1-1-2010

Mass production for mass customization : application of digital fabrication techniques on tower renewal

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Mass Production for Mass Customization
Application of Digital Fabrication Techniques on Tower Renewal

by

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B.Arch.Sci. Ryerson University, 2006

A design thesis|project
presented to Ryerson University

in partial fulfillment of the
requirements for the degree of
Master of Architecture
In the program
of Architecture

Toronto, Ontario, Canada, 2010

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Mass Production for Mass Customization
M.Arch. (2010)

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Abstract

The opportunity to regain the essence of art and customization in architecture presents itself in a variety of ways if industry becomes open-minded about the potentials our modern technologies bestow. Despite the impact of digital technologies on architectural form, representation, production, and drawing methods, there has been very little innovation in the general flattened rectilinear form of the high-rise due to material innovation and construction methods that evolved out of rationalized techniques and modes of mass production. This thesis investigates ways to re-appropriate surface depth, curvilinear form, variety, and the composition of the high rise cladding by looking at ways that the conventional high-rise envelopes construction and its materials and methods can be manipulated using new design and construction methodologies that have evolved through digital techniques of design and production. The repetitive nature of tower design and the industrial nature of the construction process create an ideal opportunity for the reassessment of this process using post-fordist design and construction methods.

Acknowledgements

Firstly, many thanks to my advisor, Cheryl Atkinson, as without her this thesis would never have been realized. Also, thanks are given to Colin Ripley and Kendra Schank Smith for participating in my reviews and for their constructive input.

I would like to thank my fellow colleagues and friends for their ongoing encouragement and generous contributions.

Lastly, much love and thanks to my family for always being supportive of my ambitions; I never would have made it through without them.

Thesis Statement

The art and customization of architecture has been gradually lost in North American construction practice since the post-World War II notion of Fordism, where the materials and rationalized construction techniques of the modernist movement have taken us from craft production to mass production. As a result of this contemporary problem, we are seeing a predominance of rectilinear, flat, weightless, abstracted form, especially in high-rise buildings, where a greater degree of volumetric form would be desirable to add depth, visual interest and variety. Tower design offers a restricted set of design parameters, wherein the exploitation of the elevational and surface effects presents the greatest opportunity to create a unique variance in design.

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Terminology

The following definitions are terms used throughout the paper and how they are used in the context of the thesis.

Modernism: A new architectural style that emerged in many Western countries in the decade after World War I. It was based on the "rational" use of modern materials, the principles of functionalist planning, and the rejection of historical precedent and ornament. Modernist architecture embodies features of little or no ornamentation, factory-made parts, man-made materials such as metal and concrete, an emphasis on function, and a rebellion against traditional styles.

Fordism: A manufacturing philosophy that aims to achieve higher productivity by standardizing the output, using conveyor assembly lines, and breaking the work into small de-skilled tasks. Fordism seeks to combine machine and worker efficiency as one unit, and emphasizes minimization of costs instead of maximization of profit.

Post-Fordism: Post-Fordism is the name given to the dominant system of economic production, consumption, and associated socio-economic phenomena in most industrialized countries since the late twentieth century. Post-Fordism is characterized by the following attributes:

- Small-batch production.
- Economies of scope.
- Specialized products and jobs.
- New information technologies.
- Emphasis on types of consumers in contrast to previous emphasis on social class.
- The rise of the service and the white-collar worker.
- The feminization of the work force.

For the purpose of this paper, post-Fordism refers to a way of constructing and designing that is not based on modernist philosophies, using our contemporary and emerging materials and technologies to their full potential, and exploring new methodologies of constructing and fabricating architecture.

Mass Production: The manufacture of a product on a large scale. The mass production of items is often done by an assembly line, or other efficient means of production. The process is often carefully determined to try to produce the greatest quantity of items while using the fewest resources. Mass production has become popular since the assembly line became prominent in the 1900s, although the process embodies principles of efficiency that have been around much longer.

Mass Customization: Production of personalized or custom-tailored goods or services to meet consumers' diverse and changing needs at near mass production prices. Enabled by technologies such as computerization, product modularization, and lean production, it portends the ultimate stage in market segmentation where every customer can have exactly what he or she wants. In the context of this thesis, mass customization is a term used to describe how to bring variety and uniqueness to our high-rise buildings.

High-Rise: A high-rise building is classified as a multistory building taller than the maximum height people are willing to walk up, thus requiring vertical mechanical transportation. This generally means a building more than 60 feet in height. Building height is measured from the lowest level of fire department vehicle access to the floor of the highest occupiable story. The term high-rise is often used in reference to the building type being addressed throughout this thesis. The existing structures used as experimentation sites are high-rise residential building from the 1960s, a set of buildings that was strictly for housing the maximum amount of people in the least expensive way during the post World War II housing boom, using the construction techniques that were available at the time. These high-rise buildings prioritize function and economy over formal concerns.

Tower Renewal: The Mayor's Tower Renewal is an initiative occurring in the city of Toronto to retrofit 1000 plus residential apartment towers found all across the city that were built between the 1950s and 1980s. Today, these concrete slab towers are aging and energy inefficient, while the open spaces surrounding them and underused, socially isolating, poorly planned, and not maintained. For the purpose of this thesis they are seen as an experimentation site, using the existing structure of these high-rises to test mass customization using printing, innately reaching the goals of better energy efficiency, and stronger, safer communities.

Organic Architecture: Organic architecture has been said to be a rebellion against the geometric norms of modernism. Therefore, for the purpose of this paper, it is simply about form-making and expression, and trying to incorporate curvilinear and organic forms to get away form the rectangular, repetitive, and weightless form of our current and historical residential developments.

3D Printing: 3D printing is a robotic building system that creates full size sandstone structures without human intervention using a stereolithography 3D printing process. This technology is used in the final design of a fabrication technique that allows building components to be digitally designed and directly translated to the printing machine, creating building components of any form and complexity. 3D printing is seen as an opportunity for creating complex curvilinear forms in our mainstream construction industry.

1. Introduction

The fact that a rectilinear, orthogonal mode of design came to dominate the twentieth century is a reflection of the materialist values of an industrially driven age, facilitated by the notion of Fordism. Defined as a manufacturing philosophy that aims to achieve higher productivity by standardizing output, the post-World War II notion of Fordism brought to the industry a system of mass production and consumption based on standardization and reproduction, exemplified by Henry Ford's system of mass automobile production. This is seen clearly through the post-World War II era of expansion; in the world of architecture we were mass-producing thousands of dwellings to accommodate in the quickest and least expensive way possible. This concept is deeply embedded in the modernist mindset and is a building model that the industry has never fully moved away from.

It has been said that organic design is a rebellion of the geometric norms of modernism, with its emphasis on function, scientific analysis, and order (Pearson, 2001). Within the last couple of decades we have seen an emerging exploration of curvilinear form through the work of Frank Gehry, Greg Lynn, and Zaha Hadid, demonstrating examples of ornate shapes created through architecture, with natural forms, free-flowing curves and expressive character. This is driven by a number of factors, including an interest in organic architecture and creating expressiveness in response to programmatic, economic, environmental, or cultural influences. This can also be considered an aesthetic or stylistic evolution where sophisticated design software is enabling designers to push beyond the boundaries of traditional forms. Now, technology is not only a rendering tool, but also a participant of sorts in the design process, allowing us to fully embody the potential of this organic form (Water, 2003). If embraced as an inspiration for expressiveness, organic form could potentially add customization to our mainstream construction industry through depth, variety, and visual interest.

The liberated and imaginative forms of this method of design are now actively sought, but currently these techniques are used almost exclusively for iconic cultural or institutional buildings such as art galleries and are not economically available for mainstream construction of high-rise residential and commercial buildings due to the limitations of the contemporary North American construction industry. While through emerging software technology we are able to design and determine more customized and particularized forms, the industry hasn't caught up. The difference today that will enable modularization and mass production to succeed is its ability to be customizable. "No longer does mass production have to produce the same repeated product; now flexible production methods allow for customization on a larger scale" (Kieran; Timberlake, 2004, p.110).

The objective of the thesis is to develop the art and customization of organic form in a way that can be economically, yet appropriately, incorporated into the standard North American construction practice and create a building envelope system that can be applied to the plethora of existing high-rise buildings. This can be attained through recent advances in digital technologies of design, analysis, and production. In a dramatic departure from the formally and materially reductive norms of much twentieth-century architecture, it is now possible to realize complex geometric forms which are enabled by the capacity of digital technologies to accurately represent and precisely fabricate artifacts of almost any complexity. Here, variation and irregularity become possible, offering unprecedented freedom from standardization. This is having profound effects on modes of architectural production while being a catalyst for new ideas in architecture. Through this we can potentially mass-produce the customization of building materials, products, and processes, creating a system that is lightweight, cost effective, and easy to produce, transport and install. As these digital technologies are becoming more globally accessible, economical, and viable, there is the opportunity to introduce these techniques into mainstream construction practices, making the craftsmanship, variety, irregularity, and textural depth of organic forms more accepted, producible, and economically feasible.

This thesis will endeavor to focus on envelope material and construction technologies of high-rise buildings, as they present the greatest opportunity for variety and experimentation. In response to the Mayor's Tower Renewal, this thesis proposes to create a new system that will allow for the greater energy efficiency these buildings require and a greater variety of unit types, paired with expressive form, while using the existing tower structure as a test case for mass customization. According to research done at the University of Toronto, the durable concrete construction of these towers is sound and perfectly suited for upgrade (Kesik; Saleff, 2009); thus, the structure will remain while the façade will be completely rethought using digital design and fabrication techniques. This will not only test the boundaries of modern technologies and construction, but also produce a system that introduces form, expression, variability, and meaning in an industry where we still have a predominance of rectilinear form, despite our current technologies.

2. How Did We End Up Here?

> "…Architecture depends upon its time. It is the crystallization of its inner structure, the slow unfolding of its form. That is the reason why technology and architecture are so closely related. Our real hope is that they will grow together, that someday the one will be the expression of the other. Only then will we have an architecture worthy of its name: architecture as a true symbol of our time". (Mies van der Rohe, 1950)

2.1 The Modernist Industrialization of Design

The concepts of mass production and standardization that developed in the Industrial Revolution transformed architecture through new building materials and methods of production. The technological innovations of 19th century industrial architecture introduced new building materials such as aluminum, cast iron and glass for curtain wall, and steel for exterior cladding support, allowing walls to become thinner and more energy efficient (Crosbie, 2005).

The Modern Movement gained momentum after World War II with the required mobilization of peoples, industries, and resources on a vast scale in which the architectural profession was deeply involved. Part of this was the planning and rebuilding of European cities, the incorporation of industrial production, and a philosophy that prioritized functionalism over style. Furthermore, speed was vital to the war effort, and anything that could accelerate the pace of design and construction was incorporated into design practice. This generation of architects appreciated the virtues of design methods predicated on standardization of types, prefabrication of elements, and substitution of new materials that facilitated rapid construction, all driven by the efficacy of rationalized design methods, enamored by the power of technology (Doordan, 2002). But prior to this, architecture was much more of a craft, and the approach of the Modernist architects was to reduce buildings to pure forms, removing these historical references and ornaments in favor of functionalist details.

Grounded in this particular design philosophy, early modernist architects such as Le Corbusier, Adolf Loos, Walter Gropius, and Mies van der Rohe designed more simple but functional buildings, where function was the style. But caught up in this age, the industry never fully moved away from the era of cheap oil and fast production, as this had been the dominant architectural style for numerous decades. Although modern architectural design never became a dominant style in single-dwelling residential buildings, it was in institutional and commercial architecture. Within this mould, the most commonly used materials were glass for the facade, steel for exterior support, and concrete for the floors and interior supports, and floor plans were functional and logical. The uncompromisingly rectangular geometry of these stark buildings becomes most evident in the design of high-rise buildings.

Figure 2.1.1. Formulaic construction of our mainstream construction – Toronto's City Place.

The modernist quest for the incredible lightness and thinness of buildings has resulted in exploration of the curtain wall, and is one of the best examples of achieving this form of building envelope. According to Cesar Pelli, "Form is the greatest expression of a tall building" (Crosbie, 2005, p.19). Most curtain wall buildings are made with 'off-the-shelf' systems designed by curtain wall manufacturers, and they are quite prosaic and uninspired. Older style "stick systems", where the curtain wall is composed of individual elements (glass, mullions, gaskets, spandrel panels, metal caps) assembled on-site, have given way to prefabricated "unitized systems" that arrive at the construction site virtually preassembled, ready to be lifted into place and fastened to the buildings structure. While unitized systems now dominate curtain wall technology, stick style systems continue to be used in some parts of the world.

"The design challenge for architects is to take the elements of contemporary curtain wall systems and interpret them in new ways, expressing the architectonic character of the wall as central to the building's architectural presence" (Crosbie, 2005, p.18). Architect Cesar Pelli & Associates achieve this through custom-designed and fabricated curtain walls that are special to the place, function, and architectural aspirations of the building. Contextual response and consideration in the design of tall buildings became all but lost by the postwar period, and an application of 'universal' design solutions resulted with skylines of replicating skyscrapers.

Disappointed with modernist design, architects in the mid-1960s began to reassess their allegiance to these principles, which had an effect on the design of tall buildings. Driven by changes in the global economy and environmental issues, architecture entered a period of diversity by the early 1980s, where many architects deliberately sought to move away from rectilinear designs, towards more diverse, expressive styles. Here, Mies van der Rohe's "less is more" was turned by Venturi into "less is a bore" (Lepik, 2004). And during this time, architects began experimenting with organic forms in which they felt were more human and accessible. This form of architecture became very popular due to its free and playful nature.

As a result of this, a new generation of high-rises appeared on urban skylines around the world by the 1990s, where the appearance of tall buildings signaled profound changes in the global economic order. The tall buildings of this time differed significantly from earlier towers in terms of their layouts, construction, operations, materiality, and sustainability, and the form of the building reflected this. Many of these designs were so far-reaching that such architects as Norman Foster and Kenneth Yeang described their efforts as nothing less than the reinvention of the skyscraper (Doordan, 2002), and for good reason (Figure 2.1.2). Many architects in the last few decades have sought to address the formal typology of the high-rise.

Figure 2.1.2. Tower designs by Kenneth Yeang (left) and Norman Foster (right).

Throughout the twentieth century, this form of building has reflected how new modes of production and the boom in information technologies were translated into material practices and concepts inherited from early modernism. The high-rise tower acted as a laboratory in which to identify and extrapolate new principles of the industrial city and its building types, thus identifying how the high-rise is typically defined and organized today. In contemporary North American construction practices we have not fully moved away from these ideologies. Many contemporary architects rebelled against these modernist philosophies, but in many ways this thesis is an attempt to build upon them. Mass production and quick, cost efficient forms of building are hard to compete against in terms of price, thus how can design to customize the industry to introduce craft, variety, and desirability without significantly transforming its comfortable methods and cost incentives? This thesis attempts to look for methods to work within the paradigms of mass production to create variety and curvilinear form through mainstream architectural production, which can be utilized in the construction of residential and commercial high-rises, to create more site specific, meaningful, visually eloquent architecture.

