Architectural Design 2.0:
An Online Platform for the Mass Customization of
Architectural Structures

By

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B.S. Architecture, University of Minnesota, 2004

Submitted to the Department of Architecture
In partial fulfillment of requirements for the degree of

MASTER OF SCIENCE IN ARCHITECTURE STUDIES
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
SEPTEMBER 2009

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ABSTRACT

Not only are there incredible inefficiencies in the current practice of design, fabrication
and construction of architecture, but, until now these processes have been limited to
costly design professionals, wasteful manufacturing facilities and labor-intensive site
work.

Architectural Design 2.0 is a vision for rethinking these processes in order to empower
consumers and users of architecture with the tools and resources necessary that will
enable them to design and produce their own mass customized architectural structures.
Such a change will be achieved by integrating digital fabrication technologies with the
massive shift in Internet usage behavior commonly known as Web 2.0. This thesis
begins with an historical framework of user-generated design and production in
architecture and follows with an introduction to a digital-to-physical translation
procedure that harnesses digital fabrication with an online open-source design platform.
Finally, this thesis provides evidence of a working model for Architectural Design 2.0 by
delivering a set of user-generated, full-scale prototypes.

Thesis Supervisor: Lawrence Sass
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Acknowledgements

This thesis would not have been possible without the guidance and inspiration of my advisor Larry. His support and encouragement got me into the SMArchS degree program and his wisdom and friendship got me through it. Along the way, Larry provided me with the opportunity and freedom to develop not only my thesis ideas and academic career, but also personal life goals. Thank you, Larry, for everything.

It was during Irving Wladawsky-Berger’s class that the ideas for my thesis began to coalesce. His unique perspectives—especially with his non-architecture background—provided me with the inspiration and challenge to address the wider audience this thesis aims to engage. Thank you, Irving.

Frank Piller’s expertise and wealth of knowledge, and his eagerness to share them with me, were unparalleled. Without his input, my thesis would not have been as well developed, critical or relevant. Thank you, Frank.

In addition, I would like to thank Bill Mitchell for his support. For a man whose wisdom and insight are more sought after than anyone else I know of at MIT, it is my honor to have him read my thesis. Thank you, Bill.

I would also like to thank all of the CNC fabricators who were willing to participate with the research and sent me excellent documentation.

I’d like to thank ShopBot Tools, Make Magazine and Boise Cascade for their generous sponsorship of projects related to the work of this thesis.

Also, thank you Meejin Yoon and Eric Höweler for your support and encouragement.
Lastly, I would like to thank my friends and family. To do any justice here, and give back what so many people have given me, I would need another hundred pages.

The most inspirational person during my time at MIT has been my friend and unspoken mentor, Kevin Parker. He was there for me in the good and the bad. Thank you, Kevin.

While my friend Dennis Michaud may be the most intelligent person at MIT, he’s also the least selfish. Many of the ideas in this thesis come from him and I owe him whatever future successes I come upon. Thank you, Dennis.

My friend Viktorija saw me through the rough times with her warm heart and ability to make me laugh. Thank you, Viktorija.

My Morgan has been the light at the end of the tunnel, everyday. She’s also the reason this thesis is written as well as it is. Thank you, Morgan.

Lastly, I would like to thank my family. Without their unconditional love and support, this thesis would have never happened. Thank you Mom, Dad, Jason, Randy, John and Leah.

I’d especially like to thank my sister, for always being there. *My thesis is for you, Leah.*
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Architectural Design 2.0

An Online Platform for the Mass Customization of

Architectural Structures
Part I

1.0 Thesis Introduction

1.1 The Thesis Question
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1.0 Thesis Introduction

1.1 The Thesis Question

How can architectural designers better utilize the Internet to empower consumers of architectural structures with more control over the design and production process and thereby enable the mass customization of small inhabitable structures?
1.2 How Can Architectural Designers Better Utilize the Internet?

This thesis proposes that architects and professional designers can better utilize the Internet by moving away from static, “portfolio” websites and shifting towards dynamic “user-driven” web platforms. Architectural designers are far behind the technology curve when it comes to using the Internet as such – common practice in the industry today is to simply display design work in the form of pictures and videos to potential clients. In other words, it is common for many architects today to use the Internet to present work that they have already accomplished – e.g., a portfolio or collection of photographs, diagrams and drawings – as a way to convey to a client what the designer could create for them. As Terry Flew describes in *New Media*, this type of communication and utilization of the Internet is categorized as “Web 1.0”: websites that serve only to publish data, offer one-way communication and contain ‘read-only’ content.¹

Technologically, this one-way communication was the result of low broadband speeds, limited browser capabilities, and a lack of Internet-based software applications and languages like Flash and Java.² Additionally, as Tim O’Riley points out, there were many concerns about privacy, copyright protection, standardization for displaying user-generated content, and widespread Internet-based computing illiteracy.³

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¹ Terry Flew. *New Media*, 33.
² Dion Hinchcliffe. “Web 2.0 Blog,” see http://web2.socialcomputingmagazine.com
As these technological barriers have been surpassed and the change in behavior of how we utilize the Internet have converged into what is commonly known as “Web 2.0,” the question arises: why have architects and designers not followed suit? In other words, why do so many architects fail to use the Internet as a platform to allow clients and users to more fully engage in the design process, allowing for two-way communication and dynamic user involvement? There are generally two cited arguments. First, it can be argued that design work is the core service offered by architects and opening this process to the user would result in architects losing their competitive advantage—they would be left with little to distinguish themselves from the user. When examining the entire process of architectural services, however, it is commonly known that design work only accounts for roughly 10% of what architects actually do. The majority of their time is spent on project management tasks, like coordinating the relationships between all of the parties involved.

The second argument is that architectural design requires a trained professional with expert skills and tools to successfully execute design work. But increasingly the tools that architects use-- such as design software and digital prototyping and manufacturing equipment-- are becoming widely available and more easily implemented by non-experts. Examples of these tools will be more thoroughly described in later chapters.
1.3 Engaging the User in the Design and Production Process

By proposing that architectural designers should offer a dynamic web platform instead of a static portfolio website, this thesis shows how architectural designers can engage the user in three traditionally exclusive processes: design, project management and assembly. Thus, such a platform would potentially allow for user-generated design, a user-controlled fabrication network, and user assembly of the physical structure. Much research exists that illuminates the possibility for user-engagement and its benefits for everyone who participates. Eric von Hippel describes how this user-centric approach has transformed the custom design of semi-conductor computer chips:

“A variety of manufacturers have found it profitable to shift the tasks of custom product design to their customers along with the appropriate toolkits for innovation. Results to date in the custom semi-conductor field show development time cut by two-thirds or more…and development costs cut significantly as well via the use of toolkits.” ^4

1.4 Focus on Accessory Scale Structures

In order to focus the research and make possible the delivery of a physical prototype of the results, this thesis limits its scope and definition of architectural design to accessory scale structures. This is a standard industry term for categorizing small yet inhabitable structures, including but not limited to: tool and storage sheds, detached studios and garages, backyard offices, kid’s playhouses and doghouses. While the concepts

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developed in this thesis could be applied to larger scale structures like residential housing or commercial buildings, the intention here is to holistically examine an entire process from start to finish and deliver a set of physical structures that are designed, managed and assembled by non-expert users.

1.5 Thesis Proposal and Deliverables

This thesis proposes a web-based platform that engages non-expert users in the design and production process for the mass customization of accessory scale structures such as backyard sheds, cabins, kid’s playhouses, etc. The web platform will serve two primary functions: First, it will serve as a membership-based design community that enables novice designers to interact and communicate with each other through the design process by sharing their designs with other community members. The platform enables these members to digitally design their own accessory structures online and have their designs translated into easily assembled kits of CNC “machineable” parts.

Second, the web platform serves as a distributed fabrication network management tool that brings transparency to the fabrication and production process, enabling users to make smarter and more sustainable decisions about the physical production of their designs. The platform allows users to select from an interactive map of local fabricators and local material sources. In providing this service, users are given the
opportunity to have their designs CNC fabricated and delivered to their front door at a lower cost and with a lower carbon footprint than (what?).

In addition to developing the web platform, this thesis delivers a set of physical prototypes testing the user-engagement process with cases where isolated and distributed users design, fabricate and assemble their own physical architectural structures. As such, these users are considered beta-testers and the thesis documents their experience and draws conclusions based on the results achieved.

