted to the process.

This tension between a tool's liberating potential and the deadening effect it can have is certainly present in architectural design's relationship with computing. It is a central theme in Malcolm McCullough's Abstracting Craft, one that McCullough uses to offer a measured defense of the role computers have to play in design. McCullough diagnoses an emerging understanding of computing that he summarizes with the phrase "digital craft." He realizes that to conceptualize a digital activity as craft-like one must first understand some connection between computing and handiwork, and that the computer begins to take the role of a tool. McCullough feels optimistic that this craft-based conception of computing will benefit design because, "(u)ltimately the computer is a means for combining the skillful hand with the reasoning mind. We never had such a tool. If designed and used properly, this already lets us apply something about what we know of symbolic processing to using tools, and this alone should become more enjoyable than industrial automation."[4] That is, a well-made digital tool expands its user's realm of possible work at the same time that it enhances it, by combining hand with mind. This is in stark contrast to the non-symbolic tool, which threatens to deaden the machine-bound industrial worker through blunt overspecialization.

While McCullough's concept of digital craft points a way out of a simple mind = freedom, computer = servitude dichotomy, his ideas of digital craft continue to focus on the designer as a user of tools. Today's approach to digital culture, and to design, has begun to break down this line between computer user and digital maker. Recent projects, such as Lego *Mindstorms* and One Laptop Per Child, are motivated by the sentiment that anyone can be empowered to craft a digital tool to match their goals. The One Laptop Per Child project states: "Using the (computer) as both their window on the world, as well as a highly programmable tool for exploring it, children in emerging nations will be opened to both illimitable knowledge and to their own creative and problem-solving potential."[5] Here the computer is not simply a tool, it is a *programmable tool*. Computer users, in this model, are empowered to create and customize the computing tools they use to get their work done. They master the computer by opening it up, both literally through its hardware, and symbolically by learning its code.

A key step in this movement towards the computer as user-definable tool has been the prolifera-

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[4] McCullough, p. 81.

[5] One Laptop Per Child Website, <http://laptop.org/en/vision/mission/index2.shtml>.

tion of open-source tool sharing over the internet. The phrase "open source," meaning that a program's source code is publicly available, indicates that a piece of software is both available to open up and test, and that its creator has chosen to explicitly allow the modification and distribution of derivative work.[6] Working in an open source context allows all users, not just those with the sophisticated skills of a major consulting firm, to have access to a collective cupboard of tool from which one can begin to build a program to achieve a given task at hand.

The concept of using *ad hoc* digital tools as part of a design process is one that remains foreign to mainstream architectural practice. This thesis, by modeling a design process that capitalizes on the wealth of digital knowledge shared by the open source community, will illustrate how design practice can change to incorporate this resource. This is a very different concept of digital tool than the model of computer-as-digital-pen that is most commonly seen today. As the platform for a form-finding tool this workflow will use the computer to solve an indeterminate form system, something that is simply not computable by a person in the time afforded by a design exercise. As such the computer is here at tool that can be customized to not just make a process more efficient, but also to unlock a new possibility for design.

Boundaries of Functionalism

The topics of tool making and tectonic expression both center on a question of constraint and its boundaries. Tectonic theories celebrate the necessary facts of a building's materials and methods of assembly, but in its pure form tectonics celebrates them for their expressive value, not for their quality as clever or economical details. Similarly, tool making can be an end in itself, but a truly remarkable tool is one that achieves a remarkable goal. Just as a single detail alone cannot be a tectonic statement, so a tool cannot explain the purpose for which it was created.

In architecture details and tools need to add up to something qualitative in order to move beyond their function. Skidmore, Owings & Merrill's Pilgrimage Terminal in Jeddah, Saudi Arabia, an enormous expanse covered by repeating membrane "tents", uses a tensile structure to argue for the pilgrim's necessary cooperation with Saudi Arabia's challenging climate. Dieste's hypar masonry roofs are inexpen-

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[6] See "The Open Source Definition", The Open Source Initiative, <http://www.opensource.org/docs/osd>.

Figures 6 & 7: SOM's Jeddah Hajj Terminal (left) and a masonry shell warehouse by Dieste (right). Photos: Flickr, Bechthold, p. 114.

sive, utilitarian statements about space enclosure, but their magic stems from a wonderful interaction between the structural regularity of the shells and the coarse texture of their masonry, a contrast that is made apparent by the chiaroscuro light thrown from the curving roof's clerestory glazing. In the end the success of a methodology that attempts to combine architectural design with the tectonic rigor of a funicular structure will depend on the project's realization of something greater than an efficient shape that was found using advanced technology. This architectural virtue is one that springs from a building's material, but that also says something about that building's reason for being in the world. It will be important to remember this need to match sophisticated means with appropriate architectural ends as this process-oriented demonstration proceeds.

Delimitations and limitations of the study

Because this thesis is a demonstration of the role that form-finding can play in architectural design there are some issues that cannot be addressed by this work, yet will naturally arise due to the subject chosen. The first of these has to do with site. While Seattle's waterfront was chosen because it currently needs a trolley barn, its chief role in this thesis is to provide a specific site and program for this design process to engage with. The larger transformation that the waterfront is undergoing, including the potential removal of the Alaskan Way Viaduct, is well beyond the scope of this exercise. This thesis will move forward under the assumption that both the planned deep bore tunnel and Seattle DPD's current long-range plan will in fact guide the development of the waterfront for the foreseeable future.[7] This design will imagine a post-viaduct waterfront and the public spaces that will be created, but only as spaces that relate to this building. Not an attempt to create a comprehensive waterfront plan, this exercise will instead contribute a single, fine-grained street corner proposal to the broad strokes of the existing plan.

A second delimitation of this thesis' scope relates to the role of the digital form-finding tool. By creating a tool that engages with structural performance the question quickly arises about how far this tool takes structural simulation. The equilibrium forms determined by this form finding tool will reflect simple load conditions. The real structural challenge posed by concrete shell design has to do with a shell's tendency to buckle under differential loading and settlement, however. This challenge cannot be resolved at the schematic level, but must be left for a secondary analysis step. This thesis will use basic tests, such as simulated asymmetrical loading and possibly physical model study, to estimate the simplest possible buckling weaknesses, but it will stop there, acknowledging that the intended product of this exercise is a schematic design, not a resolved structure.

Finally, the question of economy and constructability must be addressed at some point when considering such a non-traditional construction type. Currently there are two methods that are often used to reduce the cost of thin shell structures—reusable formwork and permanent formwork. These methods allow the major labor constraint- formwork building- to either be minimized, in the case of reusable formwork, or uses that labor to provide a permanent part of the building in the case of permanent formwork. This permanent formwork is typically chosen to have beneficial qualities, such as insulation or noise-deadening qualities. While not crucial to this thesis, some consideration of these questions of constructability will be made during design so that the project might hold up under broader scrutiny.