Mies van der Rohe believed that architecture and technology should grow together and be an expression of one another in order to be a true symbol of the times. During the late modernist period, architecture was an accurate reflection of North American growth, prosperity, cultural values, and technology. The degeneration of this formal ideology into a universally applied and commercially exploited building system has resulted in banal, monotonous, and uninspiring construction, with the loss of regional and cultural particularity. Now that we have the means and technologies at our fingertips how can we transform the methods of construction to represent our particular place and time?

2.2. Le Corbusier and the Tower Renewal

Various twentieth-century tower visions incorporated solutions to urban development problems, especially overcrowding and unhealthy living conditions. Many architects throughout the centuries have had a profound impact on the development of modern architecture and urbanism as a result of the post-World War II housing boom, one of whom was Le Corbusier. Le Corbusier understood that the product of our city plan was a direct consequence of the changes that industrialization imposed on society and land use (Ábalos; Herreros, 2003). He viewed the skyscraper as having the potential to transform the urban landscape and industrial society as a whole.

Le Corbusier wanted to dismantle all forms of pre-modem urbanism and replace them with a scheme of towers and highways, as he believed that cities needed to have high population densities to function properly. Nevertheless, Le Corbusier was appalled by the congestion of 1920s cities, which he attributed to the inefficient road network and building configurations that did not match the spirit of the machine age. The key was the famous paradox, "We must decongest the centers of our cities by increasing their density" (Hall 1996, 207). Therefore, Le Corbusier proposed an extravagant plan for a "vertical garden city," which he called Ville Radieuse, or Radiant City, where "a pact is sealed with nature, and nature is entered in the lease" (Schoenauer, 2000, p.392). His planning schemes departed dramatically from those of then-existing cities, and generally aimed to avail the technological innovations of the twentieth century. He envisioned a city for millions of people housed in skyscrapers that would cover little more than five percent of the land (Figure 2.2.1). Buildings would be elevated on stilts to allow for extensive parks and gardens that would flow right underneath, with the incorporation of restaurants, cafes, and luxury shops. Le Corbusier's ideas of urban reform were never fully realized, but many urban renewal developments and projects built after the publication of Ville Radieuse reflect Le Corbusier's ideas, and led to the popular "tower-in-the-park" design concept (Schoenauer, 2000).

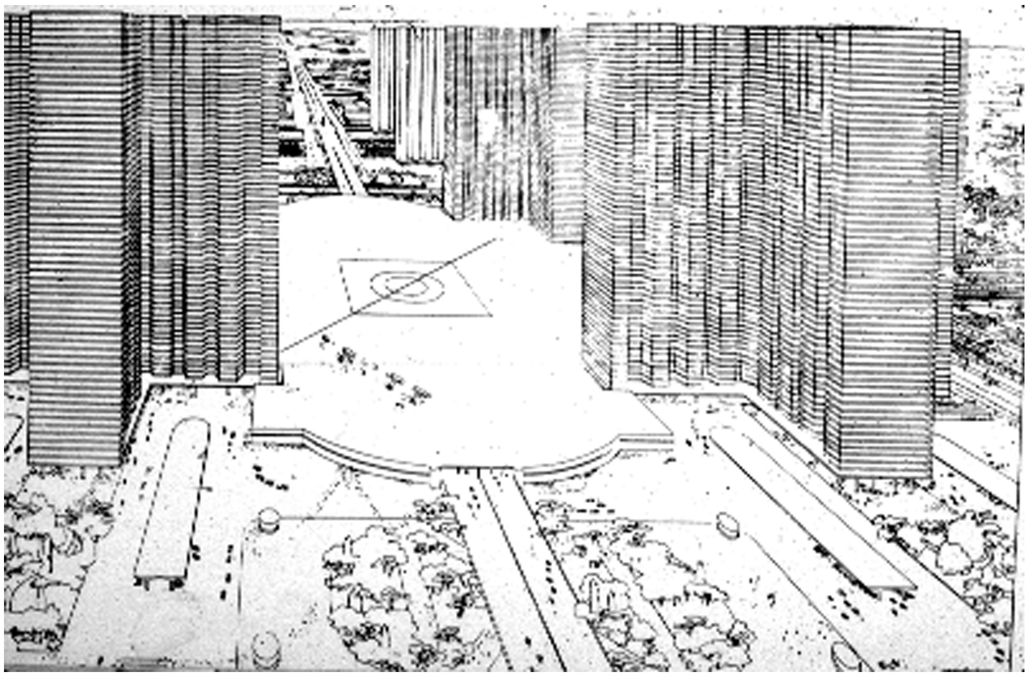


Figure 2.2.1. Le Corbusier's city planning.

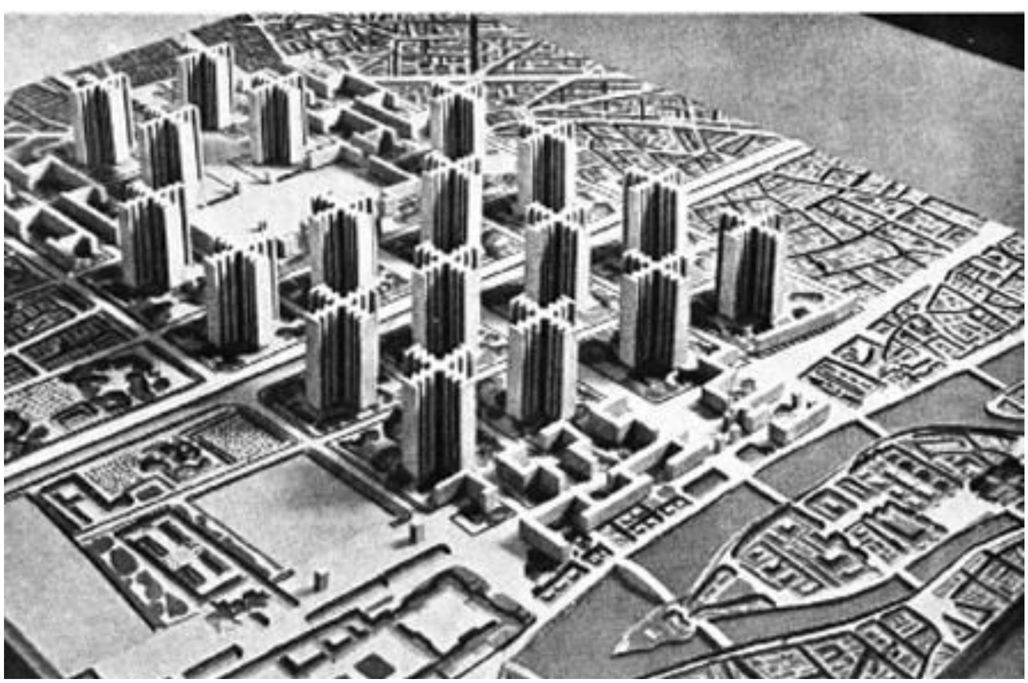


Figure 2.2.2 Le Corbusier's Radiant City: Towers in Parks.

Early design of the cruciform skyscraper (Figure 2.2.2) was accomplished through industrial practice in terms of technical know-how, mathematics, and geometry. According to Iñaki Ábalos and Juan Herreros in their text *Tower and Office: From Modernist Theory to Contemporary Practice*, “the geometry of the plan contained a precise symbolic character, and it was through vertical repetition that the skyscraper found its meaning” (Ábalos; Herreros, 2003, p.12). Here, repetition was thought to be capable of arousing the new emotions associated with this project type. Furthermore, the reproduction of the skyscraper in terms of it being a produced industrial object with its vertical repetition of floorplates, was ultimately the paradigm of an urban and technological movement in history. Thus, people were bound to be overcome with emotion, as these building types were encompassing all the technological and economical advances that were seen as positive and bringing forth a new world.

Furthermore, the symmetry and repetition found in Corbuser’s skyscrapers are implicit in the three circumstances that characterized the skyscraper: its structural frame (symmetry and mechanical repetition); its typological form (symmetry and figural repetition); and the city’s topological organization (symmetry and urban repetition) (Ábalos; Herreros, 2003). This demonstrates that the design of these monuments had meaning, and the repetition and symmetry converged with all the radicalism of a universal and generalizable principle. Often the golden section composition was imposed on the façade and geometrical methods and proportioning systems on the plans, sections, and elevations to give order and meaning (Figure 2.2.3). There was an implicit goodness seen in repetition, the connotations being of order, modernity, cleanliness, and efficiency; however, with today’s implementation of repetitiveness we are left with banality due to the cheap construction methods. The existing building industry doesn’t allow for much variation and customization in high-rise buildings, and it rewards repetition and standardization with reduced cost. We are seeing the consequences of this throughout the country.

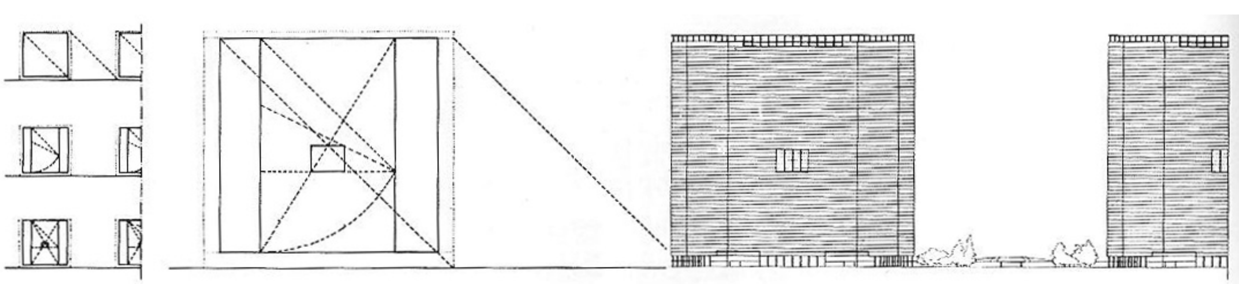


Figure 2.2.3 Le Corbusier’s skyscraper: elevation with regulating lines governing the façade.

Although Le Corbusier's *Radiant City* went unbuilt, many of these planning techniques and design strategies were implemented in North America as a solution to the post-World War II housing crisis. Toronto, in particular, contains more high-rise buildings than any other city in North America other than New York, with the vast majority of these being concrete apartment buildings built between 1960 and 1980. Present from Ottawa to Windsor, the modern tower block is one of the defining housing types of Southern Ontario, and in Toronto they make up approximately 40% of the housing stock (City of Toronto, 2008). Similar to Le Corbusier's Radiant City, we are seeing clusters of communities with up to 18 towers, surrounded by open space and parkland: the "tower-in-the-park", which is one of the defining housing innovations of the twentieth century (Figure 2.2.4). Open space around high-density developments was encouraged to provide breathing room, accessible community recreation space, and also allow for unobstructed sunlight into apartment units (City of Toronto, 2008). The modern tower became a leading approach to urban growth throughout the world, and "this towers-in-the-park scheme became a virtual cliché for all residential redevelopment" (Garvin, 2002, p.157).

Figure 2.2.4 Toronto's "Tower in the Park" in the 1970s.

But throughout the decades, the dream of housing projects erected in park-like settings gave way to the grim urban reality of communities trapped in dreary modernist buildings. This led to critics of modernist planning to voice their opinions. Jane Jacobs in her book, *The Death and Life of Great American Cities*, presents an attack on the principles that have shaped modern city planning and rebuilding, and she comments on how Le Corbusier's dream city has had an immense impact on our cities. "No matter how vulgarized or clumsy the design, how dreary and useless the open space, how dull the close-up view, an imitation of Le Corbusier shouts 'look what I made!' Like a great, visible ego it tells of someone's achievements. But as to how the city works, it tells, like the Garden City, nothing but lies" (Jacobs 1961, 23). This is a valid comment, and as the decades roll on, we are seeing time and time again that these comments remain true. These are nonfunctioning communities and the philosophy of the tower-in-the-park has led not to the rebuilding of cities, but the decline of cities. She noted that the planners' infatuation with building as many parks as possible often resulted in deserted landscapes that were breeding grounds for crime and decay. Decades later this remains true, especially in Toronto, and now these neighbourhoods are in desperate need of attention and re-planning due to delinquency, vandalism and general social hopelessness.

All of this is in sharp contrast to the neighborhoods beloved by midcentury urban planners. There, 'rational' planning kept uses strictly separate, with offices, factories, shops, and residences segregated into their own areas by strict zoning laws. As a result, neighborhood streets would be deserted for long stretches of time—and therefore dangerous. The increased danger would serve to further discourage pedestrian use of the streets. Furthermore, Jacobs mentions that the schemes of the midcentury urban planners could not have destroyed neighborhoods better if they had been designed to do so (Jacobs, 1961). Ultimately, she argued that the emphasis on traffic flows, single-use zoning, and the concentration of population in high-rise towers dispersed in park-like settings actually undermined the social and economic vitality of cities. So the question is: What can be done to address these towers and the social and economical issues that are associated with them?

2.3 High-Rise Construction

High-rise towers are now commonplace in almost every large urban area of the developed world and have redefined the nature of urban development in our time. Once thought of as an American way of building, it appears to be more appropriately described as a late twentieth century way of building, and cities are sacrificing scale, light, pedestrian amenity, and most of all, the ineffable qualities of their traditional identities (Mierop, 1995). But now, with our ever-evolving technologies we have the potential for variation and richness in form.

Throughout the 1970s and 80s, architects began searching for alternatives to the stereotypical buildings of the Modernist Movement. Clearly defined forms were distorted to create huge sculptural forms; instead of being treated as purely functional components, technical elements were exaggerated to create decorative details. There is also a new awareness of the significance of the street space and scale, with new legislations toward setbacks and zoning. But as we come closer to 'getting it right', there are still questions of how to address the modernist experiments of the concrete tower. In search of the answer to this question, a portion of the research is of façade structure and technologies, which could be incorporated to tower design and adaptive re-use strategies.

The *High-Rise Manual* is a text which extensively outlines and documents tower planning, building organization, structural systems, building science concepts, and building technology. It is a comprehensive guide to high-rise design. Karl Chu states in his article in *The State of Architecture in the Beginning of the 21st Century* that "the envelope, or exterior skin of a building, is one of architecture's most fundamental components" (Chu, 2003, p.63). Although the text is primarily focused on technical issues, it touches upon the *building façade as a garment*. The one dimensionality of a high-rise and the size of the façade areas is a result of the height and structure, which have an impact on all areas of planning and construction. It is mentioned that the combination of façade construction with the erection of the load-bearing structure cannot be realized without a high degree of prefabrication and in-series production (Eisele, 2003). It is stressed that façade construction needs to be carefully planned out in terms of functional requirements and influencing factors, to seek out synergies for the construction to allow for prefabrication in series. The advantages of series construction are optimized planning, production and assembly, and the text stresses in detail the importance of collaboration between client, architect, engineers, planners, and contractors.

Furthermore, the materials of a high-rise façade are exposed to greater weather, mechanical and maintenance related loads, while having to satisfy ambitious visual requirements. The visual design of a high-rise is more complicated than imagined, and careful planning of the material surfaces is a very important factor. Furthermore, prefabrication must be optimized to maximize construction efficiency. Prefabricated construction makes it possible to deliver the façade elements including all glass panes, panels and other mountings, which have been fully prefabricated, from the façade builder's workshop, to the building site (Eisele, 2003). Again, the importance of prefabrication is stressed, and can potentially, with the incorporation of digital design, ease the impact on construction. With new technologies and a new understanding of digital fabrication, prefabrication of elements does not necessarily need to mean repetitiveness.