1.6 Why Is an Architectural Designer Proposing This?

As an academically trained and practicing architectural designer it might seem out of place that I would pursue a thesis which empowers non-trained and inexperienced ‘amateur’ designers with the tools and resources to design inhabitable scale structures on their own, seemingly without the need for design professionals. It is important to note, however, that this thesis does not make the argument that professional designers are no longer important or needed, but rather suggests that the role of architectural design professionals is beginning to dramatically change and there is a potential for professional designers to maintain their value to society by rethinking the design process altogether.

Throughout my academic training I have come to realize that ‘good design’ has become commoditized – meaning, it is no longer enough on
its own. Needless to say, this might cause a design student to become disillusioned in his career choice – it certainly did for me. I recall a well-respected design studio critic remark that “good designers are a dime-a-dozen” and rather than concern ourselves with the function of a design or its form, she asked us to pursue in our studio work new ways of structuring the design process as a whole. For architectural designers to move forward into the 21st century and innovate within the profession, we need to reconsider the organizational framework for how design takes place.

Increasingly I have become aware of how insular the majority of the architectural design profession and academic design curriculum has become. Certainly in schools, the user or client is seldom considered an important part of the design process. According to this model of education, design takes place in a vacuum without the interference of users and clients. To this day, many still hold on to the romantic notion of the single “genius architect,” busy in his isolated studio, solving the problems (more often just creating new ones) of the world around him. Even outside of design schools, where one quickly realizes the importance of and decision-making power held by clients, this attitude is common. In addition to the numerous other parties involved, the client is considered to be one who needs to be “educated” in what the design professional has provided as the solution. My thesis is in part a reaction to this notion – not that I see this as necessarily perverse – rather I see it
as inverse – it is the designer who needs to be educated by the client and by the world around him.

It took me seven years of design training and professional practice to embrace the notion of innovation within the architectural profession. For me and most of my peers in architectural design training and practice, innovation in design has meant coming up with another iteration, or coming up with another detail or formal proposition. This idea of innovation has led to the homogenization of architectural design and keeps the architectural profession a very inward focused and exclusive community. Instead, I now see innovation in design as a complete restructuring of the process as a whole – it is a way to share with and empower those around me with the ability and resources to design for themselves. There is a major cultural shift in progress that is converging with radical online communication technologies that enables this notion of innovation to exist: the convergence is empowering ordinary online users with the ability to more directly and positively affect the physical world around them. I imagine that within the not-too-distant future, nearly all consumer products, from t-shirts, to automobiles to the houses we live in will be designed, produced and created by non-professionals and non-expert online users entirely from their home computers.
1.7 Why Is This Important and Relevant to the Design Profession and the World?

There is a long history of user-engagement in the architectural design and production process dating back to the early 20th century specifically within the development of manufactured and pre-manufactured (prefab) housing. Where the majority of existing research traces this development in terms of design output; this thesis examines design input and the level of user engagement throughout the process. Framing the research as such is important and relevant to the design profession because it will reveal the historical pattern between the convergence of new technologies and cultural shifts and how the design profession has reacted and adapted in the past. As we move forward in the 21st century with rapidly emerging communication technologies and major cultural shifts (including the current economic crisis) it is important for designers to understand the past in order to make smart decisions when planning for the future.

Outside of the design profession, this thesis recognizes the value of engaging non-experts more directly in the design and production process because it has the power to transform consumers into the producers of his or her own designs. The act of design is a very powerful educational tool that allows people to learn about themselves, learn about the world around them and learn about their role in the built environment. It is only through education and transparency that we can enable people to make
smarter and more sustainable decisions about the products they choose and use and the buildings they inhabit. Additionally, by harnessing the power of new technologies and engaging online users in the production process, local economies are strengthened and the use of local materials and community labor sharing is encouraged.
2.0 A History of User Engagement in Architectural Design

2.1 Traditional Architect-Client Relationship

2.2 Mass Produced, Factory-Built and Pre-Fabricated Architecture

2.3 Examples of User-Engagement throughout the 20th Century

2.4 Technological Advancements and Culture Shifts

2.5 User Engagement and Current Trends
2.0 A History of User Engagement in Architectural Design

This chapter surveys the history of how end-users have participated in the design, production and assembly process of architectural structures, specifically focusing on factory-built and mass-produced housing. Where the majority of existing research in this field traces the development in terms of design output—the types and styles of houses produced; this chapter examines design input—the level and degree of user engagement throughout the design and production process. Following a brief introduction of industry terminology, this chapter presents examples of user-engagement in three influential housing companies. By tracing the development of user engagement dating back to the Aladdin Home Company at beginning of the 20th century, this chapter reveals the relationship between technological advances and cultural movements that directly correlates to the level and degree of user participation in the design and production process. This frames the thesis argument within the context of recent technological advances that have converged with major cultural shifts and makes this thesis proposal possible, relevant and beneficial to professional designers and consumers alike.
2.1 Traditional Architect/Client Relationship

In the context of this chapter, user-engagement is distinguished from the typical client-architect relationship, in which an architect provides professional services to a client through direct dialogue and fee-based interactions for the design of one-off architectural structures. Rather, as used here, user-engagement within the context of factory-built and mass produced housing, refers to the ability of end-users to either directly control the design and production process, or control it indirectly through the ability to customize and personalize within a framework of component options – entirely without the need for professional service agreements.

2.2 Mass Produced, Factory-Built and Pre-Fabricated Architecture

First, it is important to introduce key terms and definitions within the industry, as today there are dozens of terms that imply factory-made housing – manufactured, prefabricated (prefab), modular/sectional, kit, pre-cut, panelized, and so forth. What distinguishes these variations of construction methods from each other is the degree to which the construction or assembly is completed off-site. For example, a manufactured house, which is most commonly known as a mobile home, is almost entirely assembled within a factory and trucked to the final destination as a completed and finished product including electrical wiring, heating and cooling systems, and finish materials such as flooring and trim. In contrast, a pre-cut or ‘kit house’ is typically delivered to the
final site as a package of construction materials that have been cut to size and specification in a factory but require assembly and finishing on site.\textsuperscript{5} Today, the most common form of factory-built housing (in the US) is modular—popularly, but inaccurately, known as prefab.\textsuperscript{6} Modular homes are constructed in a factory as a kit of units (typically one-room boxes) that are trucked to the final site and connected together with a crane and highly skilled construction crew.

These variations of factory-built housing can all be distinguished from traditionally built or on-site constructed housing in two interrelated ways. First, with traditionally built methods, the construction materials are delivered to the site in standard units that are not specified or pre-cut for one particular design and, as such, must be modified on site. For example, a standard delivery of material to the construction site might include one hundred 2x4s, fifty sheets of plywood and a palette of bricks. A builder is then required to measure and cut each one of these members individually to meet the design requirements. The other distinguishing factor between factory-built and traditional-built has to do with building codes and the stage of construction during which code approval is given.

\textsuperscript{5}Consumer Guide. The Complete Book of Prefabs, Kits and Manufactured Houses, 6.
\textsuperscript{6}‘Prefab’ housing is not an industry term and more commonly refers to a modern or contemporary style of factory-built housing. Houses that are considered prefab are usually a combination of modularized and panelized systems where the final site conditions (owner’s lot) might favor one over the other. Source: http://en.wikipedia.org/wiki/Prefabricated_home
2.3 Examples of User-Engagement Throughout the 20\textsuperscript{th} Century

Beginning at the turn of the 20\textsuperscript{th} century, the first well known housing company that offered mass-produced and factory-built houses was a company from Bay City, Michigan named Aladdin Homes. Founded in 1906 by W. J. Sovereign, the Aladdin Homes Company took advantage of mass media production and circulation along with the booming development of the national railway system to offer "mail-order" architecture to the general public through their Home Catalog (Fig. 2-1).

Fig. 2-1: Aladdin House Catalog Cover, 1917.
In this recent re-publication of the original Aladdin House Catalogue, John Freeman writes that while numerous illustrated pattern and style books had existed since the 1830s that “cut out local architects and enabled local builders to appear more sophisticated and stylish than they were,” through utilization of the expanding railway system, Aladdin Homes centralized the manufacturing and production of houses, and effectively removed skilled local labor and local millwrights from the process.7

Whether or not the removal of local labor was a favorable outcome, the Aladdin Home Catalog empowered a new consumer behavior in home buyers, aligning their decision-making power more directly with the design of a house, albeit limiting it to a selection and mix-matching process within a finite catalog of house designs. The Catalog offered consumers the choice of hundreds of different house styles and sizes via detailed illustrations, photographs, plans, and cut-away interior isometric drawings (Fig. 2-2).