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[7] See the 2006 DPD document "Mayor's Recommendations: Seattle's Central Waterfront Plan."

Previous Work

As a thesis that tracks the intersection of thin shell as a building technology with the development of digital form finding tools the previous work in both of these fields is important to the path this thesis will take.

History of thin shell structures

The technology of thin shell concrete has existed for nearly 100 years. Masonry shells, which by their nature are purely in compression, have been in use much longer than a singe century—the infill fields of a Gothic cathedral's rib vaulting behave as masonry shells, and by the 1860s masonry vaults of great beauty were developed by Rafael Guastavino in both Spain and the United States. Gustavino's work and graphic design methods would go on to influence Antonio Gaudí, still today perhaps the best-known designer whose work has been shaped by an interest in force-derived architectural form.[8] While early engineers such as Guastavino pushed unreinforced masonry's limits in thin shell construction, it was the introduction of steel reinforcement, initially in concrete, that sparked the Twentieth century's interest in thin shell construction.

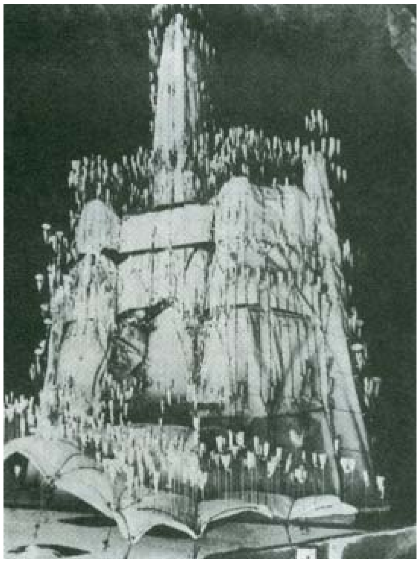

Figure 8: This cloth and string model by Gaudi's workshop illustrates his interest in deriving form from forces. Photo: Shodek, p. 24.

Early shell-builders were often engineers, and were engaged to design economical long-span structures, buildings such as aircraft hangars, train sheds and factories. The German engineering firm of Dyckerhoff & Widmann were the early leaders in thin shell construction; their most architecturally signifi-

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[8] See Bechthold p. 29 for a discussion of the work of both Guastavino and Gaudi. Allen, pp. 229-30 also notes Guastavino's contribution to thin shell design.

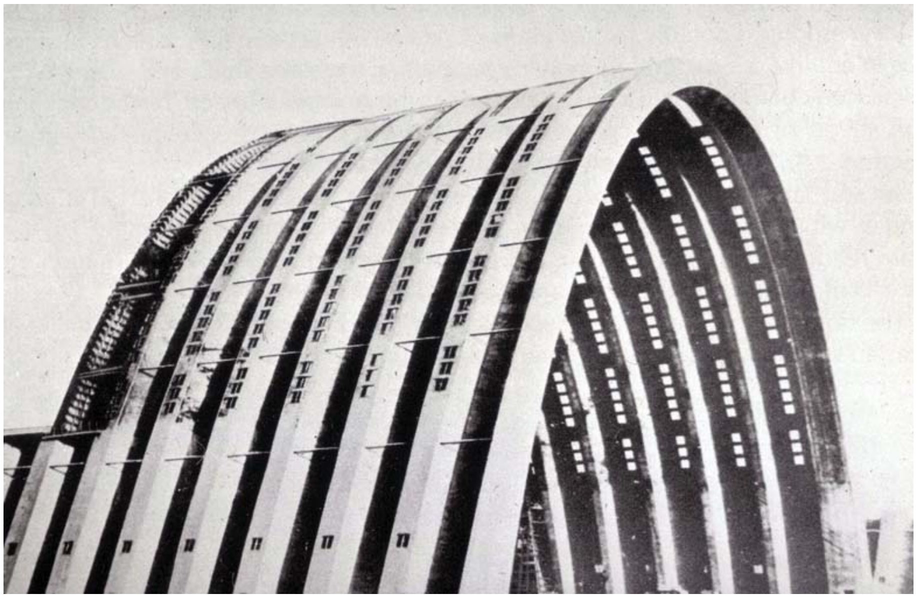

Figure 9: Freyssinet's hangar at Orly. Photo: Columbia Arch 4125: Building Systems I website, <http://www.columbia.edu/cu/gsapp/BT/BSI/ARCH/arch3.html>.

cant work was the design of the concrete dome for Max Berg's Century Hall in Breslau, a structure that in 1913 became the first modern building whose clear span exceeded Rome's Pantheon. Other notable structures of this early phase are the elegant works of Eduardo Torroja in Spain, including the Algecira market hall (1934), and Freyssinet's economical segmented system for an aircraft hangar at Orly (1921). Thin shell was chosen for these structures because they required long spans, and at the time it was the most economical choice, even though still a relatively young and experimental technique.

While the earliest shell designs were marked by the excitement of progressively greater spans and a variety of formal experimentation, the second wave of shell building (1940-1960s) faced a mounting challenge of economy. Labor costs rose over this time period, while steel and concrete prices steadily declined. However, the 1950s and '60s produced some of the most prolific shell builders of the twentieth century. Félix Candela (Mexico) and Eliado Dieste (Uruguay) both took advantage of the relatively inexpensive labor in their home countries to build a variety of shell structures, Dieste using breathtakingly thin shells of masonry as his primary material. Candela's restaurant in Xochimilco (1958) remains one of the most exemplary shell structures ever built. In Europe Pier Luigi Nervi (Italy) and Heinz Isler (Switzerland) both produced a large body of thin shell structures by focusing on repeatable elements and reusable formworks to keep labor costs low.

This second phase of thin shell design focused almost exclusively on ruled surfaces—surfaces where in at least one direction a straight line can be drawn through any point on the surface and that line will remain on the surface.[9] Ruled surfaces include hyperboloids and hyperbolic paraboloids. These forms were attractive because they were definable through mathematical formulas, which allowed the designer to understand the forces present through abstract calculations. Ruled surfaces are also significantly more constructible, because they can be created out of linear elements, such as the boards and pipes one normally sees on a construction site.

The most prominent designer to eschew ruled surfaces is the Swiss engineer Heinz Isler. In 1954, after a long period of attempting to design a structurally stable vault with domed end sections over a tapered rectangular plan, Isler hit on the idea that a "bubble" (in this case a pillow) takes the optimal shape for its edge boundaries.[10] Isler began to construct models by inflating surfaces or by hanging and then hardening them. When Isler presented his methodology to an assembly of shell designers at the 1959 First Congress of the International Association for Shell Structures it created vigorous debate, with the dissenting majority voicing concern that such irregular shapes presented too great a challenge to safe calculation and economical construction.[11] Isler has gestured in the direction that modern computing could take thin shell construction—however, due to his model of reusing formwork and designing through accumulated experience his work also unfortunately often epitomizes the shortcoming of shell design as an object in a field.