3. From Modern Geometry to Organic Form

Organic architecture is rooted in a passion for life, nature, and natural forms. It's full of the vitality of the natural world, and its free-flowing curves and expressive forms are sympathetic to the human body, mind, and spirit. "Designed architecture is conceptual and artificial, created by talent and influenced by taste, whereas organic architecture is unconscious, free and imaginative" (Beesley; Bonnemaison, 2008, p.49).

3.1. Organic Architecture

If there is an idea to bring the art and customization back into mainstream construction, then it is important to understand not only how we lost it, but also what methods can be implemented in doing so. Thus, organic form and craft-based architecture has been studied - primarily its origins and evolution, and what role it plays in today's contemporary architectural industry. It is said that organic design is a rebellion of the geometric norms of modernism, but as it evolved, one could not exist without the other, as the two are both principles of form-making and are principles of the forming forces of nature. Geometry provides man with a working framework with which he can master space, where geometry creates ordering rules. According to Hugo Haring, human evolution moved from a pre-geometric to a geometric state before it could finally move on to enter the organic (Jones, 1999).

Throughout the time of the industrial revolution, and into modern times, we have had architects such as Louis Sullivan, Frank Lloyd Wright, and Antoni Gaudi follow a philosophy of architecture which promotes harmony between human habitation and the natural world, coupled with geometric ordering. This organic architecture incorporates design approaches so sympathetic and well integrated with its site, that buildings, furnishings, and surroundings become part of a unified, interrelated composition, and primitive architecture was innately organic, based on natural forms, structures, and simple, local materials. However, nearing the end of the twentieth century, designers were awakening to a new world inspired by the creative forces of nature and biological organisms. In this sense, "the word organic refers to nature and the characteristics of living organisms" (Johansen, 2003, p.95). In turn, an organism is a living being consisting of organs which, in their interaction and interdependence, determine life processes. Through architecture, these processes of organisms may serve as man-made designs through performance systems, circulation, or distribution systems.

Figure 3.1.1 Frank Lloyd Wright's Organic Architecture (image: Fallingwater).

The meaning of the term 'organic architecture' keeps evolving with increasing knowledge of nature combined with foreseeable technologies. As new technologies emerge, architecture becomes more organic in its scope, intent and realization (Lalvani, 2003). Also, the term organic architecture has clearly meant different things in architecture throughout time; therefore, the time and place of its application is rather difficult to define (Frampton, 2003). On one hand, organic architecture shows that there are other criteria besides function and construction. "Just like art, architecture doesn't depend on outside influence but presents itself as an organic subject, following organic actions" (Giencke, 2003, p.75). Here, the mastery of form, function and construction of form become the prerequisites for the built architecture but not the architecture as a discipline (Giencke, 2003). On the other hand, one of the problems of organic architecture is that it can only be defined by architectural example and social history; yet, if the architecture of our time is to have any public and social significance, it should attempt to solve problems specific to our time. The notion of organic architecture is expressed through its shape, and its most exciting and important principle is precisely that it does not follow any formalistic and geometric rules and is removed from any special method. There is no theory, as organic architecture happens beyond rectangular geometric shapes. It has the potential to follow or combine all styles and fashions, which makes it so interesting and desirable (Giencke, 2003).

Throughout the text *New Organic Architecture: The Breaking Wave,* David Pearson explains how organic architecture is taking a new direction today. He describes a way of building that is both aesthetically pleasing and kinder to the environment, while exhibiting the work of organic architects and their inspiration, the roots and concepts behind the style, along with the challenges these architects have to overcome. It is stated that “organic architecture is rooted in a passion for life, nature, and natural forms, and is full of the vitality of the natural world with its biological forms and processes” (Pearson, 2001, p.8). It is also outlined how organic architecture emphasizes beauty and harmony through free-flowing curves and expressive forms which are sympathetic to the human body, mind, and spirit. It is said that “in a well-designed organic building, we feel better and freer” (Pearson, 2001, p.8). Given these statements, it would be incredible for these ideologies to be applied in mainstream construction, particularly in high-rise housing projects. Furthermore, Pearson describes how curved forms are stronger, more efficient, and more economical than the equivalent rectilinear structures, and that both modern and traditional materials can be used organically. Although not everyone will agree with this, it provides an argument for incorporating these forms, and as organic architecture is multi-faceted, free, and surprising, it could provide a wonderful basis for building programs, which are typically rectilinear, repetitive, and mundane.

Today, architects have taken this concept of organic design to new heights with the implementation of new materials and technologies, coupled with the application of natural shapes, rhythm, and composition. This is almost a re-emergence of organic architecture, where the meaning and visual appearance of these buildings are very different than they were just a few decades ago. “Today, organic architecture engages us and invites us to shed constrictions, to expand our expectations beyond the received wisdom of convention, and to envision the brightness present in every future. Organic Architecture is an adventure, not a test. It is not an assault, but an embrace” (Robinson, 1991, p.27). And this vision is affecting most fields of design, from furniture, lighting, and architecture to landscape and interior design, and major corporate clients are now actively seeking these innovative forms. But these imaginative designs are not yet commonplace, as they are often incorporated in one-off buildings such as museums (Figure 3.2.1, 3.2.2).

3.2 Expressive Forms

In the last couple of decades, we have architects such as Frank Gehry, Peter Eisenman, Rem Koolhaas, and Zaha Hadid who have all set out to displace order, harmony, hierarchy, and orthogonal form, through buildings full of sharp angles, dislocated spaces, and harsh, high-tech materials. These designs have been seen as a rebellion against the perceived mechanistic dryness of modernism, with its emphasis on function, scientific analysis, and order. Now we are seeing a movement from the traditional roots of organic architecture to a style that is more about direct expression and bold statements in form, where the architecture is not necessarily about a connection to nature but about the form itself. Frank Gehry states in his article from *The State of Architecture in the Beginning of the 21st Century* that "you are a product of nature. If you just follow your intuitions, you won't get out of line because gravity will hold you down" (Gehry, 2003, p.53). He believes that you just have to free yourself and let these things happen. But the question circling these expressive forms is: Who can really afford this unique form of architecture and where is its place in our mainstream construction industry?

Figure 3.2.1 Expressive design of Frank Gehry: AGO, Toronto.

Figure 3.2.2 Expressive design of Frank Gehry: Disney Concert Hall, Los Angeles.

Similarly, there are architects such as Greg Lynn who are exploring the expressionist style of curved forms. In his essay on *Architectural Curvilinearity*, Lynn offers examples of new approaches to design that move away from the traditional approaches to organic form. The curvilinear forms he explores are not necessarily a resultant of organic architecture and can be characterized by the involvement of outside forces in the development of form. Lynn explains that these "curvilinear forms are resultant of complex deformations in response to programmatic, structural, economic, aesthetic, political and contextual influences" (Lynn, 1991, p.9). Lynn also comments about attempts being made to fold smoothly specific locations, materials, and programs into architecture while maintaining their individual identity. This gives an argument for creating these forms without inspiration coming from nature and natural processes. Lyn explains this form of design as 'blob architecture', and he is its leading theorist. His use of sophisticated animation software has enabled him to push beyond the boundaries of traditional forms, and his work during the 1990s and early 2000s has put him at the forefront of digital design (Figure 3.3.3). At the heart of Lynn's approach is the notion of design 'evolution' and his pursuit of what he calls "dynamically conceived architecture" (Waters, 2003, p. 67). For him, technology isn't merely a sophisticated rendering tool, but a participant of sorts in the design process. A great example of this is his Blobwall pavilion (Figure 3.2.3), which is an innovative redefinition of the brick. Presented at the Venice Architecture Biennale in 2008, the blob unit, or 'brick', is a robotically cut, mass-produced, hollow tri-lobed shape, formed through rotational molding, which was then assembled with interlocking precision to form the wall. The philosophy of mass-produced, interlocking building components is explored through the design portion of the thesis.

Figure 3.2.3 Greg Lynn's Blobwall Pavilion.

3.3 Expressive Construction

Advances in computer aided design and manufacturing technologies are starting to have an impact on building design and construction practices, where we are now able to produce and construct these very complex forms that used to be very difficult and expensive to design, produce and assemble. But as these curvilinear and organic forms are becoming easier to create and manufacture digitally, we are presented with the question: Should we create buildings with these forms just because we can? Branko Kolarevic in the text *Architecture in the Digital Age* states that “whether an architectural topological structure is given a curvilinear or rectangular form should be a result of particular performative circumstances surrounding the project, whether they are morphological, cultural, tectonic, material, economic, and/or environmental (Kolarevic, 2003). Rightfully so, under no circumstances should the interior and overall function of a building be sacrificed; Kolarevic concludes that “in the future, as buildings become more ‘intelligent,’ it will be the information the surface transmits to and from the surrounding environment - and not its form - that will matter more” (Kolarevic, 2003, p.7). Within this future, it is our job as architects to find a healthy balance between expressive form and functional, performative aspects of a design, as “blobs” will not have a significant impact on architecture’s future if they are understood in formal terms alone. The challenge here is to understand the appearance of the digitally-driven design and production technologies in a more fundamental way than just tools for producing “blobby” forms. With that, it is the hope that architecture driven by expression in highly complex and curvilinear forms will gradually enter the mainstream construction industry as feasible, mass-produced, and customized elements. In doing so, new modes of digital fabrications need to explored as production of these elements are currently expensive and create, as traditional fordist modes of construction are still being utilized to create these complex forms (Figure 3.3.2, 3.3.2). Thus, they are not readily available for mainstream construction, especially for the high-rise.

So the question is: What are the tools that can assist in these organic or expressive forms being translated into the common place construction industry to re-create the expression, customization, and individuality that has been lost, while maintaining standard costs relating to construction?

Figure 3.3.1 Frank Gehry's AGO, under construction.

Figure 3.3.2 Frank Gehry's Disney Concert Hall under construction.

4. Mass Production and Mass Customization

Since the Industrial Revolution and the assembly lines brought to life by the Ford plants, we have embraced the phenomenon of mass production, which enables the creation of large amounts of standardized products, and is seen in almost all fields of design due to the fewer labour costs and a fast rate of production. In the case of architecture, manufacturing has gradually taken the place of the art of building, and all the minor processes of construction have shifted from the job itself to the factory. This has been a positive shift in the industry, and will continue to be if rapid production is coupled with customization to limit the mundane, repetitiveness of linear forms.

In every area of our lives, mass production is enabling customers to have a product their way, and have it faster, better, and cheaper. Today, we desire choice, expression, individuality, and the ability to change our mind. This philosophy of choice is key for companies such as Dell, Nike, Swatch, and car manufacturers (Figure 4.1). By providing choices at lower cost and higher quality, these companies respond to the widest demographic. But why is this idea not pursued in architecture and construction? Kieran Timberlake has attempted to address this question, and wonders: “Why do we continue to see costs escalate in making buildings at a rate exceeding the national average cost of living” (Kieran; Timberlake, 2004, p.135)? In architecture and design we are consistently forced to make design decisions based on costs that result in less choice, less customization, more standardization, and less quality. Kieran Timberlake believes that mass customization offers real change for architecture and construction, but the question is: Can we do it with the cost and efficiency that we have become accustomed to in our twentieth century construction industry?

Figure 4.1 Concepts of mass customization.

In the text *Architecture in the Digital Age*, it is mentioned that the rigidities of production are no longer necessary, as digitally controlled machinery can fabricate unique, complexly-shaped components at a cost that is no longer prohibitively expensive. Therefore, variety no longer compromises the efficiency and economy of production. It is just as easy and cost effective for a CNC milling machine to produce 1,000 unique objects as to produce 1,000 identical ones (Kolarevic, 2003, p.52). It is defined as the mass production of individually customized goods and services, thus offering a tremendous increase in variety and customization without a corresponding increase in costs. This idea is known as mass customization: the post-Fordian paradigm for the economy of the 21st century. This is a response and solution to the repetitive use of low-cost mass-produced components that were driven by twentieth century industrial manufacturing and logics of standardization, prefabrication and on-site installation. With this, variety no longer compromises the efficiency and economy of production, and uniqueness is now as economic and easy to achieve as repetition. We just need to enhance the use of electronics, rather than mechanics.

Embedded in the concept of mass customization is the idea that the consumer would have input in the design process. Through an investigation of this concept the question was asked: To what extent does the co-designer identify with the product? In search of an answer Gramazio & Kohler created *mTable*; a table that customers can design. Essentially, the customers choose the size, dimensions, material, and colour of the table from their cell phone (Gramazio & Kohler, 2008) (Figure 4.2). When the customer is satisfied with the design, he or she transmits the parameters that define the table as a simple series of numbers to the web-based platform at mshape.com. Following the order placement, the table is cute by a computer-controlled milling machine directly driven by the data transmitted by the mobile phone and the virtual three-dimensional model is transferred to the physical material (Figure 4.3). This allows many different designs to be produced effortlessly.

This design concept inevitably led to the question: What consequences does this development have on architecture? “The *mTable* project changes the task of designing form to defining the rules of a design system” (Gramazio & Kohler, 2008, p. 106). Embedded in the software is a framework within which the customers can have control over the ultimate outcome of the design, however the designer still retains control over which decisions are delegated to the customers and how freely they can intervene. Therefore, the consumer is ultimately the co-designer and this concept of mass customization will not cause the designer or architect to lose control.

Figure 4.2 Mass customization concept of mTable.

Figure 4.3 Final outcome of customer designed mTable.

Therefore, mass customization is a suitable production paradigm for the building industry. In buildings, individual components could be mass produced to allow for optimal variance in response to differing local conditions in buildings, such as uniquely shaped and sized structural components that address different structural loads in the most optimal way, variable window shapes and sizes that correspond to differences in orientation and available views (Kolarevic, 2003). “The notion that uniqueness is now as economic and easy to achieve as repetition challenges the simplifying assumptions of modernists and suggests the potential of a new, postindustrial paradigm based on the enhanced, creative capabilities of electronics rather than mechanics” (Kolarevic, 2003, p.53). Most importantly, the technologies and methods of mass customization allow for the creation and mass production of unique or similar buildings and building components, differentiated through digitally controlled variation and fabrication. Ultimately, the difference today that will enable mass production to succeed is its ability to be customizable. No longer does mass production have to produce the same repeated product; now flexible production methods allow for customization on a larger scale (Kieran; Timberlake, 2004).

It is no secret, though, that these philosophies have had their share of difficulties and inadequacies, and Bernhard Franken, in his article *Real as Data*, hopes that all of the prototypical projects out there will “alter the structure of the industrial building process, so that in the near future we can engage in mass-customization – a made-to-order, limited series production” (Franken, 2003, p.138). Furthermore, there is the hope of demonstrating that computer-generated architecture has the potential to cost up to 20% less than previous production methods, offers an enticing incentive for the implementation of new technologies in construction.

5. Digital Design and Production Technologies

> "The notion that uniqueness is now as economic and easy to achieve as repetition, challenges the simplifying assumptions of modernism and suggests the potential of a new, post-industrial paradigm based on the enhanced, creative capabilities of electronics rather than machines" (Kolarevic, 2003, p.53).