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7 John Freeman, Aladdin Home Catalog, 42.
While commonplace today, this type of marketing was quite innovative for its time, as Freeman notes: “What sold these homes…were these difficult-to-make interior drawings…If a prospective client can be made to put himself inside a house on paper, the final sale is more than half way to a signature on the dotted line.” In addition to choosing between house styles and sizes, the Catalog also allowed consumers to customize their house with add-on porches, interior details such as colonnades and archways, and built-in buffets and bookshelves (Fig. 2-3).
Fig. 2-3: Example add-on features from Aladdin Catalog, 1919.

Not only were consumers and end-users more engaged in the design process at a mass scale, they were also more intimately involved in the manufacturing and assembly process of their house. The Aladdin Company developed a prefabrication method that they called the “Readi-Cut” system which they used to market the “Built in a Day House”. In a clever way of further empowering the users in the manufacturing process, they included in their catalogs marketing material that explained the system in terms of direct benefits to the consumer:

“Modern power-driven machines can do BETTER work at a lower cost than hand labor. Then every bit of work that CAN be done by machines SHOULD be so done. Think of applying this system of savings
throughout all the lumber used in building your home! Think of your own good money it saves!”

With the “Readi-Cut” prefabrication system all of the lumber for a house was uniquely cut-to-fit, individually marked and numbered in the factory, and then delivered to the user’s building lot as a kit of parts, making it possible for the home buyer to assemble the house by themselves. While this assembly method certainly decreased the need for skilled labor – i.e., the construction contractors who traditionally cut, measured and constructed houses ‘from scratch’ – local labor was not eliminated but rather redefined as a social activity. In fact, a movie celebrity of the time, Buster Keaton, starred in a silent film in 1920 named “One Week” about a newly-wed couple who received a prefabricated house kit and humorously struggled to assemble it (Fig.’s 2-4 and 2-5).

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9 Freeman, Aladdin Home Catalog, 3 and 5.
10 Buster Keaton, director, “One Week.”
Fig. 2-4. Buster Keaton and Sybil Seely in the 1920 silent film, One Week.

Fig. 2-5. The humorous prefab house assembly in the 1920 silent film, One Week.
Two years after Aladdin Homes was founded, another company entered the growing industry of factory-built housing: Sears, Roebuck and Co. Sears was already very well established in the mail-order consumer goods business – by the turn of the century its catalogs offered such goods as watches and jewelry, sewing machines, sporting goods, musical instruments, firearms, buggies, bicycles, and men’s and children’s clothing.\textsuperscript{11} Thus, when Sears established its Modern Homes Department in 1908, it was not a challenge for them to quickly capture large market percentage within a few years. By 1930 they had sold nearly 50,000 of their “Honor-Bilt” houses, operated five lumber mills and had 48 nationwide sales offices.\textsuperscript{12}

While Sears’s “Honor-Bilt” houses were marketed and manufactured in similar fashion to the “Readi-Cut” houses offered by Aladdin, the shear magnitude and cross-market reach of Sears enabled them to offer consumers a much more complete and customizable home package. Through their Catalog, home-buyers were able to purchase – along with the home kits – all of the electrical and plumbing fixtures, heating systems, furniture to match the house style and even paints, stains and draperies (\textit{Fig. 2-6}).\textsuperscript{13}

\textsuperscript{11} Sears Archives Website, see http://www.searsarchives.com/catalogs/history.htm
\textsuperscript{13} Ibid, 36-37.
Though the catalogs offered by Sears and Aladdin were nearly identical in their strategies for engaging the user in the design and production processes, Sears offered a broader range of houses and more customization options. “The catalogs contained everything from modest two-room cottages to 8-10-room residences, in a range of Colonial,
English, Spanish, Norman and other architectural styles.” \(^{14}\) And with the 48 Sears sales offices, the home-buyers could receive personalized service where they would further customize the designs within the catalog, or they could bring in their own home designs and Sears fabricated it for them using the “Honor-Bilt” system. Additionally, the Sears catalog concentrated on comparing their prefabrication system with the largest competitor – traditionally-built homes. Their catalog showed detailed analyses of their assembly process compared to the traditional construction process, highlighting the time saved, decreased material waste and increased labor efficiencies (Fig. 2-7).

![Fig. 2-7: Sears’ ‘Honor-Bilt’ Prefabrication System vs. to Traditional Construction, 1926.](image)

\(^{14}\) Ibid, 25-29.
Perhaps the most well-known and highly anticipated – but certainly the most short-lived company to offer mass produced houses was the Lustron Corporation. Within one year of its founding in 1946 Lustron secured $40 million in federal funding, operated a one-million square foot production facility and planned to manufacture 100 houses per day using its state-of-the-art porcelain-enamed steel panel assembly system.\textsuperscript{15}

With the manufacturing speed, efficiency and cost-saving economies of scale only achieved to date within the automobile industry, founder Carl Strandlund set out to become the “Henry Ford of housing” by capitalizing on the recent technological advancements in the machine tool and steel material handling industries developed during World War II.\textsuperscript{16} The Lustron Corporation came to a crashing halt, however, when the company filed for bankruptcy after only 5 years of operation and building only 2,498 houses.\textsuperscript{17}

While the story of this ‘magnificent failure’ is a fascinating lesson in politics, economics, technology and social progression, the intent of this chapter is to examine the historical patterns of user-engagement in mass-produced housing. As such, when we look closely at Lustron’s offering to consumers we find, in comparison to the Aladdin and Sears houses, a decrease in user participation in the design, production and assembly processes. This is due largely in part to the economies of scale needed

\textsuperscript{16} Ibid, 2 and 14.
\textsuperscript{17} Ibid, 1.
for the one million square foot factory to be productive and was reinforced by the dealer-franchise model which rewarded high sales volume namely through large scale suburban developments. Lustron made this clear to its dealers and stated in policy circulars: “The volume of business Lustron must have cannot be achieved by ‘custom selling and custom financing.’ Houses should be built before they are sold.”18

The degree of design flexibility or even individual house design options afforded to the Lustron customer reflected this mentality: the initial offering to customer for the first four years of operation was one design, named “The Manchester,” which came in four colors (Fig. 2-8).19 Lustron was indeed managed from the top-down in terms of how they viewed and interacted with the user. For example, this was one of their national advertising slogans: “The House America Has Been Waiting For.”20 In the last year of operation, Lustron had plans to increase product range and optional amenities, however, these were never fully developed and were not widely brought to market before Lustron’s collapse in 1951.

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18 Ibid. 158.
19 Ibid, 137.
20 Ibid, 2.
In addition to exclusion from the design and customization process, the complexity, novelty and the number of steel components of Lustron’s “Manchester House” prevented users from participating in the assembly process (Fig. 2-9). This was an additional reason why Lustron implemented the dealer-franchise model: extensive training was necessary in order for local installation crews to assemble the houses. Even this proved to be difficult. The dealers complained about the level of complexity: “You could paper the walls with the assembly blueprints,” and further reported that it took nearly 1,200 man-hours to assemble each house—four times the company estimates.21

21 Ibid, 147.
Whether or not the level of user-engagement in the design and production processes played a role in the ultimate failure of the Lustron Corporation would make for good further research; this chapter, however, does not attempt to make such arguments. Each one of these companies greatly contributed to, if not altogether created, the industry of mass produced housing during the 20th century. Even though the Sears Modern Home Division collapsed during the Great Depression and Aladdin Homes was able to survive and prospered until the 1980s, throughout the latter half of the century not much innovation took place in the factory-built housing industry – especially in terms of user-engagement in the design and production process.
2.4 Technological Advancements and Culture Shifts

As this chapter touches upon throughout the three examples, there were two main factors that brought about user-engagement innovation in factory-built housing: technological advancements and major socio-economic shifts. Large technological advancements such as mass communication devices and delivery mechanisms, rapidly expanding national railway networks and mechanization of factory-based labor directly influenced the ease through which users could participate in the design and production of their own homes. When these technological advances converged with major socio-economic shifts such as the Great Depression or post World War II housing shortages, the innovation was fast-tracked, although many times at the expense of an individual company’s fate – and new industries were formed overnight.