Thin shell in the Pacific Northwest

While the mention of thin shell structures conjures up exotic names and distant structures, the Pacific Northwest did have a period of vigorous experimentation with the construction type. The region's leader was Jack Christiansen, an engineer who began practice in 1952. Christiansen's work consists chiefly of utilitarian structures, such as a 1954 warehouse for the Seattle School district in the South Lake Union neighborhood, and a pair of aircraft hangars, one at Larsen Air Force Base in Moses Lake, Washington (1956), the other at Seattle's Boeing Field (1962).[12] Undoubtedly Christiansen's best-known work was the King County Municipal Stadium, better known as the Kingdome. This 1971 building remains the

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[9] See Bechthold, p. 18 for a clear discussion of the relevant surface geometry.
[10] Chilton, pp. 15-16.
[11] See ***ibid***., pp. 17-20.
[12] Metzger, p. 9.

longest spanning concrete roof ever constructed.

Thin shell today

The completion of the Kingdome occurred at the same time that thin shell was generally falling out of favor around the world. While no single overwhelming ground stands alone, a list of factors combined to make thin shell concrete a less desirable solution for long spans by the 1970s. The first difficulty lay with the same challenge that thin shell had been facing since World War II—after more than twenty years of pressure the cost savings of thin shell concrete's material efficiency could no longer offset the labor premiums demanded by complex formworks, no matter what ingenious elements of prefabrication or reuse a designer was able to come up with.[13] A second challenge lay in energy costs. Complex thin shell shapes were more difficult to create when an insulating layer was required; the 1973 Oil Crisis resulted in much more stringent energy requirements for buildings, effectively eliminating uninsulated concrete shells as a feasible building technology for conditioned spaces.[14] A third challenge posed to compressive structures by the 1970s was the rapid development of tensile structures. Frei Otto's experiments with tensile membranes were mature enough in 1972 that they were used on Munich's Olympic Stadium. This marked the arrival of a strong competitor to thin shell in terms of material efficiency, and a superior technology in the area of flexibility, given the relative ease with which a membrane structure can be raised and lowered.[15] A less spectacular technology than membrane structures also created an economic challenger to thin shell—with the development of electric arc welding in the 1940s steel space frames and trusses became progressively easier to fabricate, driving down the price of what today has become the most ubiquitous of long-span solutions.[16]

After a twenty-year period in which few shell structures where built, in the last decade there has been a modest resurgence in concrete shell construction, despite the challenges noted above.[17] Again,

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[13] Nervi's work offers perhaps the most insistent exploration of precast formwork in shell buildings; see, for example, Bechthold, p. 155. Isler, on the other hand, employs reusable wood supports that have allowed him to remain competitive until today. See Chilton, pp. 62-65.

[14] Metzger, p.11.

[15] See Allen, p. 350.

[16] Bechthold, p. 34.

[17] Foster & Partners' American Air Museum, in Duxford, UK (1997) and planned Spaceport America in Las Cruces, NM (expected completion late 2010) are examples from one practice, Ingenhoven Architekten's Lufthansa Aviation Center in Frankfurt, Germany (2007) is another.

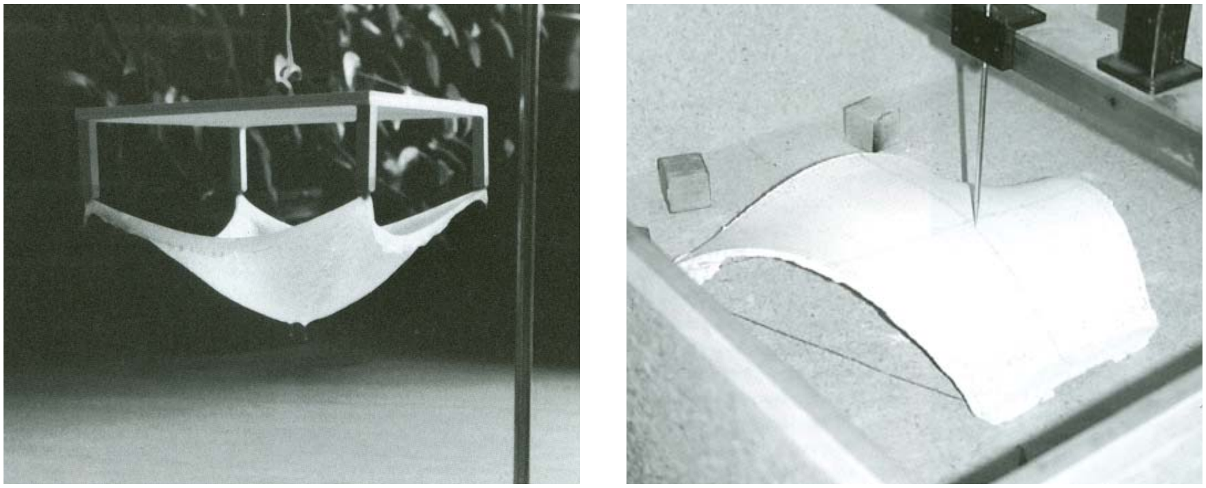
this development cannot be traced to as single magic bullet. The decade's generous construction financing created budgets that allowed designers to experiment with techniques that may not have been the most economical. The now-ubiquitous use of spray-applied concrete (shotcrete) also allowed for faster, less-expensive construction. These pragmatic factors are only a small part of today's current interest, however-- technological developments are in fact the major driver behind thin shell's return.

Three technological trends have combined to facilitate easier creation of thin shell concrete—three-dimensional modeling in design, the maturity of Finite Element Analysis (FEA) and the spread of digital fabrication. Three-dimensional modeling tools, especially NURBS-based tools, allow for the precise description of complex geometric forms. FEA, on the other hand, is a method of decomposing force systems to analyze stress and strain. In the case of thin shell structures FEA is now mature enough that it can both influence form—"solving" a force system to optimize for the least strain, as well as identifying the points where the shell will experience the largest deformations, and thus threat of buckling. Finally, digital fabrication techniques have become common enough that computer-cut formwork and digital verification of site conditions are viable construction techniques. This element of managing the sheer volume of complex data is a major part of the contribution that computing has made to thin shell construction.

Work done on form-finding programs for designers

This thesis is a demonstration of the role that computation form-finding can play in design. As such it will focus on the intersection between form modeling, such as NURBS modeling, and form-finding, which employs analysis tools such as FEA.