5.1. Digital Design

The rapid pace of technological development in the twentieth century ensured that the relationship between architectural design and building technology remained at the forefront of design. Digital technologies in particular have created new design tools for architects and have opened up new formal possibilities for designers. The digital age has essentially reconfigured the relationship between architectural conception and production, creating a direct link between what can be conceived and what can be constructed. These possibilities of digital production and design have allowed architects to restructure the post-World War II notion that the industrial production of architecture operated most efficiently when buildings were constructed using a limited set of regular, uniform elements. With the availability of computer-aided-design and manufacturing software (CAD – CAM), architects were forced to reconsider some of the central tenets of architectural modernism (Doordan, 2002). Now, with the highly complex forms prominently seen today in contemporary architecture, it is not a question of whether a particular form is buildable, but rather what new instruments of practice are needed, and what opportunities are opened up by the digital modes of production. As a result, we are seeing that these organic and expressive curvilinear forms have the potential to bring back customization in our construction industry, and have become more commonplace for standard construction practices, if the proper modes of production are properly executed.

Pre-digital architecture was a direct extension of the limits of Euclidean geometry (lines, circles, quadrilaterals, etc.), and had been somewhat restricted by the amount of information and documentation able to be attached. The introduction of digital modeling software into architectural design provided a departure from this geometry with the use of highly curvilinear surfaces and forms. New digital technologies allow for a further embedding of information within design through information such as material properties, design application, construction methods, and availability. This process is a synthesis of three fields – design, computing and fabrication, each informing the other. The actual process starts as a multistage exploration of shapes and shape relationships, while the process ends as the way most traditional design processes in architecture do with a limited amount of information for the contractor. Here, these complex curvilinear geometries are produced with the same ease as Euclidean geometries, and infinite variability becomes as feasible as modularity, and allows mass customization to present alternatives to mass production (Kolarevic, 2003). Now we are seeing a movement away from Mies van der Rohe's saying "less *is* more" to a method of less effort, less machine time, less material, and less waste: "less *for* more".

Frank Gehry's practice famously pioneered the use of sophisticated computer design programs in architecture. Called CATIA (computer-aided three-dimensional interactive application), the program was developed in the 1980s as a design tool for aerospace industries, but Gehry uses it extensively to refine and manage the complex wall and roof structures, along with unconventional building materials typical to his designs (Waters, 2003). In the text *Blobitecture* by John Waters, there is a quote from Gehry stating:

> "This technology provides a way for me to get closer to the craft. In the past, there were many layers between my rough sketch and the final building, and the feeling of the design could get lost before it reached the craftsman. It feels like I've been speaking a foreign language, and now, all of a sudden, the craftsman understands me. In this case, the computer is not dehumanizing; it's an interpreter". (Waters, 2003, p.32)

Given this desire for craft, with a departure from mass-produced repetitiveness, parametric design provides a versatile way to represent complex curves and surfaces, while presenting the greatest opportunity for mass customization in building techniques. Using parametrics, designers could create an infinite number of similar objects, as sets of equations are used to express certain quantities as explicit functions of a number of variables (Figure 5.1.1). "When these variables are assigned specific values, particular instances are created from a potentially infinite range of possibilities" (Kolarevic, 2003, p.17). In parametric design, it is the parameters of a particular design that are declared, not its shape.

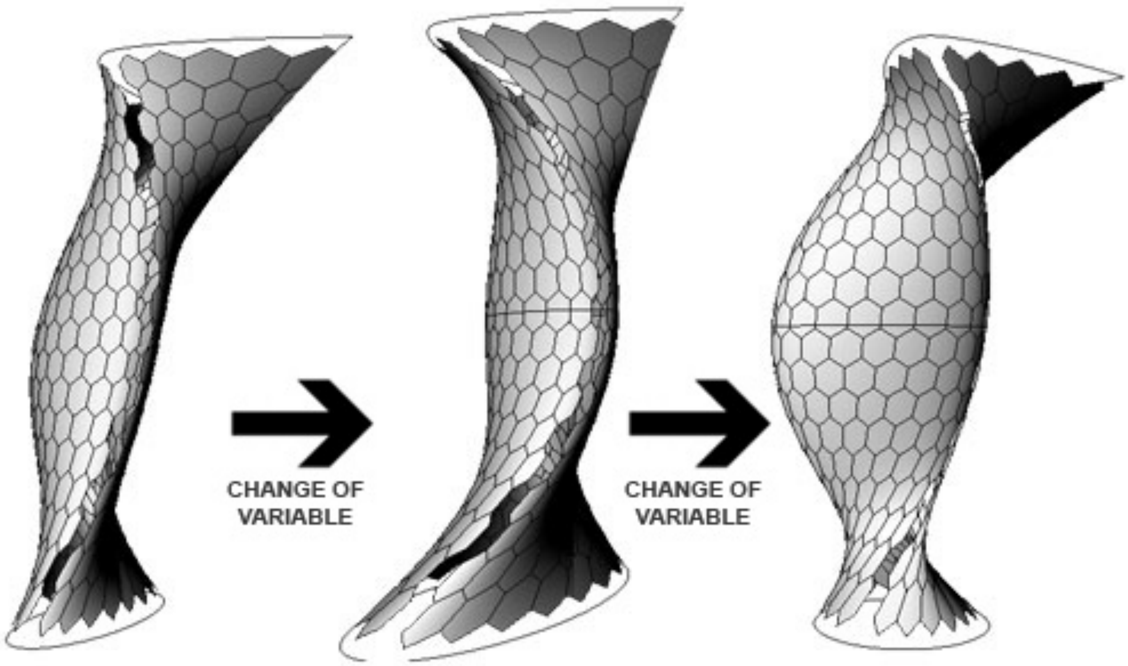


Figure 5.1.1. Illustrated concept of parametric design.

For example, Paracube by Marcos Novak uses parametric design to inform the design process (Figure 5.1.2). For this project, a cuboid was defined by six parametric surfaces, each with its own coordinate system. The parametric equations governing each surface were arranged so that a variation on a particular surface would cause reactions or permutations on adjoining surfaces, effectively creating a topological cube. The parametric cuboid was manipulated to create two forms: a skeletal frame and a smooth skin (Novak, 2000). Here, parametrization allowed the smoothness of each element to be defined and manipulated through computational formulas.

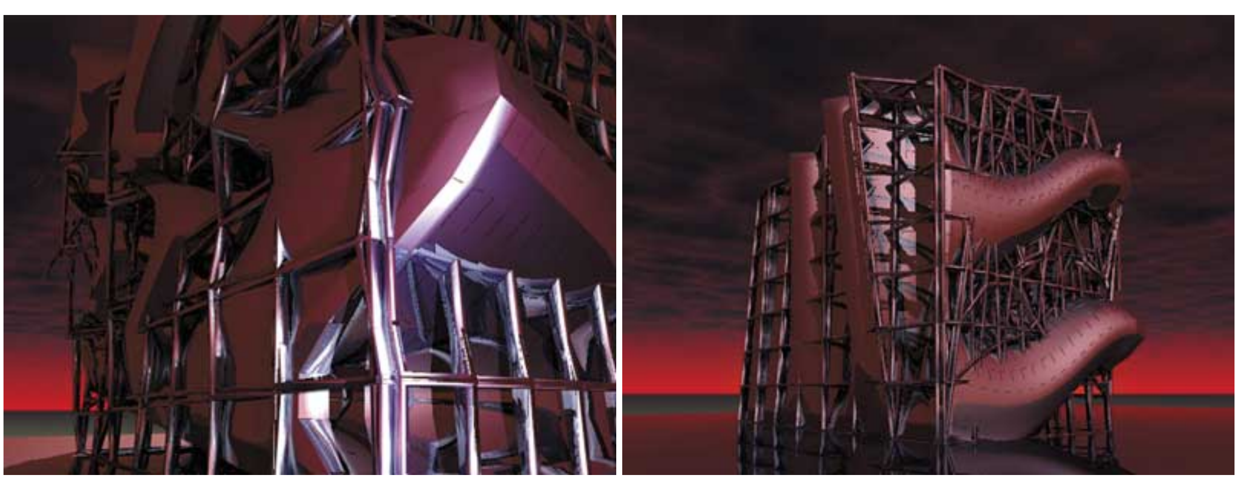


Figure 5.1.2 Paracube by Marcos Novak.

Parametric design is an example of a tool used to create forms and design parameters, but another important aspect is production techniques. Computer-aided manufacturing (CAM) is the use of computer-based software tools that directly assists in manufacturing product components. Originally used in the 1970s for car body design and tooling, this technique creates a faster production process, with more precise dimensions and material consistency. In many cases digital production uses only the required amount of raw material, thus minimizing waste, while simultaneously reducing energy consumption. With the application of this, we are going back to many of the modernist design philosophies of cheap, quick construction, but doing it in a way that utilizes our up-to-date technology in buildings that are representational of our time.

Digital techniques of parametric design have redefined the relationship between conception and representation, and digital fabrication has facilitated a closer investigation of material outcomes at the earliest stages of design. The various computationally numerically controlled (CNC) processes of shaping and reshaping, based on cutting, subtractive, additive, and formative fabrication, have provided designers with an unprecedented capacity to control the parameters of material production, and to precisely craft desired material outcomes (Kolarevic, 2008, p.122). In addition to CNC milling are: laser cutting, Stereolithography (SLA), solid ground curing (SGC), laminated object manufacturing (LOM), selective laser sintering (SLS), and high-pressure jet cutting. Through these forms of digital fabrication, designers are becoming more directly involved in the production process again, as they can create the information to be translated by fabricators directly into control data that drives the digital fabrication equipment.

Herzog & De Meuron's de Young Museum in San Francisco (2005) demonstrates the use of digital fabrication technologies in sheet-metal production (Figure 5.1.3). For exterior rain screen panels, unique cut-out and embossing patterns were created from abstracted images of surrounding tree canopies, using parametric design (Kolarevic, 2003). Then, slight variations of parameter values produce a series of differentiated yet repetitive objects. Having the opportunity to work so meticulously and directly with the material outcomes of a project, allows the customization and craft to be brought back to the design and production process. All of this assists in the mass customization of building materials, and processes, paired with the efficiency of building construction, transportation, and installation. Here, the technologies and methods of mass customization allow for the creation and production of unique or similar buildings and building components, differentiated through digitally-controlled variation.

Figure 5.1.3 Herzog & De Meuron's de Young Museum in San Francisco.

5.2 Digital Fabrications and Production

Architecture is built from components, and since the time of industrialization, those elements have been standardized and general building systems have evolved, which allow prefabrication and very efficient planning and construction processes. However, those systems only work when the shape of the building stays within the rigid boundaries defined by its standardized components. The so-called “free-form” architecture of our times challenges this approach, because it constantly tries to break those rules (Kolarevic, 2008). Nonstandard architecture needs nonstandard components, and the following attempts to investigate this.

Figure 5.2.1 Digitally fabricated elements. (retrieved from: http://jlaucks.wordpress.com/)

In studying this form of architecture, the text *Digital Fabrications* is a great resource for exploring designs made possible by recent advances in digital fabrication techniques. Digital fabrication has spurred a design revolution, yielding a wealth of architectural invention and innovation (Iwamoto, 2009). How designs use digital fabrication and material techniques to calibrate between virtual model and physical artifact is the subject of this book. Furthermore, it explores the methods architects use to calibrate digital designs with physical forms. The book is organized around five techniques: sectioning, tessellating, folding, contouring, and forming. Many of the projects’ outlines are on a small scale, but nonetheless demonstrate just what can be done with our ever-evolving technologies. The following examines the advances in tessellation and contouring, given that these would be the most acceptable to apply to high-rise construction. The other techniques offer great insight, but are more afforded for small-scale projects and installations.

Tessellation is a collection of pieces that fit together without gaps to form a plane or surface. These can be virtually any shape as long as they puzzle together in tight formation, and in architecture the term refers to both tiled patterns on buildings and digitally defined mesh patterns (Iwamoto, 2009). This system is typically used to create decorative surfaces to filter light or view, define space, or convey symbolic meaning. Typically, curved and ornate surfaces are far more complex and expensive to construct than flat ones, but tessellation offers a way to build smooth form using sheet material. This could potentially be a solution in our construction industry to eliminate the boring repetitiveness of our current housing stock. In making this statement, numerous case studies were examined.

Fabio Gramazio and Matthias Kohler have made significant strides in revolutionizing computer-aided building in the specific area of assembly and formation of three-dimensional tessellated wall units. For these units, they have experimented with algorithmic design to bring new life to numerous materials such as traditional brick, concrete cubes, liquid foam, and timber (Figure 5.2.2).

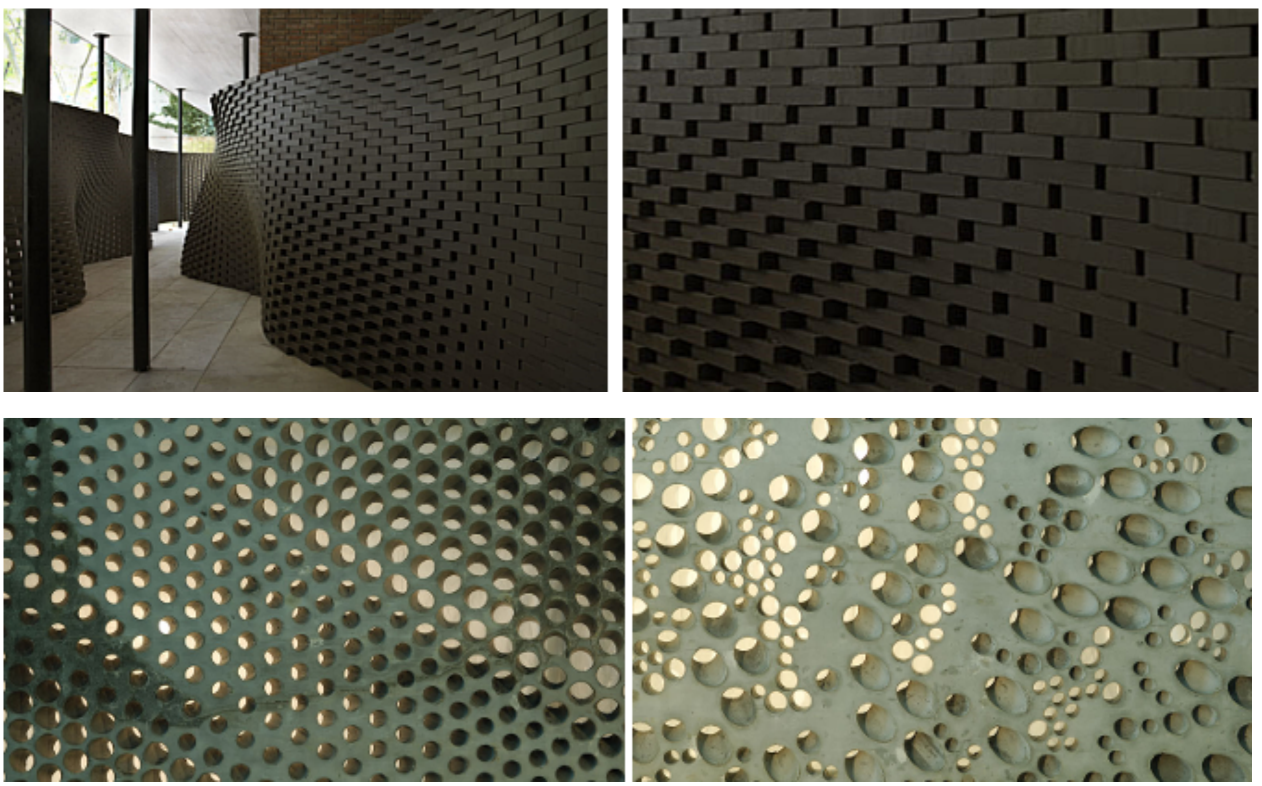


Figure 5.2.2 Gramazio & Kohler's three-dimensionally tessellated wall units.