2.5 User Engagement and Current Trends

In conclusion, it can be proposed that today society is in the midst of another pivotal convergence of major technological advancement and socio-economic change that will directly impact user-engagement in the design and production of factory-built and mass produced houses. Where the development of mass media in the early 20th century opened up a one-way communication line between manufacturers and consumers, the development of the World Wide Web in the late 20th century opened up two-way communication between consumers and manufacturers, as well as an unprecedented channel of communication
amongst the users themselves. This type of communication is still in its infant stage and with the recent phenomenon known as Web 2.0, the interaction between users will undoubtedly become increasingly sophisticated and multi-faceted. When this communication technology is coupled with user-friendly online design tools and readily-accessible personal fabrication equipment, the possibility for user participation in the design and production process increases exponentially. These technologies are impressive on their own, but what ignites the possibilities and transforms them into realities are major socio-economic shifts. The debate is still out on whether our current economic and housing crises will be the ignition for a new paradigm of user-engagement in the mass-produced housing industry.

22 Interestingly, owners of Lustron Homes have recently been using the Internet to re-establish nostalgia and popularity of the historically significant homes. Many owners have created websites and blogs where they share photos of their prized houses, along with their experiences and stories of maintaining their homes. See: http://www.lustronconnection.org/index.html.

3.1 Convergence of New Technologies and Cultural Shifts

3.1.1 Digital Fabrication Technologies

3.1.2 Web 2.0

3.2 Digital Fabrication + Web 2.0

3.3 Architectural Design 2.0 Web Platform

3.4 Distributed CNC Fabrication Network

The vision of this thesis is a paradigm shift that will transform architectural design and production by rethinking the traditional processes and platforms through which our built environment has been designed, manufactured and constructed. The rethinking of such processes and platforms means that any online user, whether they farm in rural China or work as busy professionals in New York City, can play an active and participatory role in the design and construction of the built world around them. This paradigm shift challenges the traditionally closed architectural design and production processes. Users no longer need to rely on expensive design professionals, resource-intensive manufacturing, or wasteful and laborious construction processes: the vision of this thesis integrates the knowledge and expertise of design professionals with readily available digital design and fabrication technology in an open-source platform where online users, both expert and non-expert designers alike, communicate and collaborate through the act of design.

Figure 3-1 is an illustrated diagram of this web-based design and production process.
Fig. 3-1: The vision for a web-based architectural design and production system.
This shift in architectural design greatly impacts our culture and environment on many levels. The web platform proposed here not only allows for an open-source model of design information and resource sharing between users world-wide, but it promotes the utilization of local manufacturing. A central component of the web platform is a distributed fabrication network linking together local and small-scale CNC fabrication facilities which bring manufacturing closer to the end user, dramatically reducing carbon emissions generated during the delivery process. In addition, the distributed fabrication network has the potential to strengthen local economies by engaging people in the making of things – a social mandate recently praised by the Obama administration.23

This thesis is relevant and critical to our era and it proposes more than simply another design tool that capitalizes on new technology and it also offers more than just mass customization and personalization opportunities. Instead, it proposes an open-source design process and fabrication network that engages and empowers users throughout the design, manufacturing and delivery process – giving them access to the tools and resources that will enable them to make smarter and more sustainable decisions about how they impact the built and natural environment.

23 President Barack Obama, Inaugural Address. Washington, DC: January 2009. “In reaffirming the greatness of our nation we understand that greatness is never a given. It must be earned. Our journey has never been one of short-cuts or settling for less. It has not been the path for the faint-hearted, for those that prefer leisure over work, or seek only the pleasures of riches and fame. Rather, it has been the risk-takers, the doers, the makers of things -- some celebrated, but more often men and women obscure in their labor -- who have carried us up the long rugged path towards prosperity and freedom.” See http://www.whitehouse.gov/blog/inaugural-address/
3.1 Convergence of New Technologies and Cultural Shifts

Integral to the vision of this thesis is an understanding of recent technological advancements and major cultural shifts that make the proposal of an open source design and distributed production process achievable and relevant in architectural design today. Where as Chapter 2 presents an historical overview of user-engagement in architectural design and illustrates how certain technological and cultural changes facilitated this engagement; Chapter 3 will provide an overview of recent advancements – the timely development of digital design and fabrication technologies which have converged with the phenomenon in internet usage behavior, commonly known as Web 2.0. Following this overview the chapter will describe how this vision harnesses such technological advancements and cultural changes through which the web platform will allow for user-engagement in the design and production of architectural structures.

3.1.1 Digital Fabrication Technologies

Digital Fabrication can be generalized as the integration of two processes: digital or computer-aided design (CAD) and Computer Numerically Controlled (CNC) fabrication. Digital design dates back to the mid 1960’s when Ivan Sutherland first developed a software program for his MIT PhD thesis called “Sketch Pad,” which was further developed
into what is now known as AutoCAD.24 This has been the industry standard for professionals in industrial, architectural and civil design for the last 3 decades; however, numerous other design software have recently been developed which are pushing the role of digital design beyond a ‘digital drafting board’ and into the realm of 3D life-like and information-rich modeling. Computer Numerically Controlled (CNC) fabrication also dates back to the mid-20th century where it was developed for and used in military and aerospace manufacturing25, but has, in the last three decades, been applied in non-industrial markets such as by furniture manufacturers and cabinet makers. CNC fabrication works by taking digital information from the geometry of a design model and generating cut files that can be read by a computer that automatically controls a cutting device, typically a router bit or laser beam, and precisely cuts the design geometry out of a material substrate, such as wood, plastic or metal (Fig. 3-2).

Central to the vision of this thesis is a recognition of the transformation in and trends for making digital fabrication technologies such as these accessible to and useable by non-expert individuals. The outcome and power of this transformation is well stated by Eric von Hippel in

Democratizing Innovation:

"When the cost of high-quality resources for design and prototyping becomes very low, these resources can be diffused widely, and the allocation problem diminishes in significance. The net result is and will be to democratize the opportunity to create."²⁶

As discussed above, throughout most of their development, digital design software and CNC hardware were used by highly skilled professionals and craftsmen who required technical training and years of experience to apply these technologies in their fields. Recently, however, as the cost of these technologies has dramatically decreased, they are becoming available to novice users with little to no technical training.

Examples of this transformation are found in both digital design software and digital fabrication hardware. 3D design software packages such as Google SketchUp, Alibre and Design Workshop Lite are now available online as free downloads. There are also dozens of low-priced 3D home design software packages such Instant Architect, and Punch! Home Design Architectural Series, and Better Homes and Gardens Home Designer Suite that enable novices to instantly begin designing and visualizing architectural designs without any formal training. In addition to digital design software, the availability and usability of digital fabrication hardware such as CNC milling machines, laser cutters and 3D printing devices has increased. Companies such as ShopBot Tools and Desktop Factory are now offering consumer grade fabrication tools, such as CNC

²⁶von Hippel, Democratizing Innovation, 14.
milling machines and 3D printers, respectively; at one-tenth what they
would have cost 20 years ago (Fig. 3-2).

![Figure 3-2. A CNC milling machine (left) and a home desktop 3D printer (right).]

### 3.1.2 Web 2.0

*Facebook, Myspace, YouTube, Flickr, Twitter, BitTorrent, LinkedIn, Delicious, Wikipedia.* These are all familiar and popular examples that broadly define Web 2.0. What makes these and the thousands of other examples of Web 2.0 applications unique to the last 5 years of web development and internet usage behavior is the large degree to which the users, rather than singular or professional developers, contribute to and generate the content. Originally coined in 2004 by Dale Dougherty and Tim O’Reilly of O’Reilly Publishing, Web 2.0 was conceived as a marked transition from using the web as a static source or collection of websites for information retrieval, to using the web as a dynamic framework or
platform where information is created, shared, transformed and openly
distributed by any and all users.27

While there were technological advancements in computer programming
that helped facilitate this change and have made it easier to develop such
open platforms (including programming languages such as XML,
JavaScript and Ajax), the development of Web 2.0 is more appropriately
understood as a cultural shift. Tim Berners-Lee, who is considered to be
the ‘inventor’ of the Internet as we know it today, argues that in the initial
conception of the web (now dubbed Web 1.0) the technological
framework for facilitating user collaboration already existed:

“Web 2.0 means using the standards which have been produced by all
these people working on Web 1.0. It means using the document object
model, it means for HTML and SVG and so on, it's using HTTP, so it's
building stuff using the Web standards.”28

With the existence of this framework in place since the early 1990s, it is
clear that Web 2.0 is less about a technological feat and more about a
massive change in online user behavior. The number of users
participating in and driving this cultural change is staggering – Facebook
alone has 250 million active members.29

27 Tim O’Riley. “What is Web 2.0? Design Patterns and Business Models for the Next Generation
20.html
http://www.ibm.com/developerworks/podcast/dwi/cm-int082206.txt
29 See: http://en.wikipedia.org/wiki/Facebook
3.2 Digital Fabrication + Web 2.0

While the development of new digital design and fabrication technologies and discussions of the cultural shift of Web 2.0 are interesting in their own right, this thesis focuses is interest with a vision that integrates these changes and outlines their unified potential for application in architectural design. While the massively popular social networking sites mentioned above now allow online users to share and communicate with each other, the resulting product still remains in virtual space or digital form— that is, people are only generating digital input and output. And whereas consumer-level digital design software and hardware allow people to more-easily-than-ever design and physically produce their own creations, the result is still limited to individual use. People are still isolated and cannot communicate together through these processes. By bringing together the millions using Web 2.0 applications and services and who already are accustomed to creating and generating their own online content with the emerging consumer-level digital fabrication processes, this thesis hopes to initiate a paradigm shift that transforms and captures user-generated input (digital design) into user user-generated output (physical architectural structures).