The term "form-finding" implies that a certain correct form exists independent of the designer, and the designer's task is to uncover it. To a certain extent this is true. For any given set of supports, loads and material characteristics there is a unique and correct form that a free-form shell in equilibrium will take. This is based on the definition of a funicular surface presented earlier. But this does not mean that the activity of design is the activity of finding these equilibrium forms. As Axel Kilian states nicely, in a form-finding design exercise "(t)he expression of design intention shifts away from the literal form giving and towards the specifications of the contextual parameters and starting conditions and of course the system



Figures 10 & 11: Isler's process of hardening an inverted surface (left) and then carefully measuring the resultant form (right). Photos: Chilton pp. 37 & 45.

of optimization itself."[18] That is, the activity of design migrates away from creating form, and moves into the process of stipulating the constraints that lead to a given equilibrium form, as well as, in the most extreme case, reconsidering what equilibrium itself might be.

Early form-finding was done with physical models, such as Gaudi's famous string models or Isler's experiments with hanging cloth. These methods work well, but are extremely laborious—the time to build a model is significant, yet is in fact the fastest part of the process. Measuring the final form is extremely slow, and errors at this stage can lead to potentially fatal flaws. For example, in a 1:100 model a measuring error of 0.5 mm would scale to a design irregularity of 5 cm, potentially the full thickness of the shell. Clearly this imposes severe limits on what can be achieved by model study.

These limits of model study lead architectural researchers to turn to the computer. By the 1970s designers such as Frei Otto were using computation to analyze the properties of the funicular structures they were designing. Indeed, some of the early mathematical research into form-finding algorithms comes from Otto's circle.[19] These programs were, and remain, highly specialized, and the most accurate methods, such as FEA, remain too computationally intensive for quick sketch-like design use.

Particle Systems & Processing

A similar but more sketch-like form-finding tool is offered by a method called a particle system. While FEA divides a surface into units and simulates the effect of external loads to those units, a particle

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[18] Kilian 1, p. 286.

[19] See Bechthold, pp. 73-78 and Drew 1, p. 20.

system abstracts a surface into a simple network of mass particles and force springs. Originally developed by the computer graphics community to simulate cloth, this method is relatively simple, but yields results that are similar to, although not exactly the same as, more sophisticated tools.[20]

Particle-spring systems, while simpler than FEA, are still complex tools, and the creation of the software that drives them would be well beyond the scope of an architectural thesis. Fortunately, in their spirit of tool exchange, the raw material for creating a particle-spring system is available through the open-source community. Several of these tools are written for a Java-based environment called Processing, a programming language developed at MIT by Casey Reas and Ben Fry.   Processing's basic capabilities can be extended through libraries, several of which give Processing the ability to run a particle-spring system. Currently the best-documented particle-spring library is traer.physics 3.0, created by Jeffrey Traer Bernstein.[21] Its apparent stability and thorough documentation have made it the easiest particle-spring engine to adapt to this thesis' exploration.

A model for this thesis' tool building is offered by CADenary Tool, a similar schematic tool built at MIT in several phases, chiefly by Axel Kilian. Kilian's tool features a three-dimensional modeling space where the user is able to select start points onto which chains and nets are affixed. The program then

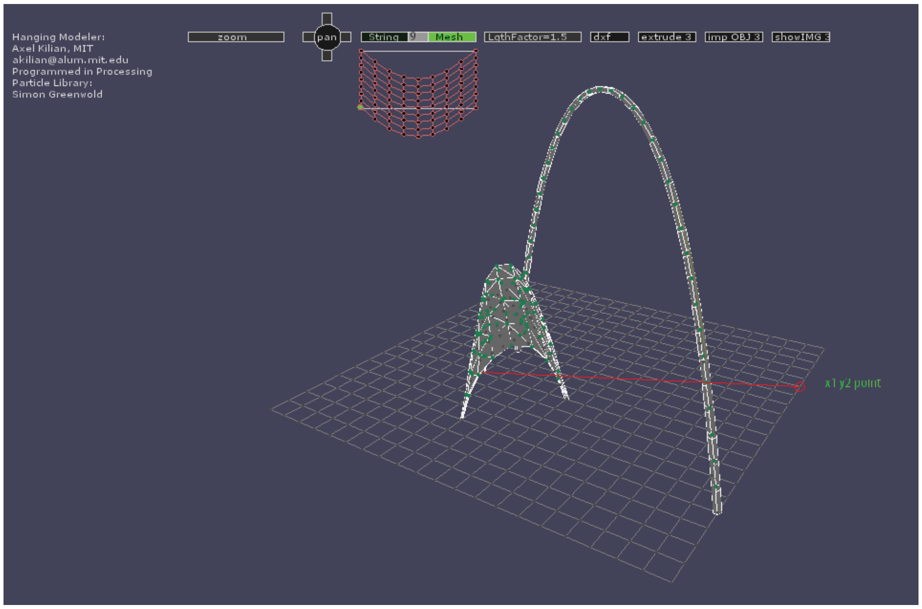

Figure 12: A screen capture of Kilian's CADenary Tool, < http://www.designexplorer.net/newscreens/cadenarytool/applet/index.html>.

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[20] Bechthold p. 133, Kilian 2, p. 7.

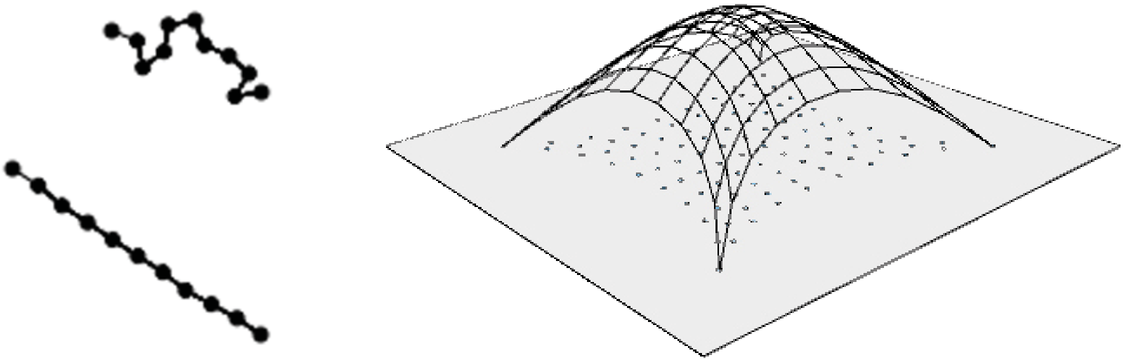
[21] traer.physics is available at <http://www.cs.princeton.edu/~traer/physics/>.

creates "loose" geometry, and it falls into place as would a hanging string or net. The user is able to control the number of links in each chain and net, as well as to determine the overall length. Once a network is in a hanging position the user can rotate the geometry in order to visualize the form as a schematic compressive structure, rather than as a series of hanging chains and nets.