In creating these units, technology was adapted from the automotive industry as a basis of digital fabrication using robots to weld, finish, drill, and handle materials. These robots accurately place materials based on digital data that describes the desired horizontal and vertical placement and orientation, similar to the information given to direct a CNC router. An example of this is *The Programmed Wall*, which was one of the team's first robotic investigations (Figure 5.2.3). Computer scripts were written to assemble the modules digitally, addressing the necessary constraint of traditional brick construction. The robot used this data to assemble the wall brick by brick, much as a traditional mason would have (Gramazio & Kohler, 2008). This demonstrates that the typology of the high-rise doesn't need to be reinvented, but can be simply revisited through the rethinking of how we use our standard materials. This particular text provides great insight and inspiration on what can be done using digital fabrication.

Although, if the basic manufacturing conditions of architecture shift from manual work to digital fabrication, it is worthwhile to investigate the design potential for traditional architectural elements - for example the brick. In saying that, what does this mean for our construction industry as a whole?

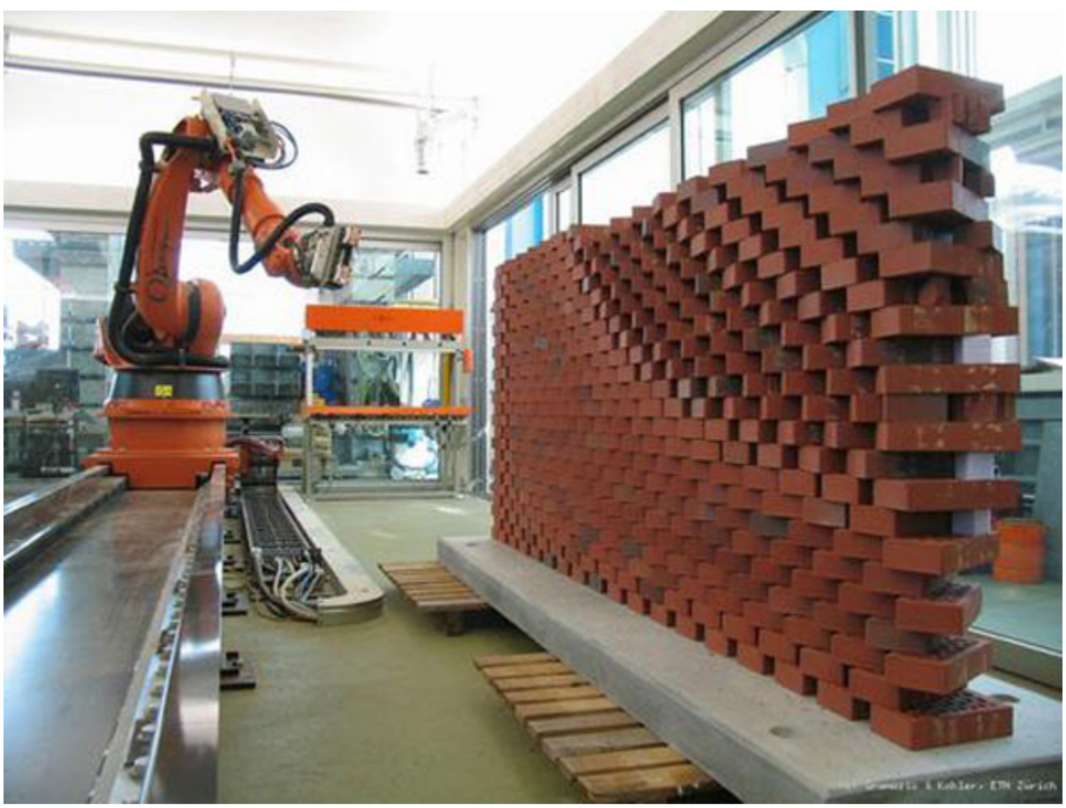


Figure 5.2.3 Gramazio & Kohler's Programmed Wall.

This text also explores the world of contouring. This is an interesting area to explore, given the connections to and influences of organic architecture. There is a long history of wood and stone carving in craft and architectural practice, for example column capitals, friezes, rock-cut architecture, and Jain temples. While the tradition of this technique is rich, it has nevertheless had limited application in architecture since the Industrial Revolution, largely because the hand and machine labour required to produce pieces is variable, limited by scale, and cost and time prohibitive (Iwamoto, 2009). Digital fabrication has enabled architects to explore this once again using tools that include CNC routers and mills, which use tool-path data derived from digital models to carve away material and create a series of contours. Although highly effective, contouring is material and time intensive. As a subtractive fabrication process, CNC milling removes material from sheets or blocks to make parts (Iwanoto, 2009). Contouring is used by architects to elevate relatively ordinary building materials to extraordinary levels. For example, Greg Lynn has experimented with using the routing process to generate surface texture. Using ridged tool paths, the material becomes highly textural, increasing visual value. This is another direction or option in the category of contouring that may be less wasteful of material. Compared to the previous example, these forms of construction may not yet be completely acceptable to high-rise design given the vast amount of material required, although they do offer a solution to mass producing organic and ornate forms with the potential application in contemporary construction practices.

Therefore, in the act of openly embracing nonlinearity and expressive forms, these new digital design and fabrication techniques challenge architectural conventions of stable design conceptualization, reasoning, and order, which are still the underlying foundation for the design of mainstream architectural production. In doing so, we are moving to a future where these become more commonplace; and as stated in the article *Digital Morphogenesis*, now, “the non-linearity, indeterminacy and emergence are intentionally sought out” (Kolarevic, 2003, p.27), thus further solidifying the argument this could become a feasible way of designing and building in our North American construction industry.

5.3 Materials and Digital Fabrication for Mainstream Construction

The construction industry is clearly in need of radical change. It consumes much of the world's resources and produces approximately 30% of the world's waste. It is also the most inefficient of the world's high-capital industries (Spiller, 2009). To compound the problem, buildings themselves are wasteful and inefficient. Norbert Young in an article from the text *Architecture in the Digital Age* comments about the life cycle of a project, and how a project is never really done. He states that over half the dollars spent on a project are after the project is done in the repair, refit, maintenance, and renovation. This sets up the argument that there will always be a need to renew our old buildings. The incorporation of new materials and technologies should be given as much, if not more, attention than that of new building construction. If the way we build and our attitudes towards it can be fundamentally changed, huge gains could be made towards a sustainable future.

In an article from *The State of Architecture in the Beginning of the 21st Century*, Toshiko Mori ponders the use of material in our time. Although technology and innovative materials thrive in our generation, they are rarely applied to architecture due to economic reasons. He believes this is a result of the slow rate of return to investments in innovation. As architects, we need to alter this mindset, and prove that there are huge gains in appropriate material selection, paired with digital technology. "Architects must be more ingenious, inventive, and imaginative in using material technologies" (Mori, 2003, p.31). As demonstrated by Fabio Gramazio and Matthias Kohler, digital materiality linked with production technology leads to new expression and sensuality in architecture. Materials in this age do not appear primarily as a texture or surface, but are exposed and experienced in their whole depth and plasticity. Even familiar materials, such as bricks and concrete, are appearing in new ways (Gramazio & Kohler, 2008). Simply with the application of these ideologies through digital technologies, we could bring back the art and customization to high-rise construction without compromising their history and integrity. Here, data and material, programming, and construction are interwoven; it is just a matter of how they are produced.

Digital technology is often used to produce images, but it is now having a different effect of architecture, a more direct and physical one, through fabrication. Through CNC cutting, computer-directed laser welding, and cutting machine tools, digital fabrication technology is more globally accessible, economical, and viable (Kolarevic, 2008). With this, we have the knowledge and tools to act as Mori believes we should. In doing so, a useful application is digital fabrication, where the production of building parts is directly controlled by the design information. The seamless link between data and material design and building dissolves the apparent incongruities between digital and physical realities and allows a new constructive understanding of the discipline (Kolarevic, 2008). As demonstrated throughout the book *Manufacturing Material Effects*, fabrication components and materials not only accessorize construction, but also now contribute to essential structural and cladding systems, especially in high-rise construction. Tower design offers a restricted set of design parameters, wherein the exploitation of the elevational and surface effects presents the greatest opportunity to create a unique variance in design, and the application of digital design and fabrication allows for this.

Over the past decade we have seen in architecture the re-emergence of complexly shaped forms and intricately articulated surfaces, enclosures, and structures, whose design and production were fundamentally enabled by the capacity of digital technologies to accurately represent and precisely fabricate artifacts of almost any complexity. In a dramatic departure from the formally and materially reductive norms of much twentieth-century architecture, it is now possible to materially realize complex ideas that were previously unattainable (Kolarevic, 2008). With digital parametric design and production, variation becomes possible not only in spatial layouts and component dimensions, but also in material composition and surface articulation, offering unprecedented freedom from standardization that defined design and production for much of the twentieth century (Kolarevic, 2008). Such variability presents a radical departure from the present normative practice.

Ruban Suare from 3form is a leading practitioner in the creation of opportunities for high levels of material innovation. 3form is a manufacturer of resin panels based in Salt Lake City, Utah, with the idea of creating an architectural studio within the manufacturing business structure. The studio acts as the connection between the manufacturer, the architect, and the contractor (Kolarevic, 2003). For the project for a façade of a boutique on Sunset Boulevard in Los Angeles, designed by Patterns, 3form was engaged in model rationalization and redefinition, panel fabrication and heat forming, and structural design, fabrication, and installation of the support system (Figure 5.3.1). A main aspect of the project was to find areas where the geometry could be rationalized to make the process of fabrication cost effective (Kolarevic, 2003). According o Ruban Suare, another cost-saving technique is the use of ruled surfaces (single-curved), which allows the fabrication of less expensive molds. Rationalizing geometry is always a collaborative process with the goal of arriving at an ideal balance between aesthetics and cost. Here, the outcome of the design was informed by the fabrication process, which goes to show that these processes can be incorporated in the standard construction industry, with the incorporation of a third party. We no longer need to have prefabrication with repetitive outcomes.

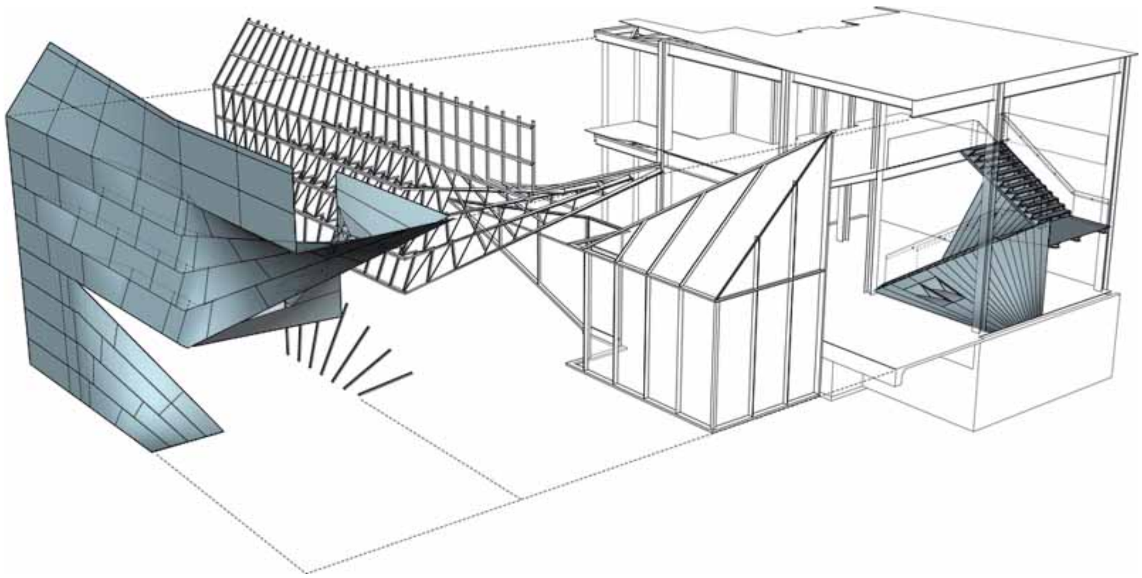


Figure 5.3.1 Exploded axonometric of façade: boutique on Sunset Boulevard in Los Angeles.

Figure 5.3.2 Façade of a boutique on Sunset Boulevard in Los Angeles.

Furthermore, throughout the text *Manufacturing Material Effects: Rethinking Design and Making in Architecture*, there are many projects that examine the typology of the tower. Given that there is little room for innovation in high-rise tower construction, the case studies presented and examined give attention to the form of the façade, the production methods, and materials and technologies used. The firm Front, Inc. is a collaborative design practice focused on the creative development of façade systems and engaged generally in the activities of architecture, fabrication, procurement, construction, and development. In his article from *Manufacturing Material Effects: Rethinking Design and Making in Architecture,* Marc Simmons explains that "very often the challenge is economic constraints, where creative sourcing, process innovation, and optimization are simultaneously required to generate value, while preserving a certain set of intentions" (Simmons, 2008, p.262).

6. Precedents

6.1. Digital Design and Materiality

Materials create an ambience and provide texture or substance to architecture, and this is especially important when the architecture is one of limited expression. Given that the focus of the thesis is on high-rise construction, with major focus on façade techniques, exploration of materiality is important.

Throughout the years, technology has changed the way that form is generated, rationalized, and realized. As building design becomes more sophisticated, so does the use of materials. We are seeing an increasing amount of contemporary designers taking materials from different contexts and environments and applying them inventively in architecture. Furthermore, the re-emergence of traditional building materials are being realized through parametric design and digital fabrications, which are allowing us to re-explore and re-realize the potential for some of these materials.

If the basic manufacturing conditions of architecture shift from manual work to digital fabrication, it is worthwhile to investigate the design potential for traditional architectural elements, for example: the brick.

6.1.1 290 Mulberry Street

Architect: SHoP Architects
Location: New York, New York
Completion Date: 2008
Material Use: Traditional brick
Form of Production: Robotics, CNC router, parametric modeling

Fabio Gramazio and Matthias Kohler, have made significant strides in revolutionizing computer-aided building in the specific area of assembly and formation of three-dimensional tessellated wall units. They have adapted technology from automotive industry as a basis of digital fabrication using robots to weld, finish, drill, and handle materials. These robots accurately place materials based on digital data that describes the desired horizontal and vertical placement and orientation, similar to the information giving to direct a CNC router. An example of this is The Programmed Wall, which was one of the team's first robotic investigations (Figure 6.1.1.1). Computer scripts were written to assemble the modules digitally, addressing the necessary constraint of traditional brick construction. The robot used this data to assemble the wall brick by brick, much as a traditional mason would have (Iwamoto, 2009). Like Gramazio and Kohler, SHoP is capitalizing on the potential of brick tiling, specifically for the creation of large curtain-wall panels (Iwamoto, 2009). For a site at 290 Mullberry Street in New York City (Figure 6.1.1.2), the firm had proposed a decorative masonry façade.