3.3 Architectural Design 2.0 Web Platform

The Architectural Design 2.0 web platform proposes to capture and harness digital fabrication technology and Web 2.0 and performs two critical roles. First, it serves as an open-source online design community.
This is where members can communicate through and participate in architectural design by sharing ideas and iterating on other member’s designs. In contrast to the dozens of existing online design communities that allow users to custom design and have fabricated consumer goods and whose primary aim is to create mass customization marketplaces where members can sell their designs, the focus of the platform proposed here is concerned more with enabling users to collaborate and share ideas through the act of design. On the Architectural Design 2.0 platform, users can register as Community Members where they get access to the 3D digital designs of architectural scale structures created and modified by the thousands of other members. As a member of this community, users will be able to freely upload and download such 3D models and if and when they desire, they may also choose to have their design fabricated into a kit-of-parts and delivered to their site, whether that design is completely of their own making, of someone else’s doing, or of some combination thereof (see Appendix for images of Architectural Design 2.0 Web Platform).

3.4 Distributed CNC Fabrication Network

Second, the Platform will serve to establish and manage a geographically distributed fabrication network comprised of small scale and individually operated CNC fabrication facilities (Fig. 3-3).
Similarly to how individuals register as Design Members of the Platform so that they can design architectural structures; individuals who own and operate CNC milling machines can become Fabricator Members allowing them to fabricate architectural structures as a service to the Design Members. The vision of establishing such a network is to capitalize on an already existing but yet-to-be unified infrastructure of architectural fabrication, where dependence on traditional large-scale, centralized and energy inefficient manufacturing facilities will no longer be needed. What makes this network possible, scalable and manageable is the common computation language found both in digital design and digital fabrication. Where traditional manufacturing in architectural design relies heavily on complex and project-specific communication between humans – the
designers, suppliers and manufacturers, etc; all that is needed with a
Distributed Fabrication Network is a computer network to transfer
fabrication files from one computer – which contains the design – to
another computer which operates the CNC machine. Thus, the Platform
will serve as the online hub that coordinates this file transferal between
the Design Members and the Fabricator Members.
Part II

4.0 The Missing Link: a Digital-to-Physical Design Translation Procedure

4.1 How This Is New and Why It Is Important
4.2 Current Practice
4.3 Design Configurator Limitations
  4.3.1 Physical Production Process: Standardized Modules and Components
  4.3.2 The Problem with Parametric Relationships
4.4 Digital Fabrication for Architectural Design and Production
4.5 Background Work
  4.5.1 Precedent Project: MIT Instant House
  4.5.2 Precedent Project: MIT Digitally Fabricated Housing for New Orleans
4.6 Digital-to-Physical Design Translation Procedure
  4.6.1 Translation Step 1: Defining Model Boundaries and Overlaying 3D Grid
  4.6.2 Translation Step 2: Generating Structural Ribbing from Grids
  4.6.3 Translation Step 3: Removing Rib Interference and Adding Attachment Geometry
  4.6.4 Translation Step 4: Generating the Outer Skin
  4.6.5 Translation Step 5: Connecting Rib and Panel Geometry
  4.6.6 Translation Step 6: Subdividing Panel and Rib Geometry
  4.6.7 Translation Step 7: Generate a CNC-ready Cut Sheet
  4.6.8 Future Work for the Translation Procedure
4.0 The Missing Link: Digital-to-Physical Design Translation

The following chapter discusses in detail a CAD modeling procedure- or high level algorithm- that illustrates the process for describing or 'translating' any 3-dimensional digital design of an accessory scale architectural structure into a kit of non-standardized interlocking flat parts which can be precisely and automatically fabricated on a computer numerically controlled (CNC) milling machine. One of the deliverables of this thesis is to describe this translation process as a clear and finite sequence of steps within a structured framework, through which future work may develop a computer programming language as a means to further automate the production process.
4.1 How This Is New and Why It Is Important

As discussed in Chapter 3, the vision of this thesis is to empower novice users and non-expert designers through an online platform with the tools and resources that will enable them to mass customize their own digital designs and have physically produced their own architectural scale structures. The examples in Chapter 3 demonstrate that these two processes (user-enabled design and participatory physical production) already exist or have existed to some degree, regardless of whether or not the design was digital and/or customizeable or whether or not the production process was computer controlled and automated. What does not yet exist and has not yet been proven possible, is a direct relationship between the digital design input process and its physical production output process that does not rely on the standardization of modules and components. Chapter 4 proposes one possible solution for this missing link.

4.2 Current Practice

Currently there is one widely used online method that attempts to achieve customization (beyond a simple mix-matching process or a component-based selection process found in the modular prefab industry) of architectural design and production at the mass scale. Most generally this method is known as ‘design configuration,’ whereby users are given parametric control over a set of pre-determined design constraints or possible configurations through a Graphical User Interface (GUI).
However, this method has achieved limited success both in terms of significant user-generated customization and significant mass appeal.

To illustrate this process, imagine the following scenario of someone who wants to design a backyard shed. She visits a website that offers customization of four different ‘styles’ of sheds – one with a single-pitched roof, one with a double-pitched roof, one with a flat roof, and one with a hipped roof (Fig. 4-1). Through the GUI she selects one of these styles and begins the customization process by using the design configurator. With the configurator she is able to push, pull and modify the existing features of the shed style that she originally selected. For example, she might pull the side wall further out to make the shed wider, or she might increase the roof pitch to match the design of her house, or she might make the shed taller by stretching the walls up further from the ground.

![Fig. 4-1: Clockwise from top left: Single-pitch, Double-pitch, Hip, and Flat roof styles.](image)
4.3 Design Configurator Limitations

To some degree, she has indeed *customized* the design, and for many users like her, this may provide enough customization for her needs. However, what is important to understand academically and to distinguish design configuration from what this thesis proposes, is that all the design choices made while using the configurator were already pre-determined as acceptable because they were within the limits of the physical production process. For example, to illustrate this key limitation of the configurator, imagine that a different user selected the flat roof shed style, however, during the configuration process he decides that he would like a barrel vaulted roof because he wants to show-off his aesthetic aptitude to his neighbor. He will be dismayed to discover, however, that a barrel vaulted roof is not possible through the configurator because it requires a radically different physical production and construction process which falls outside of the acceptable, predefined limits of the configurator. To expand upon and clarify this point, let us reframe the same design configuration scenario described above in terms of the physical production process and its pre-determined constraints as they are embedded in the configuration process.

4.3.1 Physical Production Process: Standardized Modules and Components

The key factor that pre-determines the limitations of any mass customized physical production process is standardization – both in terms of the
components (i.e. individual parts) and in terms of the modules (i.e. relationship between parts within a particular assembly system). In their recently published book, Lars Hvam, Niels Mortensen, and Jesper Riis, confirm this, adding:

“[One of] the central elements in a mass customization strategy is the mass production of a product range based on modules, so a customized product is put together by selecting, combining and possibly adapting a set of standard modules.”

30 Hvam, Mortensen and Riis, Product Customization, 1.

In contrast to this competitive business strategy defined by standardized modules and components, this thesis notes a limitation in this model and proposes an alternative strategy for mass customization.