The forms CADenary Tool generates are simple, but instantly evocative of compressive forms. By allowing the user to vary the support locations, the number of geometrical segments and element length it also allows for interactive changes to most of the major factors that determine equilibrium form—the only input omitted is the ability to vary load from node to node. CADenary Tool is far from complete, however. Its modeling inputs severely limit the geometry that a user is able to create. For example, chains and nets can only be composed of segments of equal length. This results in a default geometry that tends to be highly symmetrical, something that can be overcome only by laborious link-by-link modeling. Because of this shortcoming Kilian's CADenary Tool, while instructive as an interactive tool for illustrating the basics of funicular form-finding, is not ready to be used in a design process of any complexity. Instead CADenary Tool serves as model on which this thesis' own tool making will improve.

Role of this demonstration

Thin shell concrete is currently experiencing a minor renaissance, due in large part to the development of new computational tools. Yet the only digital tool in this field built to support a design process, CADenary Tool, remains incomplete, and is limited enough that it can create only the simplest forms. By demonstrating a method that uses open source code to create a new, more versatile form finding tool this thesis will demonstrate a way for architects to benefit from this active field of computation. By doing so it will demonstrate the potential to adapt thin shell to conditions that are significantly more complex than were previously possible. Moreover, it will be a study that the designer can engage in actively as part of the design process. Here the designer will not being forced to leave shell design to an engineer from the very earliest stages of design, as has always been the case.



Figures 13 & 14: Screen captures of early particle-spring systems programmed by the author. A simple chain of springs moves interactively (left), while a more complex surface finds an equilibrium shape in three dimensions (right).

Methodology

In order to demonstrate the possibilities and potential drawbacks of a form-finding tool in schematic design this thesis will both produce a tool and use it in a design exercise. Far from a linear process, this method will require a repeated back-and-forth between design context and tool making.

Early Tool-making

The initial steps of tool-making will create the basic functionality that this tool needs. Processing and the traer.physics library will be used to create a tool that has basic visualization ability, rendering springs as lines in three-dimensional space. The view of equilibrium shapes will need to rotate and preferably zoom, so that a geometry evaluation can occur in Processing without the need to export into another program. Because this tool is *ad hoc*, to be used only be the author, sophisticated interface methods for creating spring systems are not worth the time required to create them—instead spring geometry will be created through written code.

With a tool that displays the basic ability to find equilibrium form this demonstration will be able to move on to an exploration of equilibrium forms that are appropriate to the site and program.

Architectural Design

While tool making can certainly become an end in itself, the argument central to this thesis is that digital tools can be integrated much more effectively with the design process if part of design is the creation of an *ad hoc* digital tool. In the case of this thesis the author has chosen to design a maintenance barn for Seattle's currently-defunct waterfront trolley.

Program

The basic property of thin shell concrete that allowed it to become a viable technology in the early twentieth century was that it is able to span large distances in single-story structures with the use of very little material. While the relationship between labor and material costs in concrete may have changed in the intervening decades, this basic structural fact has not. Thus a single-story long span building is an appropriate type to consider for this thesis. It is certainly an application that continues the long history of compressive structures being used in this manner, for example by Isler, Dieste and Christiansen.

In fact, Seattle does need a simple long-span structure, in the form of a waterfront trolley maintenance barn. Opened in May, 1982, Seattle's waterfront streetcar line (officially named the George Benson Waterfront Streetcar Line in 2002) was shut down in November 2005. The line ceased operation because its maintenance barn was located on land that was needed to for Seattle Art Museum's Olympic Sculpture Park. The existing barn was demolished, trolley service was stopped and the cars were put in storage, replaced by summer-only busses covered in a decorative trolley wrap.

King County did make a push to build a replacement maintenance facility. In 2005 a $9 million deal was struck with a private developer to provide space in a new infill building on Main Street, immediately adjacent to Occidental Park in the Pioneer Square neighborhood. The mixed-use building was to consist of trolley maintenance and restaurant space on the ground floor, with nine stories of office and residential above. Designed by Mithun and developed by Urban Visions, this project completed schematic design in 2007, but was put on hold soon thereafter due to market conditions.

This thesis will use the program developed by Mithun as the trolley program to be accommodated in the current design. It includes space for five vintage trolleys, the opportunity to convert to longer, modern trolleys in the future, and a variety of maintenance and work spaces. As a recent program that was meant to service both the waterfront's current needs and allow for the opportunity to adapt to future uses this program offers solid material for this design process to respond to.

Site selection

The trolley barn site, like the program, serves chiefly as a set of particularities that challenges this demonstration to respond to reality's contingencies. The waterfront trolley line runs from the Olympic Sculpture Park south on Alaskan Way, until it turns east on Main Street to the International District transit tunnel entrance. This short route limits the number of possible sites, and this list is further shortened by the fact that several of the available lots are much larger than the approx. 10,000 SF that the trolley barn requires. An empty lot on the corner of Alaskan and Yesler stands out, as it is approx. 9,600 SF and wedge-shaped. A preliminary feasibility study indicates that there are several options for accommodating the basic geometry of the line's five vintage trolleys, but that all of them will be snug (see appendix). This is exactly the challenge of accommodation to site and program irregularity that this thesis set out to explore. An additional benefit of the site is its location, near both the Ferry terminal and Pioneer Square. This site will offer ample context to which the massing and orientation of the trolley barn will need to respond.

Iterative Development

Once a basic tool is in place and the site and program are clear an iterative design process, moving between code-based tool and three-dimensional visualization, can begin. A first step to this process will be the creation of a variety of form classes for the tool that may be appropriate shell shapes to explore. In Java a class is a piece of code that defines a type of object—a class will explain how that object is created, what properties it has, and what operations can be done to the object. In the case of the particle-spring system potential classes will be different types of particle-spring groupings—square nets, strings, concentric spring circles, etc. By creating these classes a library of potential forms will be accumulated as the design process moves forward. This exercise will be akin to building a series of mockups or concept models— a process of generating a family of equilibrium forms that begin to develop a vocabulary with which the design can work.

This vocabulary development will be a heavily iterative process. Each class will require cycles of code testing and refinement. Once the class is developed a second type of iteration will occur, one that iterates between the constraint definitions and the resultant form. A class may be completely appropriate, but the correct combination of dimensions and support locations will need to be arrived at through a process of trial and error. This trial and error process of refining both the parameters that construct a shape, as well as the code that defines that shape, will be at the core of the design process using this form-finding tool.

Final Design

Even the most rigorous of shell structures is more than simply a structural system. Aspects such as material finish, the treatment of openings and non-shell surfaces and the shell's bearing on the site are important elements of a shell structure as architecture. These are qualities that will be difficult to convey in a well-developed drawing, and will be impossible to explore in a monochromatic stick representation in Processing. At some point in design a shell form will have to be selected and design will need to move away from form-finding. At this point it is unclear when this will need to occur, but the idea of iteration explored above is useful. Just as the basic forms will need to be explored iteratively as they are applied to the site and program, it is likely that an exploration of more specific qualities will also require subtle changes to shell form. As such it is unlikely that final design will be a discreet step—instead it will begin as one of many concerns, and will command progressively more design time as the design's iteration becomes more polished. The form-finding tool, as well as the entire design method, will be tested by exactly when form-finding must be abandoned due to the work it requires to achieve further refinement.