One of the most striking aspects of this and other SHoP projects is the visual and tactile richness achieved through the modulated treatment of highly standard building materials (Iwamoto, 2009). The design team researched fabrication constraints with top panel manufacturers in the US and Canada, to understand how to detail the panels in a costly and efficient manner. Complexity of the panel design, including cost, weight, brick coursing, fabrication, transportation, and installation, reaffirmed the use of parametric modeling as essential in order to be cost effective from a design standpoint (Sharples, 2008, p.45). To be economical, SHoP worked with a standard brick size, and the manufacture of the panels is fairly standardized. Here, the software was the interface through which all variables of the project were controlled.

This project demonstrates that the typology of the high-rise doesn't need to be reinvented, but can be simply revisited through the rethinking of how we use our standard materials. The use of parametric design strategies and digital fabrication allow us to transform building facades in a costly and economic way. Furthermore, through the use of traditional building materials, buildings may have the opportunity to respond more appropriately to surround context.

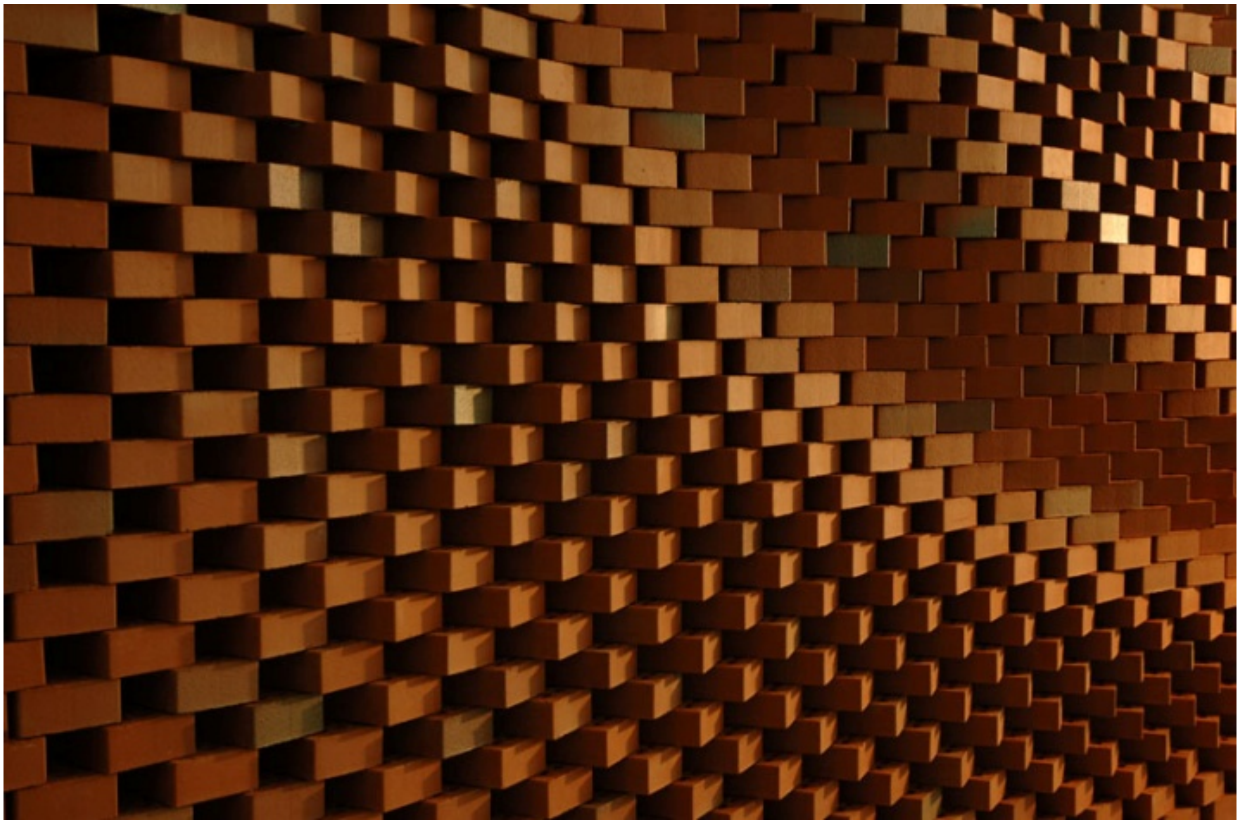


Figure 6.1.1.1 Surface effects of the Programmed Wall.

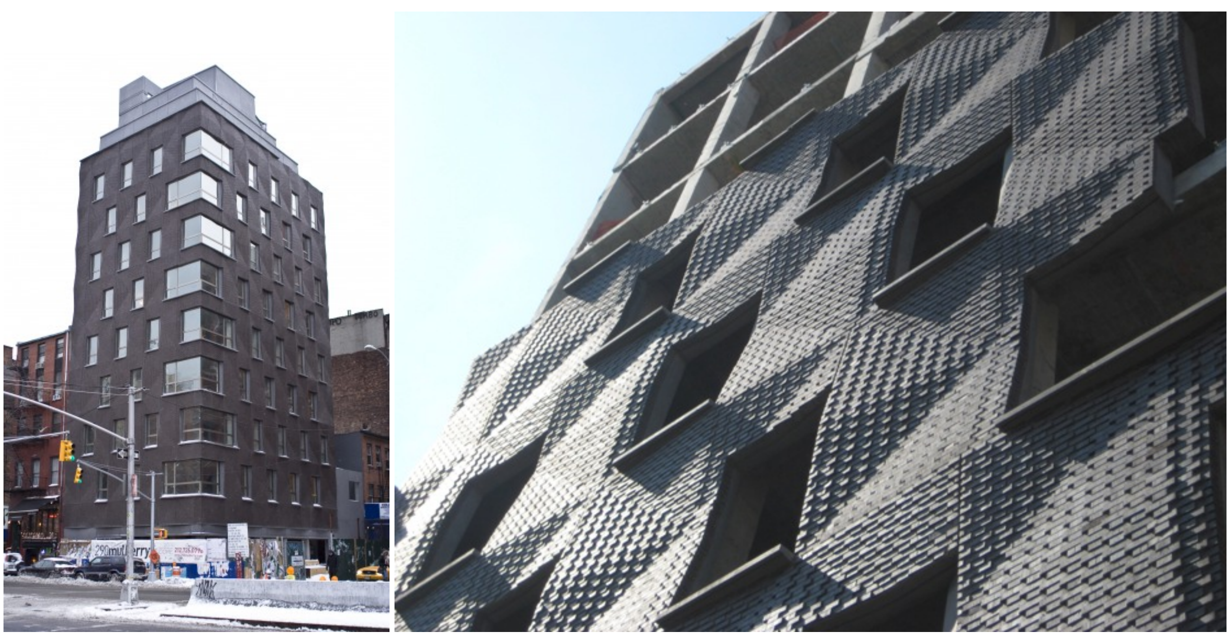


Figure 6.1.1.2 Façade of 290 Mulberry Street.

6.1.2 The Sequential Wall

Architect: Gramazio and Kohler
Location: Zürich, Switzerland
Completion Date: 2008
Material Use: Traditional timber
Form of Production: Robotics, CNC router, parametric modeling

This project, done by a group of students studying digital materiality, investigates the architectonic and constructive potential of additive digital fabrication in timber construction. This was a process designed in which a robot would first cut commercially available timber to length and then stacked them in a free arrangement (Gramazio & Kohler, 2008). Here, straight lines flow into curved ones, and there is a repetition of wooden slats, which become unique in their length.

Algorithmic tools allowed variation in design, along with the ability to integrate the functional requirements of an external timber wall. For example, individual wooden slats that protruded outwards and face down were used to shield the structural parts from water by channeling it away from the façade, much like shingles (Gramazio & Kohler, 2008). This technique was also used as a strong and expressive design element. Similar to the exercise done with the programmed wall, this could be translated into a panelized system for building construction.

Although timber is not necessarily a material we see typically in mainstream construction, it could be substituted with similar material that may be more practical for our environment. The important thing to note is that customization is possible, and with the use of algorithms and digital robotic fabrication, this could be translated into a feasible architectural design.

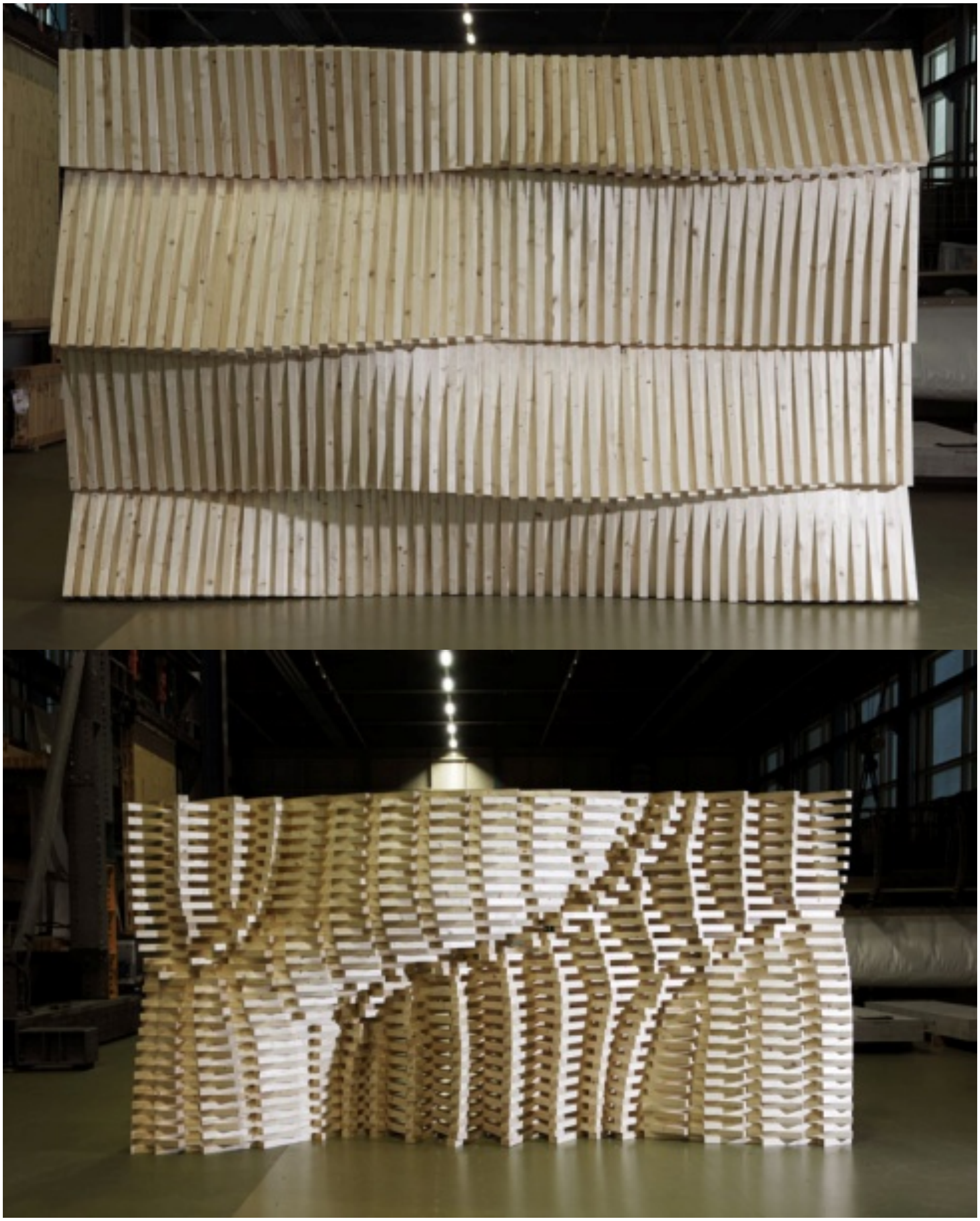


Figure 6.1.2.1 Various form creation from the use of robotics coupled with timber.

6.1.3. Airspace Tokyo

Building Architect: Hajime Masubuchi (Tokyo)
Screen Architect: Thom Faulders
Location: Tokyo Japan
Completion Date: 2007
Material Use: Sheet material: aluminium and plastic composite
Form of Production: Parametric Software Program

Tessellation technique can be used to create screening elements that visually enhance the exterior façade, by simply cutting and recombining sheet material. The main structure of the residence was designed Hajime Masubuchi, of Studio M in Tokyo. The Airspace screen, however, was designed by Thom Faulders, and uses straightforward rectangular panels welded together to form a seamless screen. The tessellation pattern is, in this case, achieved through cutouts in sheet metal. Inspired by the abundant greenery that previously occupied the site, the screen façade comprises four different overlapping organic patterns (Figure 6.1.3.1).

The openings' size and shape are determined by using a parametric software program to manipulate a tiling pattern based on the Voronoi diagram – a geometric pattern found in nature (Iwamoto, 2009). The result evokes both an interior and an exterior effect of filtered light. With an air gap of 15cm in-between, the 3mm-thick curtain-like coverings of laser-cut aluminium and plastic composite, frame views and light according to the internal floorplan. The thickness of the screen is visually enlarged by the effect of the compressed patterns, making the screen a dynamic buffer of shadows and oddly framed views (Figure 6.1.3.2).

This project also demonstrates how we can take standardized building material, and transform and manipulate it, creating a unique building façade. Although this is not a panelized system, it still presents opportunities for application in high-rise facade design. With its fast and unique fabrication, ideas and techniques from this could be applied.

Figure 6.1.3.1 Exterior façade: Airspace Tokyo.

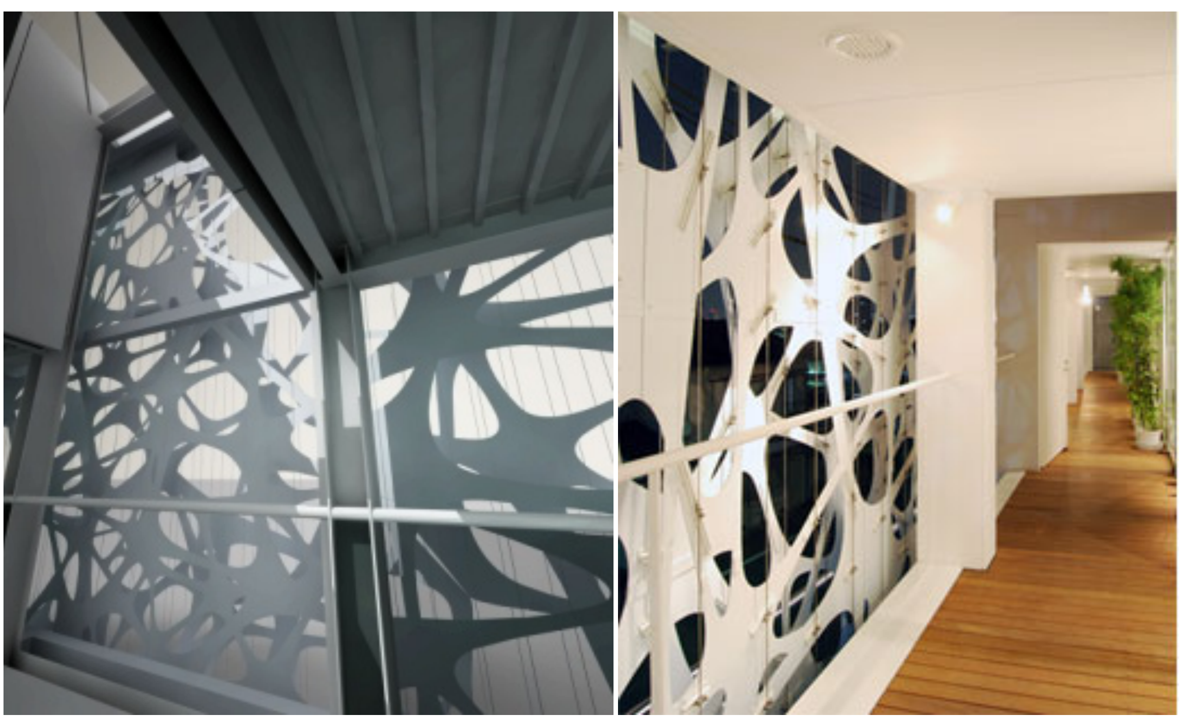


Figure 6.1.3.2 Screen patterning: Airspace, Tokyo.