4.3.2 The Problem with Parametric Relationships

Returning to the custom shed design configurator scenario, let us examine the standardization of its modules and components within the physical production process and illustrate specific and tangible examples. The components of the physical production process include standard building materials – 2x4's, 2x6's and sheet materials such as plywood and oriented strand board (OSB). The modules within the production system include assembly standards such as 16” on-center spacing between the stick components (2x4’s and 2x6’s) and 4’ and 8’ spacing between sheet components (plywood and OSB). What are essential to this production system are the pre-determined relationships that define how modules and components relate to one another. This is known as a

30 Hvam, Mortensen and Riis, Product Customization, 1.
parametric relationship. For example, looking closely at a particular wall within the shed that is 8’ long and assembled with 2x4’s and plywood, the parametric relationship determines that there should be six 2x4’s each spaced 16” apart and two sheets of plywood spaced 4’ apart.

Working with these standardized components and modules and the parametric relationships that define their assembly, we can now clearly understand the link between the custom design configurator process (digital input) and its physical production process (physical output). When the user in the above scenario decides to ‘pull the side wall further out to make the shed wider’, the configurator is programmed to ‘update’ that change. Whereas the wall started off being 8’ long made up of six 2x4’s and two sheets of plywood, once the user pulled and extended the wall to 12’ long, the parametric relationship determines that there needs to be nine 2x4’s and three sheets of plywood. So far, this user generated design choice, along with the two other initial choices (changing the roof pitch and making the shed taller), has been within the acceptable predetermined limits – that is, the original parametric relationship can just as easily define a 12’ long wall as it can define an 8’ long wall. It is able to by adjusting the number of components and relying on a modular assembly.

When the user, however, wants to express his unique creativity by changing the flat roof into a barrel vault he experiences the major
limitation of the design configurator and its integrated parametric relationships. As with the wall assembly, the original flat roof is pre-defined as a parametric relationship between components (i.e. 2x6’s and plywood sheets), and modules (i.e. 16” O.C. spacing and at 4’ intervals). Changing the flat roof to a barrel vault roof presents an insurmountable challenge to this pre-determined relationship – it is impossible to define a curved roof using the same components and modules that define a flat roof. In order to make this change, the relationship, including the set of standardized components and modules, needs to be completely redefined and ultimately replaced – which is beyond the control of the user.

While this is a very simplified example of how a design configurator works by integrating parametric relationships, which are defined by and limited to the physical production process, the underlying limitation on user-customization with design configurators is clear. There is a counter argument to this limitation, however. One such argument is that there could easily exist, in addition to the original four shed styles, a fifth choice – the barrel vaulted roof shed style – with its own unique components and modules defined by a new set of parametric relationships. While this is certainly true, the danger of this argument is that the number of unique sets of relationships that need to be predefined can quickly escalate and become unwieldy in practice. Hvam, Mortensen and Riis confirm this danger and suggest:
“An important precondition for the company being able to use modules and configuration systems is that it is possible to develop a product range and a set of business processes that are stable over time. This will normally pre-suppose a focused market strategy, in which the company chooses which customers it wants to service, and which customers it does not want to sell products to.”

4.4 Digital Fabrication for Architectural Design and Production

This thesis proposes a different approach to resolving the danger of such instability and the need for continuously redefined design configuration systems. While the solution presented by Hvam, Mortensen and Riis might indeed be a sound market-based business strategy, it nevertheless reduces the level of “mass-ness” possible in customization. Why should a customization process be suited to some users and exclude others? For mass customization to be truly ‘mass’, there should be no pre-determined criteria that favor one user’s creativity over another’s.

The remainder of this chapter presents a possible solution for mass customization that requires little to no pre-rationalized design criteria (such as the parametric relationships between standard components and modules found in design configurator systems) that are beyond the control of the user. This solution conversely abandons such standardization by proposing a ‘post-rationalized’ CAD translation procedure that more directly and precisely links the digital design input process with the physical production output process.

4.5 Background Work

First, a brief summary of the background research work and prototype projects that have led to the development and formulation of this new process is necessary. Beginning in 2003, the Digital Design and Fabrication Group at MIT, directed by Professor Lawrence Sass, began experimenting with the use of Computer Aided Drafting (CAD) tools combined with Computer Aided Manufacturing (CAM) tools with the intent to establish a new production and assembly system for mass customized housing in rural villages.32

4.5.1 MIT Instant House Project

Prof. Sass and Marcel Botha describe in their paper, “Instant House: A Model of Design Production with Digital Fabrication,” that their house project demonstrates the possibility for the use of digital design and fabrication based on physical construction rules (Fig. 4-2). Additionally, they cite evidence for the possibility of on-site and rapid manufacturing through utilization of small scale CNC fabrication machines.33

33 Ibid, 120.
Sass and Botha also note the labor-intensive CAD modeling limitations of their system and recommend a better solution:

“A formalized model of production will lead to computer programs that generate geometry for digital fabrication from an initial design shape.”

**4.5.2 MIT Digital Fabricated Housing for New Orleans Project**

Following the Instant House project, Sass was selected and sponsored by the Museum of Modern Art (NYC) in 2008 to design, fabricate and

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34 Ibid, 121.
assemble a New Orlean’s Style Shotgun house for their exhibit on pre-fabricated housing: “Home Delivery: Fabricating the Modern Dwelling” (Fig. 4-3). With this project, Sass, along with the author and other members of the Digital Design and Fabrication Group, set out to establish the ‘formalized model of production’ that was conceived of during the Instant House project.

Fig. 4-3: Digitally Fabricated Housing for New Orleans, Exhibition at the Museum of Modern Art, NYC, 2009.

The framework for this model of production was developed, and includes a rationalized system of component subdivision modeling and a library of attachment geometry features. But the ultimate success of the project is the evidence it provides for the use of digital fabrication on a large scale. Furthermore, by taking the form of an ornately-complex, traditional,
cultural New Orleans-style house, this project indicates that the system can be used for pre-existing and particular design applications as desired or required.

4.6 Digital-to-Physical Design Translation Procedure

The procedure outlined below builds upon Sass’s research and proposes a step-by-step CAD translation process, or high level algorithm, which can be used in future work as a framework for further computer programming automation. As discussed above, this method of ‘post-rationalization’ enables greater up-front design freedom by the user since it does not require knowledge or implementation of standardized modules and components. Instead, more emphasis can be placed on the desired shape, size and style of the design.

To begin the procedure, the initial design must be generated - in full or in part- by the user. Much discussion throughout the development of this thesis has centered on the user’s ability to perform such a design task in the first place, but for the purposes here, this thesis will assume the user has generated the following design of a backyard artist’s studio (Fig. 4-4).
Fig. 4-4: Prototypical user-generated design for a backyard artist's studio.

Fig. 4-5: Isometric view of the studio design.
4.6.1 Translation Step 1: Defining Model Boundaries and Overlaying 3D Grid

The first step of the translation procedure is to define the extents of the design with a massing volume that encompasses the entire model (Fig. 4-6). A 3-axis Cartesian grid is then overlaid on the volume and defined as the X-Grid, Y-Grid, and Z-Grid.

![3-axis Cartesian grid](image)

Fig. 4-6: Step 1. 3-axis Cartesian grid surrounds the massing volume.

The purpose of the grid will be made clear in Step 2; however, it is important to note that many considerations for optimizing structural needs and material usage should be taken into account when developing the grid. For example, a denser grid may be desired for long or open spans,
and a less dense grid may be desired for smaller spans. A more accurate structural analysis would also include consideration for the direction of the load force and its path to the ground. While balancing and choosing between these factors does require extensive knowledge, one of the core attributes of this translation procedure is the ability for this type of knowledge to be embedded in the steps. Since structural analysis can be, and already is, computed through numerous existing software applications, such equations can be applied and integrated here. In addition, structural factors need to be optimized for material weight and use efficiency. For the purpose of this thesis, it will be assumed that all material used in the physical structure will be a consistent, flat sheet material such as plywood or plastic, whose structural performance can be integrally computed.

4.6.2 Translation Step 2: Generating Structural Ribbing from Grids

After the grid spacing has been determined, structural ribbing is generated (Fig.’s 4-7 and 4-8). This is achieved by using the grids to slice through the original shape model design, which transforms the grid into a web-like structure that exactly defines the exterior and interior shape of the design. Included in this step is the defining of the thickness of the ribbing. This is determined from the thickness of the material from which the project is ultimately fabricated.
4.6.3 Translation Step 3: Removing Rib Interference and Adding Attachment Geometry

After the X-, Y-, and Z-Ribs have been generated from Step 2, the assembly procedure and connection joints must be considered (Fig.’s 4-9 and 4-10). This involves removing and adding geometry from the ribs.
that allow them to align and intersect with each other. As seen in Figure 7, slots are removed from each of the ribs where other ribs intersect with them. Additionally, attachment geometry is added to the perimeter of each rib. This attachment geometry allows the ribs to connect and properly align with the panel, or ‘skin’ geometry generated in Step 4, below.