Presentation format(s)

A significant part of this thesis consists of methodology—tool-making, form-finding, and integrating digital tools with architectural design. As such both the written document and presentation will need to dedicate more space to process than a typical project might.

Written Document

The written document faces the challenge of needing to convey process and interactive digital tools in a static printed format. Interaction will be addressed by the use of sequenced screen-captures to convey movement. Process will be discussed in the text, and an appendix will be included of a project diary, kept by the author, that will record the design process as it unfolds.

A further challenge of a thesis written document is the difficulty of presenting a large-scale visual product in letter-sized format. Fold-out pages are ungainly, and substantially detract from the reader's ability to move through a thesis document smoothly. This thesis will use sections of full-page imagery in place of fold-outs. These will be placed at natural breaks in the text and will serve to continue the flow of the text in non-verbal form.

Thesis Presentation

In contrast to the written document, which will be read by one reader at a time, the presentation must communicate with a group of reviewers and audience members. Presentations have the benefit of taking place in real time, so digital tools can be shared in their original medium.

This thesis will use both static printed imagery and projected media. This will provide a narrative presentation that still allows for viewers to refer to printed material that does not disappear when the narrative moves on. Digital media will be projected onto the same surface that the drawings will be mounted on, with the goal of maximum relation between the digital and printed imagery. This is intended to reflect the interrelation between digital design tools and architectural product that is at the core of this thesis.

Space support needed

***Spring & Summer 2010*:** The author will take a leave of absence, in order to gain professional experience and do independent research. Informal workspace may be provided in the Design Machine Group, but no assigned workspace on campus will be needed.

Fall 2010: The author will enroll in Architecture 700: Master's Thesis. A studio workspace will be needed for this quarter.

Annotated Bibliography

Ahlquist, Sean and Moritz Fleischmann. "NET.SIM: digital simulation of tension-active cable nets for design investigation of material behaviours on structure and spatial arrangement." Diss. Architectural Association, 2007-2008.

This Dissertation from the AA covers two students' investigations into the software available for cable net form-finding (part I), the fabrication of a cable net installation at the AA (part II), and (part III), which I haven't yet read. It is a very useful source for information on finding computational techniques-- they obviously spent a lot of time scripting in Processing and Rhino Script, and their knowledge in this area is apparent. Unfortunately there is little discussion of larger issues in the Dissertation, at least as far as I have read. This surprises me, considering that I imagine a dissertation to require an awareness not just of technique, but also of the theoretical issues surrounding a field of inquiry.

Allen, Edward, Waclaw Zaleski and Boston Structures Group. Form and Forces: Designing Efficient and Expressive Structures. Hoboken, NJ: John Wiley & Sons, Inc., 2010.

This is an engaging text on graphical statics, and has several chapters on catenary structures and tensile structures. But it is trapped at two extremes that I'm not comfortable working at right now-- on one hand the graphical solving is extremely general, and relies on a ton of abstractions to work. Software for solving indeterminate systems seems to be much more attractive. On the other hand Allen loves his detailing, so there is a lot about rebar diameters, minimum concrete covers, etc. All of this is too fine of a grain to allow for much design lattitude, at least in my mind. Maybe this one will be more appropriate as I get further into my design process.

Bechthold, Martin. Innovative Surface Structures: Technologies and Applications. New York & Oxon, UK: Taylor & Francis, 2008.

A very strong overview of surface structures, in both tension and compression. The book has a historical component, a research/design/formfinding component, and an interesting fabrication component, too. Bechthold does a very good job of covering a ton of different projects at all different scales and still communicating basic principles. I'll be coming back to this one often.

Chilton, John. Heinz Isler. Series: The Engineer's Contribution to Contemporary Architecture. London: Thomas Telford, 2000.

This book came to my attention because Axel Killian repeatedly cites it when discussing his understanding of thin shell design as it relates to his CADenary program. So far it seems like a thorough snapshot of Isler's work-- most of it is based on personal interviews with the author in the late 1990s, so there is not a lot of historical coverage. Rather it is more like a 3rd-person recollection of what Isler has learned over his 40-year career as a shell builder and designer. It is quite informal, but packed with

information about Isler's "intuitive" method of designing shell structures.

CityDesign, Seattle Department of Planning and Development. "Mayor's Recommendations: Seattle's Central Waterfront Concept Plan." 29 June, 2006. <http://cityofseattle.net/DPD/Planning/Central_Waterfront/Archive/DraftWaterfrontConceptPlan/default.asp>.
The most complete document available on the city's plans for the downtown waterfront. This document will provide me with the broader urban design moves that I'll be responding to with this design.

Drew, Philip. Frei Otto: Form and Structure. Boulder, CO: Westview Press, 1976.
Drew is obviously an architectural historian who is interested in the intersection of technology and art in architecture. He often references both Giedion and Banham, and is clearly in dialogue with their ideas of technology and architecture. This volume covers a wide range of Otto's work, and looks at it as a mediation between the mechanical determinism of engineering and the willful artistry of architecture. Frei Otto was a very out-there thinker, but with incredible rigor. I'm very attracted to the care Otto takes in his method, although I have to agree with Drew that Otto's buildings' relationship to their site is often strained or lacking.

Drew, Philip. Sydney Opera House: Joern Utzon. Series: Architecture in Detail. London: Phaidon, 1995.
Another one by Drew, he is definitely into the high tech and "tectonic". This book does a good job of talking about some of Utzon's basic design principles and how they feed into the Sydney Opera House. I like the idea of a strong division between platform and roof-- I hadn't thought of it until I read about this book, but after looking more closely at the Opera House this dichotomy was very clearly a driving factor in its design.

Frampton, Kenneth. Studies in Tectonic Culture. Cambridge, MA: The MIT Press, 1995.
I've only read a short excerpt from this book, but it is an excellent statement of the tectonic position-- the best one I've read so far. I'll try to get to the rest of the volume over the summer.

Hensel, Michael, Achim Menges and Michael Weinstock. "Emergence: Morphogenetic Design Strategies," AD: Architectural Design Vol. 74, No. 3. May/June, 2004.
This volume is halfway between a journal and a magazine... this issue is edited by these three men, who all work in the Emergence and Design Group at the AA-- the program from which Ahlquist and Fleischmann graduated. This volume is a little dated, but its aggressive embrace of ideas of biological emergence helps to explain some of the intellectual currents that have lead to the recent interest in form-finding. Some good articles about Arup's form-finding work, as well as Frei Otto's.