6.2 Tower Facades and Technologies

Tower design offers a restricted set of design parameters, wherein the exploitation of the elevational and surface effects presents the greatest opportunity to create a unique variance in design, and the application of digital design and fabrication allows for this. The case studies presented below showcase tower designs, and represent various ways to manipulate the exterior facade to create a unique form. Within the parameters of tower design, expression of building skin is important.

Given the focus on tower restoration and potentially working with the existing structure of the building, looking at various manipulations and applications of exterior skin is beneficial in its application. Through these case studies, it will be shown how the construction of this could be carried through, along with a variety of material options, all which could be mass-produced. Furthermore, the tower designs outlined work with a reasonable simple core and structure, with the focus being on the skin of the building. Also, with the focus being on residential towers, glass will be imperative to the design, therefore, a majority of the case studies examined have a focus on curtain wall design, production and manipulation.

6.2.1. Trutec Building

Architect: Barkow Leibinger Architects
Location: Seoul, Korea
Completion Date: 2007
Material Use: Highly Reflective Viacon Glass
Form of Production: CNC saw, mass produced facade panels

As the production of both architectural designs and construction elements (materials, systems, etc.) have evolved with computers, more complex and varied designs are possible. One example is folded glass facades, which take once-modular components of glass and steel and make them appear more malleable. Barkow Leibinger Architects' Trutec Building in Seoul, Korea synthesizes the modular and the folded by taking a regular rectangular grid and infilling the cells with a prismatic pattern of triangular and trapezoidal glass panes (Barkow, 2008, p.100).

The Trutec building is a rather standard core and shell office building on the periphery of Seoul. This lead to some areas of the project having more control over than others, therefore considerable attention was paid to the skin of the building. In doing so, a combination of a regular grid and prismatic cells with highly reflective glass gives the alternating images of sky and built context, creating an irregular but relatively consistent pattern across the main facade (Figure 6.2.1.1). It could operate both visually as an urban public mediator, while giving an identity to the otherwise speculative office spaces interiors (Barkow, 2008).

The facade profile panels were locally built and are relatively standardized, and mass produced with the angle with a CNC saw. Then the frames were combined with a reflective Viacon Glass (Figure 6.2.1.2). This makes the building unique as changes in light, weather, traffic, people, and seasons, animate and transform the building. Here, the idea of taking a rather ordinary building type and transforming it, through digital technologies, have achieved extraordinary results, at a relatively low cost.

This project relates well to the methodologies of the thesis, as it is working on a shell of a standard office tower, with the main focus being the facade. Given that the main focus was proving the building with an identity through a panelized system, many of the techniques could be further explored for implementation into a tower renewal.

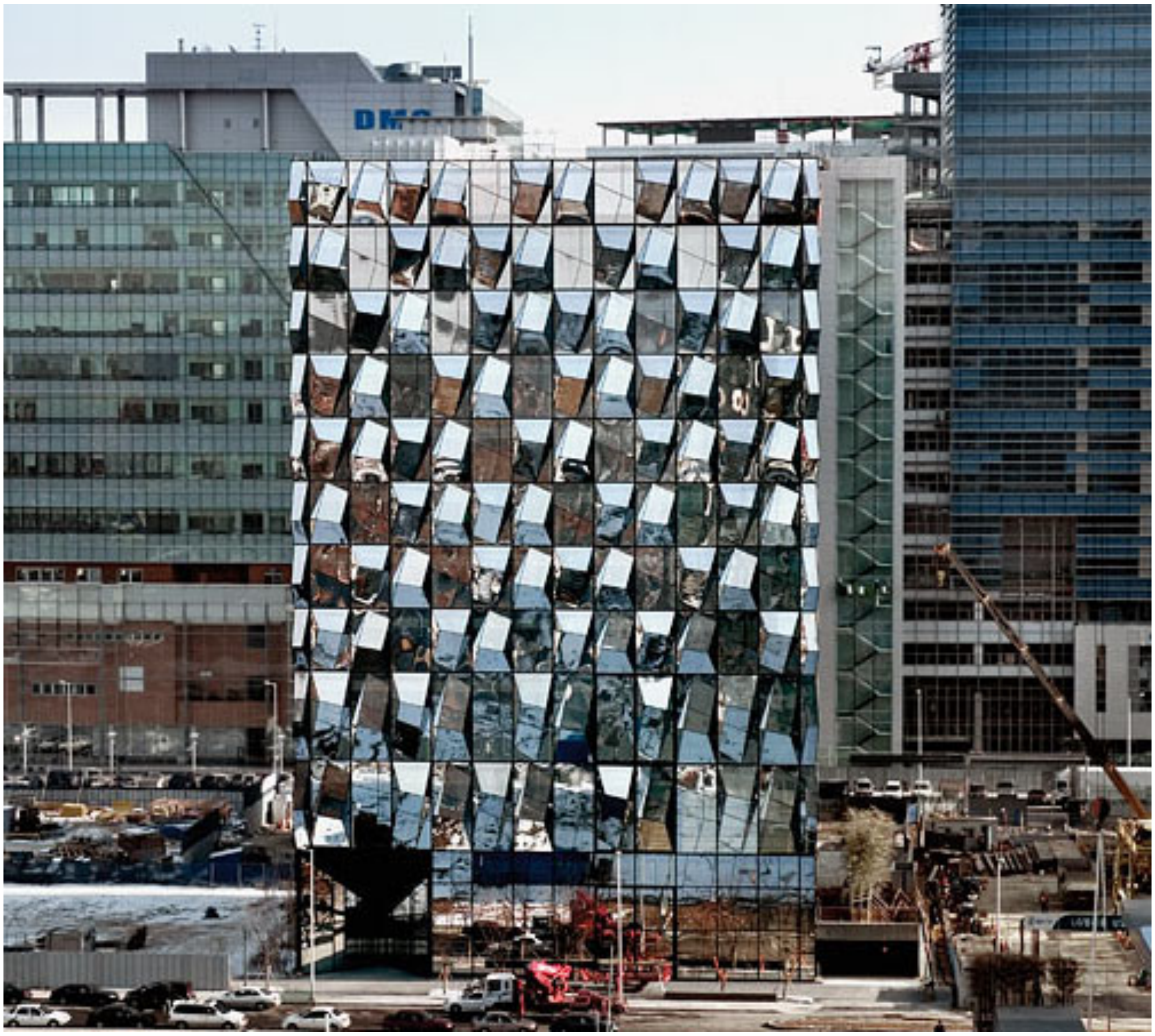


Figure 6.2.1.1 Exterior Façade

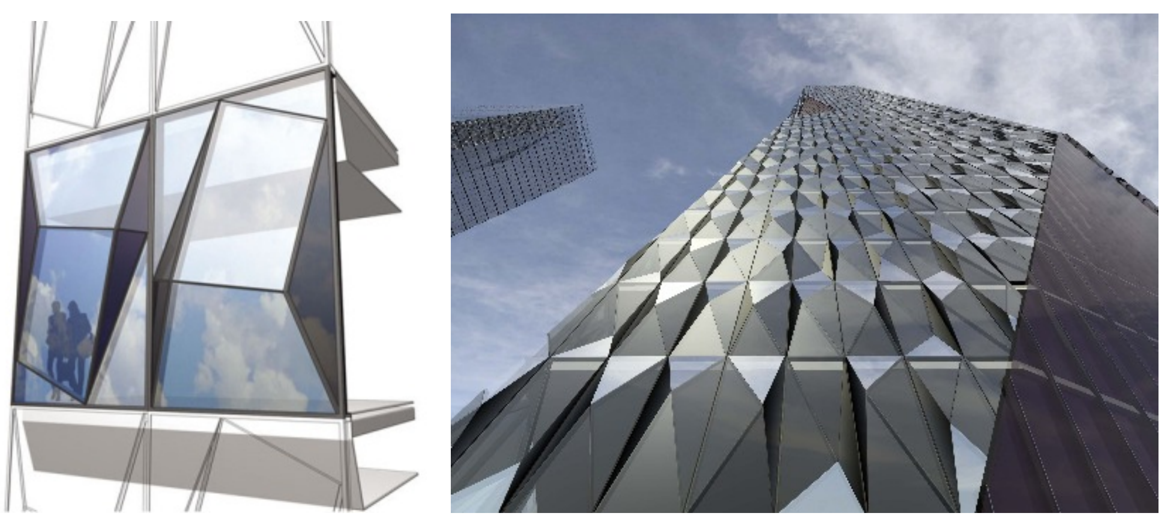


Figure 6.2.1.2 Panelized window system.

6.2.2 100 11th Avenue Residences

Architect: Jean Nouvel
Location: New York, New York
Completion Date: 2008
Material Use: Patterned glass panels
Form of Production: designed using CATIA with associative parametric assemblies

The 100 11th Avenue project, a 23-storey residential tower, described by its architect Jean Nouvel as “a vision machine,” is located along West Side Highway in Manhattan, New York. The building features a faceted facade, composed of glass panes of varying sizes, shapes, and materials, tilted along different axes within a complex steel and aluminum framing system (Figure 6.2.2.1). The design intent was for a facade with a single composition, as opposed to a traditional curtain wall with discernible panels (Simmons, 2008, p.274). The objective was to introduce a regulating order to the facade, and resolve it into a system that makes sense in terms of sound construction practices.

The facade was designed using CATIA and the related Digital Project, and locating “vision” panels and operable windows based upon the interior of the residential units. Groupings of glass panes were organized into megapanels (Figure 6.2.2.2), whose overall dimensions conform to the rooms they cover. There are 192 megapanels, 87 of which are unique. Seven megapanels cover each floor. The entire facade wall features 1,351 individual glass panes, composed of four different material variations, with each pane tilted on one axis by several degrees (Simmons, 2008).

The frame was constructed from steel mullions, which will carry the loads when formed into the irregular patterns of the facade design. The mullions vary in width from 3 to 6 inches to support the various tilts of the glass panes. Three-dimensional modeling in CATIA enabled the definition of fully associative parametric assemblies, which in turn facilitated the automatic production of two-dimensional shop drawings.

This case study is a perfect example of how to incorporate a mass-produced digitally fabricated panel system, while still having it look completely unique. For this technique to be realized, having limited panels, the interior units need to be relatively standardized.

Figure 6.2.2.1 Exterior façade.

Figure 6.2.2.2 Organization of megapanels during construction.

6.2.3. High Line 23 Residential Building

Architect: Neil Denari
Location: New York, New York
Completion Date: 2008
Material Use: Concrete, Metal, Curtain wall
Form of Production: Panelized facade

High Line 23 is a 13-storey residential building along the West Side High Line in New York, which is a continuous elevated bridge structure that will be transformed into a unique linear urban park. “According to the architect Niel Denari, the building is ‘precisely shaped by a confluence of forces’ and is a ‘combination of both found implanted in ecologies,’ like the High Line itself” (Simmons, 2008, p.278). The east facade facing the High Line is formed as a sculptural surface with framed views of Manhattan. A curtain wall of glass and stainless steel panels hangs on a complex cantilevered steel frame, generating expressive forms and surfaces (Figure 6.2.3.1).

The glass facade employs a panelized system with framing elements from milled steel that was over-clad with fine break-formed stainless steel profiles. Custom aluminum cassette profiles are “skinned” onto the steel, holding structurally siliconed glass panels (Figure 6.2.3.2). The glass is low iron, low-e, floor-to-ceiling, laminated, and insulated, with the majority of panels having a custom applied silk-screen pattern. The pattern was developed as a projected shadow of the primary structural steel behind the facade; it reinforces the building’s structural configuration, which has an offset core with irregular steel columns and diagonal bracing elements. The frit pattern is a super-graphic, but does in fact correlate directly to the structural diagram of the building, yielding a certain level of legibility and abstraction, and simultaneously giving the building one of its strongest iconic drivers (Simmons, 2008).

This study offers an exploration of materials and how they can be formed and cut to create unique shapes through the use of glass and steel. Many of the ideas here could be incorporated into design and the systems could be easily attached to an existing structure.

Figure 6.2.3.1 Exterior façade.

Figure 6.2.3.2 Panelized window system.

6.3 Mass Production and Customization

Noticeably, manufacture has gradually taken the place of the art of building, and all the minor processes of construction have shifted from the job itself to the factory. In architecture and design we are consistently forced to make design decisions based on costs that result in less choice, less customization, more standardization, and less quality. The prospect of mass customization, transfer technologies, and off-site fabrication should be give-ins for questions in architecture, just as issues of structure, enclosure, and use have been given for a thousand years (Wallick, 2007). Kieran Timberlake believes that mass customization offers real change for architecture and construction. The following case studies demonstrate this.

6.3.1. SmartWrap

Architect: KieranTimberlake Associates
Location: Various locations across the United States
Completion Date: 2003
Material Use: Combination of technologies
Form of Production: Printing

The premise of the SmartWrap was to prefabricate as many of the systems as possible through mass production, to create a wall to be installed in as few pieces as possible by a single crew of workers. As stated by KieranTimberlake Associates: SmartWrap is the building envelope of the future: a composite that integrates the currently segregated functions of a conventional wall and combines them into one advanced composite.

Since the architects ultimately wanted to print, roll, and see through the wall, many materials were given close consideration (Figure 6.3.1.1). SmartWrap is comprised of a polyethylene teraphathalate (P.E.T.) substrate printed (although laminated in the prototype) with organic light emitting diodes (O.L.E.D.s), organic photovoltaic's (O.P.V.s), phase change materials (P.C.M.s), thin film batteries, and printed circuitry (Wallick, 2007).

Furthermore, the essential and inherent characteristic of SmartWrap is that future applications would not all have the same type of components. There is intended to be a menu of program parts, giving variability to the architect depending on site, orientation, climate, program and use, aesthetics, privacy and publicity. In the production of this, multiple building contractors would be traded for a single printer. It is said that "the technique would be exactly like an ink-jet printer except instead of depositing droplets of ink, we would deposit droplets of P.V.s or conductive circuits" (Wallick, 2007).

These processes were tested and produced as an installation. The intention of the pavilion is to explain the concept of the wrap in its architectural and artistic context, to describe its various components, and demonstrate the transfer technologies associated with it.