Fig. 4-9: Step 3. Structural ribbing with connection joints is generated.
4.6.4 Translation Step 4: Generating the Outer Skin

To execute this step, the original shape model is recalled in order to generate the outer skin, or panels, that will enclose the ribs of the design. Up until this step, the translation procedure has operated on the design shape as a solid model. For Step 4, the original model needs to be transformed into a surface model. This can be achieved via numerous modeling methods, depending on the specific CAD software used. However, here the model was “exploded,” transforming the solid design model into corresponding non-dimensional planes commonly known as “surfaces.”  

Once the non-dimensional planes are generated and a complete surface model of the original design is created, the surfaces are given a

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35 In this example, the author used AutoCAD 2006 to execute the Translation Procedure.
dimensional thickness (*Fig. 4-11*). This part of the procedure is similar to *Step 2*, where the ribs are given thickness according to the ultimate material from which the design will be fabricated.

![Fig. 4-11: Step 4. Outer skin with material thickness is generated from surface geometry.](image)

4.6.5 **Translation Step 5: Connecting Rib and Panel Geometry**

This step unifies the two separate models generated from Step 3 and Step 4. It does so by subtracting the rib attachment geometry from Step 3, as seen in *Fig. 4-9*, from the panel geometry generated from Step 4. The result is a unified model that allows for a precise and self-reinforcing connection between the ribs and the outer panels (*Fig. 4-12*).
4.6.6 **Translation Step 6: Subdividing Panel and Rib Geometry**

The last few steps in the translation procedure involve preparing the model for CNC fabrication. First, the panels and ribs must be appropriately subdivided so that they can properly fit on the CNC fabrication equipment. Standard CNC table sizes range from 4’x4’ to 5’x10’, however much larger machines are available and used in practice for industrial applications. For the purpose here, however, the ribs and panels will be subdivided for a CNC bed size of 4’x8’ which is not only the most common, but also takes into consideration the ease of assembly by individuals. It is important to consider several factors for ease of assembly if it is to be accomplished by individuals, including: size and weight of individual panels and ribs and the location of panels within the structure. (Large panels and ribs may be desired for speed of assembly,
but they may also be too heavy and cumbersome for individuals to manage on their own).

*Figure 4-13* shows the roof panel subdivision and highlights another critical aspect of this step: staggered joints. The exact positioning and logic of this staggering can easily be computed and defined with structural analysis. The purpose here is only to explain why such staggering is important. By staggering the rib and panels joints, the structural loading is diffused throughout the structure and prevents a single fault line from emerging during structural stress.

Fig. 4-13. Outer skin geometry is subdivided to accommodate CNC table size and assembly management.
4.6.7 Translation Step 7: Generating CNC-ready Cut Sheets

The final step in the translation procedure is to organize and label each of the individual parts in preparation for CNC fabrication (Fig. 4-14). This organization contains multiple determining factors, including the size of the CNC machine, the size of the material, assembly sequencing desired, and material use and efficiency. After the cut sheets have been organized accordingly, the files are ready to be CNC fabricated. They will require additional modification depending on the specific computer language that the CNC machine can read and compute.

Fig. 4-14: Step 7. Rib and panel geometry is separated and laid flat for CNC fabrication.

4.6.8 Future Work for the Translation Procedure

It is important to note that the intent here is to provide an accurate framework for a step-by-step translation procedure that with future work
can be developed into a fully automated algorithm or software application. As shown here, it is possible to isolate and clearly define these translation steps in such a manner that they may be easily followed and repeated by a peer in the field of digital fabrication. In the following chapter, this thesis documents a set of physical prototypes that have successfully been generated using these steps.
Part III

5.0 Demonstration of Physical Prototypes

5.1 Prototype Web Platform

5.2 3D Design Templates

5.3 Distributed Fabricators and Physical Prototypes

5.3.1 Fabricator Member: A.H., Virginia

5.3.2 Fabricator Member: M.Z., from Ohio

5.3.3 Fabricator Member: H.O., from Sweden

5.3.4 Fabricator Member: D.H., from Minnesota

5.3.5 Fabricator Members: B.Y. and R.B., from Virginia
5.0 Demonstration of Physical Prototypes

In the beginning of Chapter 4, this thesis provides a backdrop of research that has been conducted in the field and application of digital fabrication for architectural structures. Up until now, however, its development and application has only been proven successful for single designs and within controlled environments, where the researchers maintained continuous hands-on direction and supervision. It is the vision of this thesis to release such strict control and demonstrate how digital fabrication enables numerous and geographically isolated individuals to participate in the design and production process of architectural structures. What makes this freedom possible and ultimately allows for the mass customization of architectural structures is the harnessing of new communication processes, such as that found in Web 2.0, with digital fabrication technologies—specifically the digital-to-physical translation procedure developed in Chapter 4. Chapter 5 subsequently demonstrates these possibilities for user-participation and takes the initial steps for developing Architectural Design 2.0.
5.1 Prototype Web Platform

To demonstrate this possibility and conduct such an intentionally uncontrolled experiment, a prototype web platform was developed (see Appendix) to serve as an online community for distributed designers and CNC fabricators. Though the web platform is technologically underdeveloped, it proved successful in generating a sufficient network of designers and fabricators. As seen in Fig. 5-1, over the 7 month period of developing this thesis, the platform has received over 15,500 page-views from nearly 4,000 unique visitors from over 1,600 cities around the world. From this activity, over 50 designers and fabricators have become members.

Fig. 5-1: Prototype Web Platform Activity, Google Analytics.
5.2 **3D Design Templates**

To begin the experiment, 3 simple architectural designs were generated to serve as ‘3D Design Templates’ for novice designers to have a starting point. *(Fig. 5-2).* Each of these designs is free to download from the web platform and can be modified using Google SketchUp according to the designer’s particular desires.

![Fig. 5-2. Prototype web platform with free downloadable 3D Design Templates.](image)

For each of these designs -- a doghouse, a kid’s playhouse, and a storage shed, among other -- the translation procedure outlined in Chapter 4 was used to generate the CNC cut files. These cut files could then be used by any of the online community members to fabricate the structures. The
procedure proved successful in translating each of the designs, even though they were all unique in size, shape, style and level of geometric complexity. *Figures 5-3, 5-4, and 5-5* illustrate the Design Model and Translation Model for each of the three designs.

Fig. 5-3. Dog house Design Model and Translation Model.

Fig. 5-4. Kid’s play house Design Model and Translation Model.
5.3 Distributed Fabricators and Physical Prototypes

Though none of the original designs were significantly modified by the member designers as intended, many of the Fabricator Member successfully cut out and assembled the free download templates as originally designed. To date, seven fabricators from across the United States and one member fabricator in Sweden have shown how this distributed network of fabricators is possible via a Web Platform. Their success reinforces the vision of the thesis. During the membership registration process, each of the fabricators was required to sign Non-Disclosure Agreements in addition to follow a few simple terms and conditions. These terms required that the fabricator supply his own material as well as provide photographic documentation his experience during the process. The following section shows some of this
documentation as provided by each of the fabricators and is used with permission.

5.3.1 Fabricator Member: A.H., Virginia

A.H., from Virginia was the first fabricator to register with the Web Platform and to cut out one of the designs (For the sake of privacy the each of the Fabricators will be addressed by their initials and location). He chose to first fabricate the doghouse, as it is the smallest design and requires the least amount of material and time investment. A.H. fabricated the dog house out of CDX grade plywood (Fig. 5-6 – 5-8).

Fig. 5-6. Fabricator A.H.’s CNC milling machine with the dog house parts cut out.
Fig. 5-7. Fabricator A.H.’s dog house assembly documentation.

Fig. 5-8. Fabricator A.H.’s assembled dog house.
5.3.2 Fabricator Member: M.Z., from Ohio

M.Z. was the first fabricator to cut out the kid’s playhouse, as he was intending on purchasing one anyways (Fig. 5-9). Instead of fabricating the playhouse out of plywood, M.Z. used OSB which is a much less expensive material, and proved to be structurally sufficient. In addition to successfully fabricating and assembling the playhouse, he decided to add finish materials including: roof shingles, siding and operating doors and windows (Fig. 5-10).