Kilian, Axel. "Design Exploration through Bidirectional Modeling of Constraints." Diss. MIT, 2006.

While a lot of this dissertation has very little to do with this thesis' interest, its section on Kilian's work with CADenary Tool is helpful-- it both discusses the tool, and adds reflection on the tool's role in design, an investigation that is lacking in his earlier work on the subject.

Kilian, Axel. "Linking Hanging Chain Models to Fabrication." ACADIA (PDF from Killian's website, <http://www.designexplorer.net/newscreens/cadenarytool/KilianACADIA.pdf>).

A paper describing Killian's motivation in developing his hanging chain software, with a lot of good citations of other work done on hanging models as resources for formfinding of shells. I think I will come back to this one often.

McCullough, Malcolm. Abstracting Craft: The Practiced Digital Hand. Cambridge, MA: The MIT Press, 1996.

A thoughtful volume on the role that computing should play in our work lives. McCullough sees our activity as productive beings as vital (especially in our "post-manufacturing" economy) and at least as important as our symbolic, abstract doings. Computers are tools that can combine these two activities, in a merger of the best of craft traditions with more contemporary knowledge work. His argument is attractive, although often stops short of calling for anything visionary, possibly because he was attempting to write a mainstream book. In the end I would have appreciated a harder push.

Metzger, Rainer. "Jack Christiansen: Thin Shell Concrete in the Pacific Northwest." Column 5 20 (2006): 8-11.

A good short article about Jack Christiansen, a Seattle engineer who built a number of notable local thin shell structures, including the Kingdome. Metzger argues for the importance of thin shell on the grounds that it is structurally efficient and tectonically honest.

Reas, Casey and Ben Fry. Processing: A Programming Handbook for Visual Designers and Artists. Cambridge, MA: The MIT Press, 2007.

This is the handbook for Processing, a Java-base language that the two authors created while at MIT's Media Lab. It combines fairly exhaustive technical documentation (every once in a while I need to look at the project's site for more info) with a lot of documentation on process, how artists use digital technology, and more. It is a very good resource, essentially indespensible, for anyone wishing to explore processing.

Schanz, Sabine, ed. Frei Otto, Bodo Rasch: Finding Fom, Towards an Architecture of the Minimal. Fellbach: Edition Axel Menges, 1995.

An exhibition catalogue put together by the Bavarian Werkbund on the occassion of awarding a prize to Frei Otto, who in turn invited Bodo Rasch to join in the award. It looks back at their work in form-finding and architectural design, pushing hard on

the idea that they are involved in an activity of uncovering existing natural laws and phenomena rather than designing things. Maybe this is the case, but that removal of agency makes me a nervous. Still, the illustrations and photos are beautiful, and the texts, while quirky, illuminate how Frei Otto understands his own work.

Schodek, Daniel L. Structures. 5th Ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2004.

This is an excellent basic textbook on structures that divides structures by the basic principles that determine the system. Reading this book was the first time that I thought much about funicular structures, and considering that Bechthold works at the GSD with Schodek I suspect that his excellent book on surface structures must be in part influenced by Schodek's work.

Vandenberg, Moritz. Cable Nets. Series: Detail in Building. Chichester, West Sussex: Academy Editions, 1998.

This one is fairly tame-- a short introduction to the principles behind cable structures, a very nice discussion of some of the detailing questions that come up during design development, and then a series of case studies. It made me feel like I could give a crack at designing and building a cable net structure myself. Not terribly deep or broad, but a nice thin book on a narrow topic.