![Fig. 5-9. Fabricator M.Z.’s assembled playhouse.](image-url)
5.3.3 Fabricator Member: H.O., from Sweden

The fourth fabricator, who was from Sweden, fabricated the dog house as well. Though very minimal, there was initial concern for material dimensional differences, due to the use of metrics in Sweden. The conversion, however, proved to be insignificant and did not prevent the proper cutting and assembly of the structure (Fig.’s 5-11 and 5-12).
Fig. 5-11. Fabricator H.O.’s CNC milling machine with the dog house parts cut out.

Fig. 5-12. Fabricator H.O.’s assembled dog house, Sweden.
5.3.4 Fabricator Member: D.H., from Minnesota

The fifth fabricator to register with the Web Platform and cut out one of the designs was from Minnesota. D.H. provided thorough step by step documentation of the dog house that he fabricated and assembled (Fig.’s 5-13 – 5-16).

Fig. 5-13. Fabricator D.H.’s dog house assembly process 1, Minnesota.

Fig. 5-14. Fabricator D.H.’s dog house assembly process 2, Minnesota.
Fig. 5-15. Fabricator D.H.'s dog house assembly process 3, Minnesota.

Fig. 5-16. Fabricator D.H.'s dog house assembly process 4, Minnesota.
5.3.5 Fabricator Members: B.Y. and R.B., from Virginia

The last set of documentation in this chapter is from B.Y. and R.B. who collaborated with the author, along with the aid of three sponsors: Make Magazine, ShopBot Tools, and Boise Cascade. The project, which included the dog house and kid’s play house, was exhibited at the 2009 Maker Faire in San Mateo, CA. For this project, B.Y. and R.B. fabricated the parts in their shops in Virginia and shipped them to California for the exhibition. At the exhibition, both the author the R.B. assembled the structures (Fig. 's 5-17 - 5-19).

Fig. 5-17. The dog house and kid’s play house exhibited at the Maker Faire, CA.
Fig. 5-18. Assembly of the dog house and kid’s play house, CA.

Fig. 5-19. Assembly of the kid’s play house, CA.
6.0 Conclusion and Future Work

6.1 Thesis Contributions
6.2 Thesis Limitations
6.3 Future Work
6.0 Conclusion and Future Work

In order to articulate the lessons learned from this thesis and with the hope to address its future development, the thesis question is reiterated and re-evaluated:

How can architectural designers better utilize the Internet to empower consumers of architectural structures with more control over the design and production process and thereby enable the mass customization of small inhabitable structures?

The success of this thesis comes from its ability to prove from real-world evidence that a new model for architectural design and production is possible. As discussed in Chapters 2 and 3, the processes of design, manufacturing and assembly have historically been closed and limited to costly design professionals, wasteful and oversized manufacturing processes and labor intensive site work. Through the integration of digital fabrication technologies (user-friendly design software and digital fabrication CNC milling machines) and Web 2.0, the Architectural Design 2.0 Web Platform lays the groundwork for user-generated design and mass customization at the scale of architectural structures.
6.1 Thesis Contributions

Up until now, digital fabrication in architecture has only proved possible in very controlled and isolated experiments where the researcher maintained strict control and supervision over the processes. This thesis has taken the next steps to introduce and test digital fabrication for architectural design in less controlled and more ‘real-world’ situations that involve distributed and independent CNC fabricators. Through the Digital-to-Physical Translation Procedure developed in Chapter 4, the ability to share digital design and fabrication information across a wide and diverse network of independent individuals proves possible, as evidenced from the numerous prototypes illustrated in Chapter 5.

In addition, the Translation Procedure proves that an alternative for mass customization to the commonly used design configurator is possible. The beginning of Chapter 4 outlines many of the limitations inherent in existing online configurators—such as the integrated parametric relationships and the subsequent need for continually re-inventing rule sets, as well as the overall limitation on potential customer creativity. In comparison, the Translation Procedure outlined in this thesis demonstrates the near-limitless possibility for digital-to-physical output. What allows for this limitless possibility is the use of and direct connection between digital design software and digital fabrication hardware. For companies pursuing mass customization, especially within architectural design, the benefits of utilizing a direct digital-to-physical translation process is
obvious: there is no need for human re-interpretation of construction and fabrication information (which is possibly the most common cause for miscommunication and error). Rather, with direct translation, design information is sent directly to fabrication machines-- there is no need for interpretation, estimation, or re-work. *The digital file and physical structure are the same.*

Ultimately, the most critical result of this thesis is the impact the digital-to-physical translation procedure has for the end user. The goal of this thesis is to empower the consumers of architectural structures by providing them access to the knowledge and tools that will engage them at mass scales in the design and production process. This thesis attempts to address and provide for this concern by integrating Web 2.0 applications and the massive behavioral change in Internet behavior they indicate and instigate. Many other examples of engagement and empowerment exist in other consumer goods industries-- mass customized clothing, household goods, and digital entertainment media, to name a few—though little progress has been made within the architectural design industry.

As described in Chapter 3, most researchers define mass customization offerings in terms of marketing strategies -- i.e. potential design selection and configuration settings. This thesis presents an option for consumers
to more comprehensively address their underlying creative differences and impulses.

6.2 Thesis Limitations

Though the work in this thesis focuses on the holistic development of a working model for offering mass customization at the architectural scale, much work needs to be completed for this model to be operational at the real-world, 'mass' scale. Probably the most critical limitation of this thesis lies within its underdevelopment of more automated processes and a programmed software. Most lacking is the full automation of the Digital-to-Physical Translation Procedure. Here, such automation development was not possible due to time constraints and lack of sufficient technical skills. However, the key work linking previous research (as presented from the background research in Chapter 4) as well as a potential software program is illustrated with the algorithm. With a more advanced understanding of CAD programming languages, progress can be made towards automating the Translation Procedure. Such automation would drastically reduce the amount of time required to translate a design model into a kit of flat CNC fabricated parts and make a truly mass scale of customization possible.

In addition to a lack of automation developed for the Translation Procedure, the Architectural Design 2.0 Web Platform was limited in terms of the number of consumers and beta-testers who participated in
the research experiment. Though the Platform received tens of thousands of visits over a seven month period, the automation of membership registration was significantly underdeveloped and consequently reduced the number of participating members. (For example, to confirm fabricator membership, the author was required to conduct extensive email correspondence and telephone communication.) With a further automated web platform, time and energy would have been saved and likely would have led to a greater number of members.

With these two limitations in place, the variety and complexity of the design models that were potentially fabricated was also reduced. Though the thesis was successful in demonstrating and testing the Translation Procedure with different designs-- which had not been accomplished previously-- the degree of variation in the designs was not as great as hoped for. For example, testing designs with more complex geometry such as curved surfaces or non-orthogonal angles would have greatly extended the evidence for capabilities of the Translation Procedure.

Lastly, and perhaps the most critical limitation of this thesis was its inability to engage non-expert users in the design process. The initial strategy of this thesis to prevent this known challenge was two-fold. The first strategy was to link the Translation Procedure with the widely-used and user-friendly 3D modeling software, Google SketchUp. As such, any design model generated by the users with the software could be
translated because it shared file type standards. In the end, however, file type continuity was not enough to engage consumers in the design process.

The second strategy was also not as successful as desired. In addition to the technical importance of common file types was the underlying problem of varying consumer behavior and skill sets. The consumer’s overwhelming inability and/or presumed lack of time to generate architectural designs proved to be a daunting obstacle. In order to engage users and non-expert designers, 3D design templates were provided for consumers to use as a starting point for their customized designs. Though these design templates were freely available from the web platform, and many downloads were recorded, ultimately, a very limited number of user-generated designs were returned to the author.

6.3 Future Work

Though in some respects the thesis was technologically underdeveloped, it was successful in answering and demonstrating a working real-world model for utilizing an online platform for the mass customization of architectural design and production. Further technical research and development will bring about automation both to the Translation Procedure and Web Platform. However, for the full development of mass customization in architectural design the development of a sustainable business model and an understanding of consumer behavior in terms of
design is necessary. This will be an educational process both for the consumer and the architectural designer.

Thank you.

Daniel Smithwick, August 2009
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Abridged List of Illustrations

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Appendix
Prototype Architectural Design 2.0 Web Platform


Membership page
http://www.physicaldesignco.com/membership.html

Projects page
http://www.physicaldesignco.com/projects%and%events.html
3D Design Templates page
http://www.physicaldesignco.com/get%20physical_3D-design-templates.html