Appendices

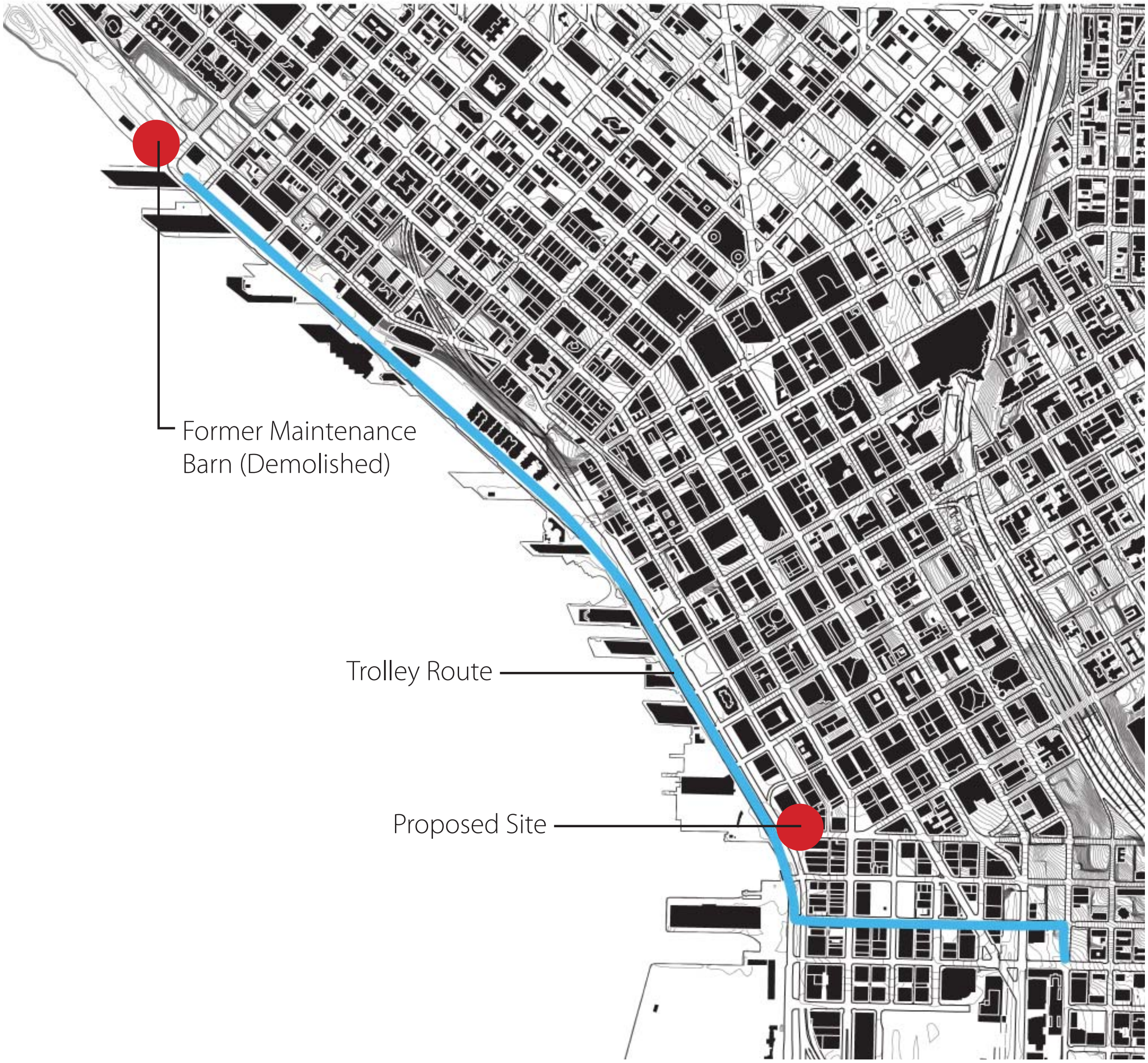
Calendar of work

Draft Schedule

End Winter Quarter		
March 19		Submit Thesis Proposal
Spring Quarter		
March 29 - June 11		Develop class library for form-finding tool Prepare site documentation-- photographs, sketches, etc.
Summer Quarter		
June 21 - August 20		Attend AA/CCA Workshop, explore Kangaroo form-finding option Massing studies of project Participate in peer project reviews w/ other thesis students Develop "attitude" towards trolley project
Fall Quarter		
Week 1	9/27	Schedule Fall Quarter in Detail
Week 2	10/4	Digital and physical site models done
Week 3	10/11	
Week 4	10/18	
Week 5	10/25	Early Review
Week 6	11/1	Begin moving from massing/feasibility to developed design
Week 7	11/8	*Veterans Day (11/11)*
Week 8	11/15	
Week 9	11/22	drawings/diagrams
Week 10	11/29	
Week 11	12/6	Mid-Review
Finals Week	12/13	
Winter Quarter		
Week 1	1/3	
Week 2	1/10	
Week 3	1/17	*MLK Day (1/17);* finalize design, transition to process evaluation & presentation prep
Week 4	1/24	
Week 5	1/31	
Week 6	2/7	Draft document complete
Week 7	2/14	
Week 8	2/21	*Presidents Day (2/21)*
Week 9	2/28	Present Thesis
Week 10	3/7	Submit Document
Finals Week	3/14	

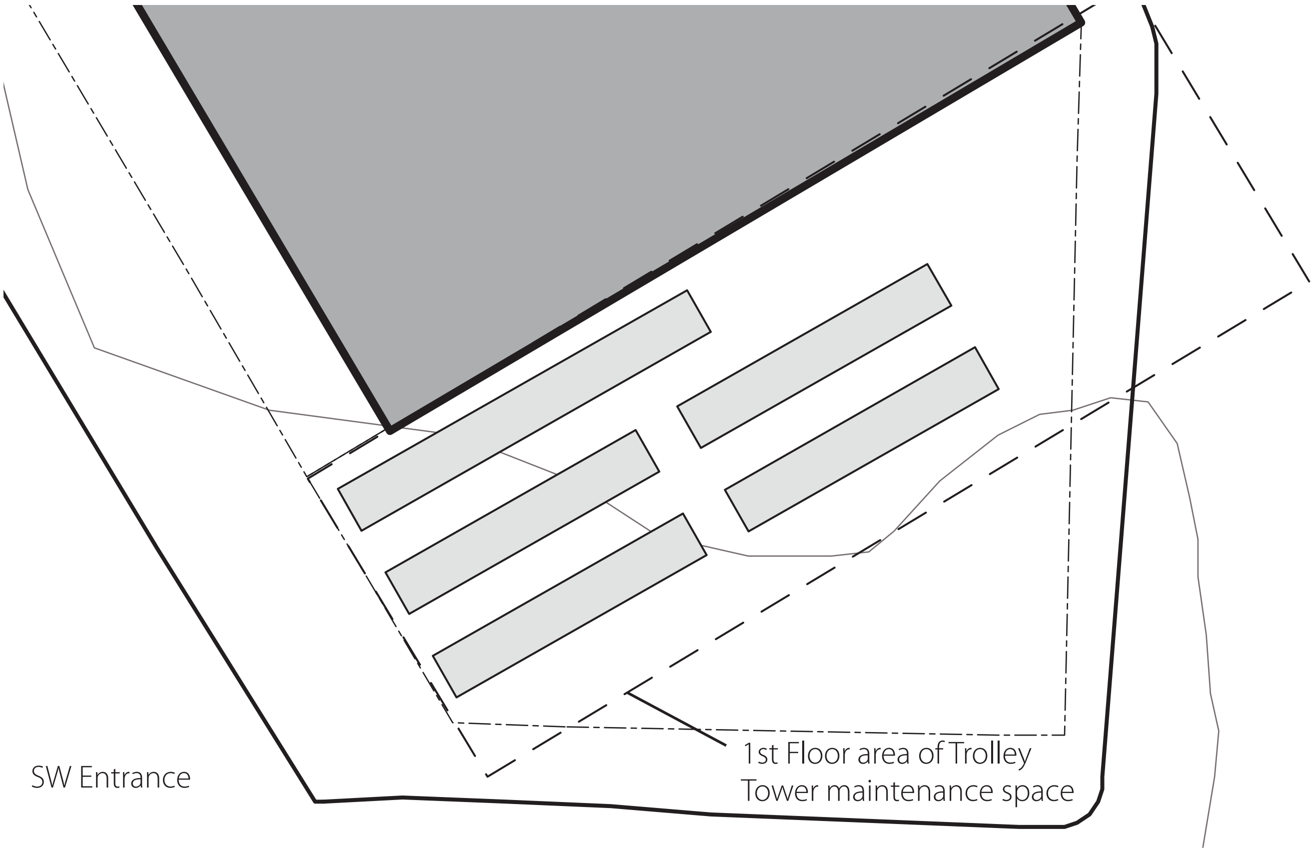
Trolley Line Plan

1: 15,000



Preliminary Feasibility Studies

1/32″ = 1′



Program info

Program adapted from 2007 Mithun Trolley Tower design

Trolleys	(dimensions in feet)		
	l	w	h
Vintage Car	48	9	10.5
Modern Car	67		
Wire heights (min)	18 (in shared ROW)		
	17 (in exclusive ROW)		
Avg Rail Radius	82		
Min Rail Radius	66		

1st Floor					
	l		w		SF
Overall	**180**	**x**	**58**		**10,440**
Work Area	160	x	58		9,280
Straight Track Run	115	long			
2 x sunken work pits	68	x	10		
	47	x	10		
Aisles	8	wide			
Support Areas	20	x	58		1,160
Storage Areas	22	x	12		
	20	x	12		
1/2 Bathroom					
Work Sink Area					
Garbage / Recycling					
2nd Floor					
Floor-to-floor	13.25				
Overall	**58**	**x**	**25**		**1,450**
Breakroom	10	x	12		120
2 Offices	9	x	12	2x	216
Wet Areas	12	x	15		180
1/2 bath					
Shower room					
Lockers					
Electrical testing bench	12	long			
Storage area	14	x	20		280
Total					**11,890**