Although this process appears promising in terms of construction and fabrication, there are more practical issues coming into play such as excavation, existing conditions, and structure. Although this system is a work in progress, the overall goal is to achieve a printable, mass-customizable wall system. The argument is strong as to why this is feasible, but the details and processes are still be ironed out. Here, the balance between craft, technology, and construction is being tested, and with many of these issues being addressed thought the thesis, this was a valuable project to evaluate.

Figure 6.3.1.1 Exterior façade.

Figure 6.3.1.2 Wall cavity.

6.3.2. Embryological House

Architect: Greg Lynn, FORM
Location: Conceptual
Completion Date: 2000
Material Use: Double skin: aluminum and glass; solar shading
Form of Production: Digital design and fabrication

The Embryological House represents a new approach to fabrication and growth. Historically, a modern house would be thought of as a kit-of-parts. Each part is distinct and discreet, and you customize the house through the addition or subtraction of parts from the kit. Over forty percent of all the new houses in America are built in factories and assembled on-site. The Embryological House would try to participate in that economic reality, but with a completely different implicit lifestyle and relationship to the environment (Dery, 2000).

Lynn had an interest in developing a mid-market, single-family dwelling that could be customized easily for virtually any setting (Figure 6.3.2.1). What has evolved was a structure defined by a soft, flexible surface of curves, rather than a fixed set of rigid points (Waters, 2003). To accomplish this, the design drew upon manufacturing techniques from the auto and airline industries. The goal is to build a design system that supports free variation. The trick was to set up a design program that would control changes.

The Embryological House has a double skin. The first skin, which is the building enclosure, is built of aluminum and glass. To avoid punched windows, the skin has very fine shreds in it; the wall can go from something like punched windows to something like a glass wall, depending on far apart you have these shreds. The wall is translucent and filigreed, like a screen. Because of that fenestration system, there's a second skin over the first, a shading skin (Figure 6.3.2.2). Solar data for any region in the world was collected, put it in the computer, and calculates where the daylight and shadows will fall on the form (Dery, 2000). That information is then used to map a double skin onto all those undulations and indentations. This second skin is a system of strips, almost like a Venetian blind, but in 3-D, wrapping around the contours of the house.

Greg Lynn's Embryological House was an interesting project into computer-driven design. He wanted to explore how you could use animation software to change mass produced suburban housing from being "kit-oriented" to a more organic model where variations are generated uniquely through software. Greg Lynn stated, "I wanted to make this point, that you could basically mass produce the idea of the Palladian villas. They weren't variations on a single theme. They were unique objects, but the computer would allow us to churn out an infinite number of them at the same cost as a dumb 1950s box" (Waters, 2003, p. 71).

By thoroughly integrating the computer into their design process, technology can be used as a tool of investigation as well as expression. Although many of these types of experiments with software-driven design have remained unrealized, their impact on architecture has been profound.

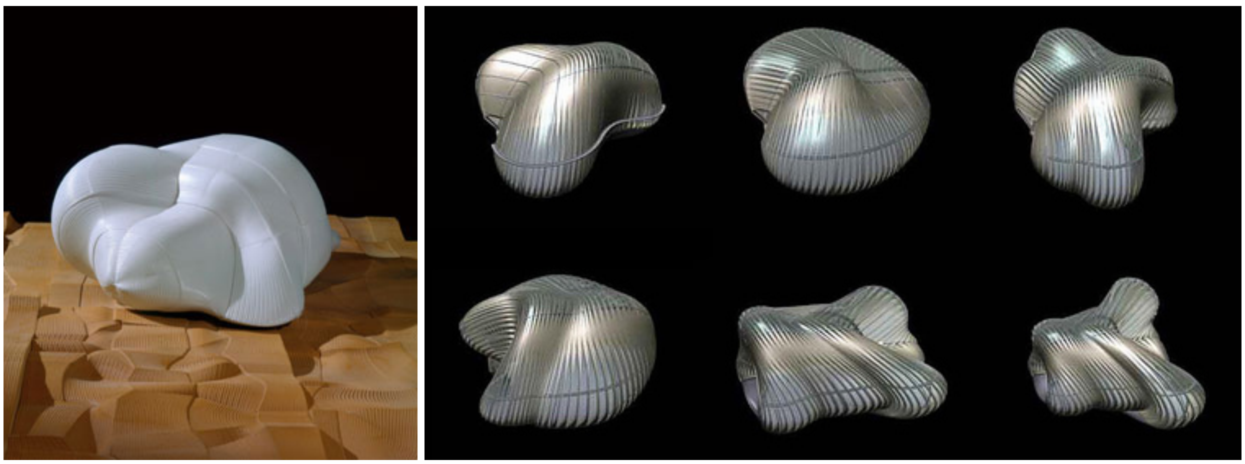


Figure 6.3.2.1 Not site specific, with various form options.

Figure 6.3.2.2 Façade 'screening'

6.4. Digital Fabrication and Form

Digital technology is often used to produce images, but it is now having a different effect of architecture, a more direct and physical one, through fabrication. Through CNC cutting, computer-directed laser welding and cutting machine tools, digital fabrication technology is more globally accessible, economical, and viable (Kolarevic, 2008). In doing so, a useful application is digital fabrication, where the production of building parts is directly controlled by the design information. The seamless link between data and material design and building dissolves the apparent incongruities between digital and physical realities and allows a new constructive understanding of the discipline (Kolarevic, 2008). As demonstrated throughout the book *Manufacturing Material Effect*s, fabrication components and materials not only accessorize construction, but also contribute to essential structural and cladding systems, especially in high-rise construction.

Over the past decade we have seen in architecture the re-emergence of complexly shaped forms and intricately articulated surfaces, enclosures, and structures, whose design and production were fundamentally enabled by the capacity of digital technologies to accurately represent and precisely fabricate artifacts of almost any complexity. In a dramatic departure from the formally and materially reductive norms of much twentieth-century architecture, it is now possible to materially realize complex ideas that were previously unattainable (Kolarevic, 2008). With digital parametric design and production, variation becomes possible not only in spatial layouts and component dimensions, but also in material composition and surface articulation, offering unprecedented freedom from standardization that defined design and production for much of the twentieth century (Kolarevic, 2008). Such variability presents a radical departure from the present normative practice.

6.4.1. Nordpark Cable Railway

Architect: Zaha Hadid Architects
Location: Innsbruck, Austria
Completion Date: 2007
Material Use: Thermoformed glass
Form of Production: CNC milling and thermoforming

This project is a series of railways stations comprised of four new stations and a cable suspension bridge. The design for each station adapts to specific site conditions at various altitudes, while maintaining a coherent overall architectural language (Figure 6.4.1.1). This approach was critical to the design for the railway, and demonstrates a modernist approach to organic architecture. New production methods such as CNC milling and thermoforming were used in order to create a very precise and automatic translation of the computer generated design into the built structure. In an online article Zaha Hadid states that “Each station has its own unique context, topography, altitude, and circulation. We studied natural phenomena such as glacial moraines and ice movements - as we wanted each station to use the fluid language of natural ice formations, like a frozen stream on the mountainside” (arcspace.com, 2008).

Production methods such as CNC milling and thermoforming guaranteed a very precise and automatic translation of the computer generated design into the built structure (Figure 6.4.1.2). The architects used state-of-the-art design and manufacturing technologies developed for the automotive industry to create the streamlined aesthetics of each station. Each of these stations consists of roof structures made from thermoformed glass, where NURBS modelling techniques allow for the creation of highly continuous double curvatures within the roof’s surface modulation (arcspace.com, 2008).

The design pushed advanced glass technology to its limits. There were a total of 850 glass panels, and each panel was unique in its sculptural form, as the fluid shapes of the canopies are to lend themselves naturally to the flow of water (arcspace.com, 2008). The glass technology was developed by structural engineer Bollinger & Grohmann, of Frankfurt and Vienna, and manufacturer Pagitz Metalltechnik, of Klagenfurt, although the panels were actually made in China using CNC machines linked directly to the design team’s CAD system in Europe.

Demonstrated here is an example of modern approaches to organic architecture through the use of materiality and form. This project is a unique approach to form and fabrication, but represents potential for mass produced forms through parametric design and digital fabrication.

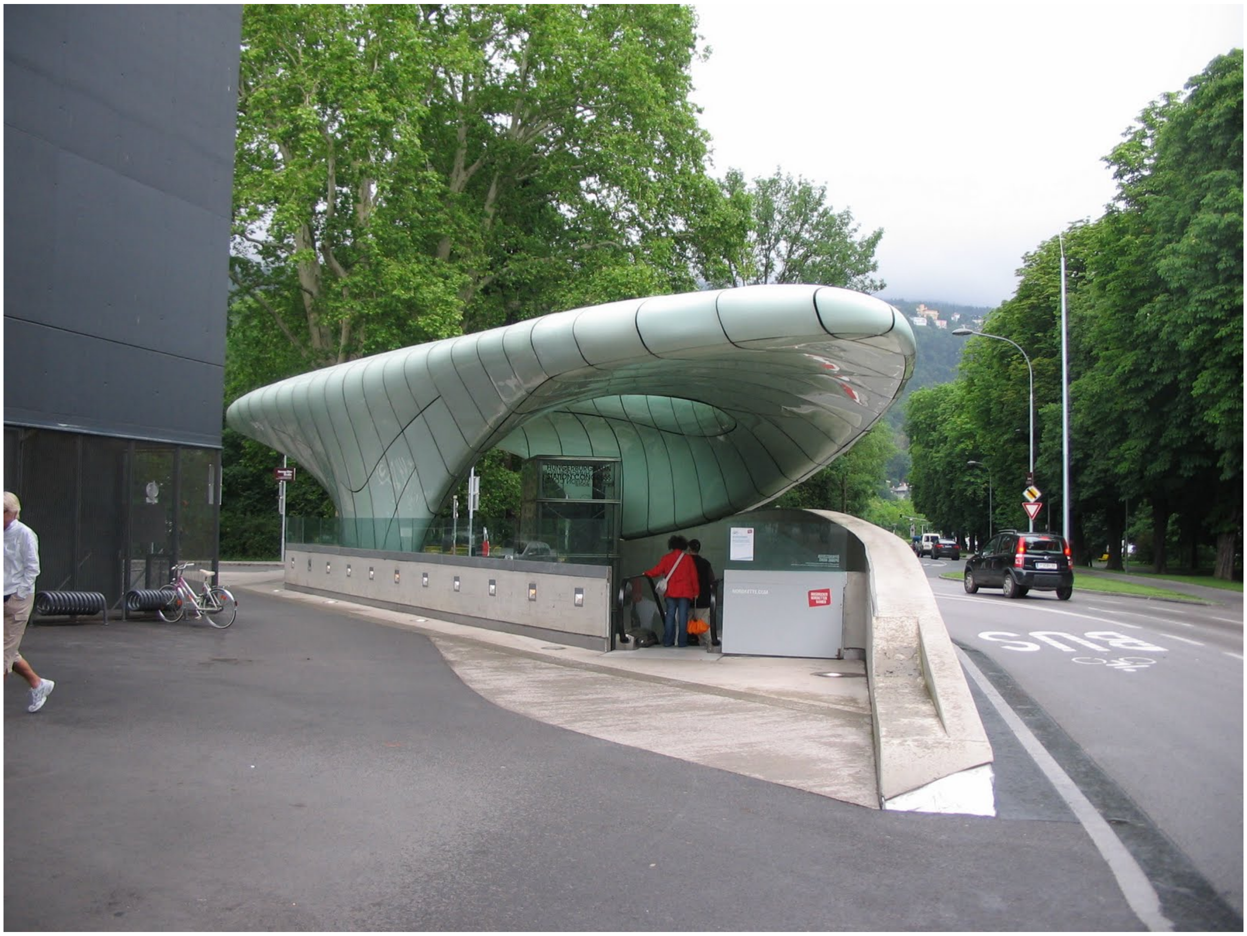


Figure 6.4.1.1 One railway's exterior entrances.

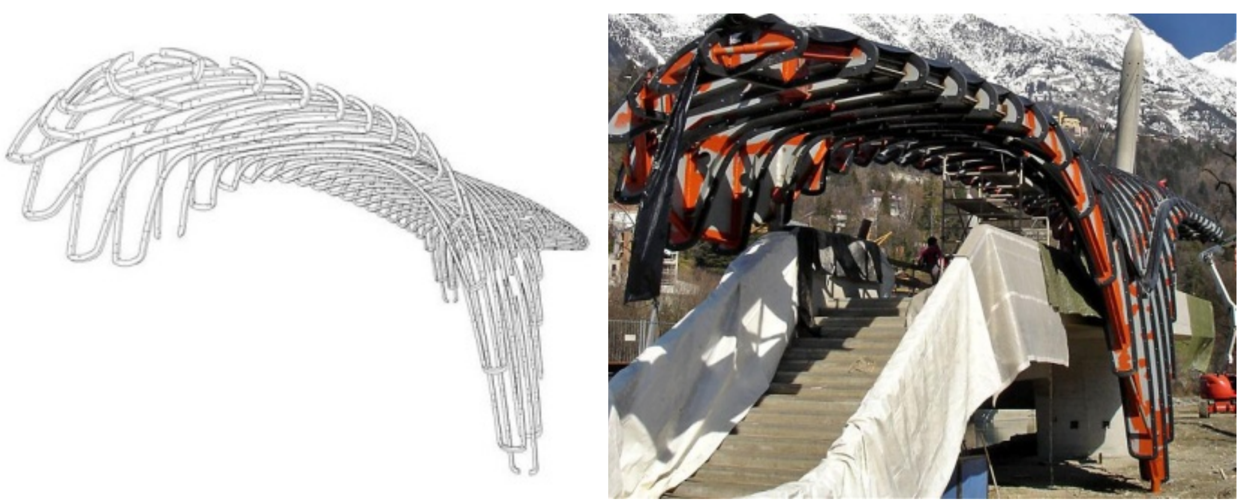


Figure 6.4.1.2 Fabrication of structural form.

6.4.2. Der Neue Zollhof

Architect: Frank Gehry and Associates
Location: Dusseldorf, Germany
Completion Date: 2001
Material Use: Brick, stucco, stainless steel
Form of Production: Digital fabrication

Der Neue Zollhof is situated at the Eastern edge of the Rhine River harbor front in downtown Düsseldorf. Previously occupied primarily by warehouses, this stretch of the waterfront was part of a redevelopment plan to convert the area to an urban public zone.

The argument is that the architecture is merely an ecstasy of forms with confetti-like superficiality, countered by this design's spectrum of pragmatic solutions that make these buildings both economically successful and user-friendly (Mathewson, 2007). Gehry envisioned three separate building structures, coined "Mother, Father, and Child," where the forms are harmonious given that each building has a different facade surfacing, consisting of brick, stucco, and stainless steel (Figure 6.4.2.1). The most interesting of the bunch is the middle building, coined the "child," and is sheathed in stainless steel. This organicness of the form, coupled with the stainless steel, creates changes in appearance throughout the day.

Although created with fairly standard materials, Gehry adds detailed visual elements of extruded punched windows, in addition to the curved forms, to add another dimension of excitement to the exterior of the building (Figure 6.4.2.2). Through geometry, massing and exterior material, each building has a unique identity, but the articulation of the window and its relationship to the exterior skin is similar in all three structures, unifying the project. Although windows are typical construction details that every project has, taking a second look and exploring these details could result in a spectacular visual appearance.

The construction and design technology used here were previously unexplored at the time. Integration of innovative drafting and modeling software enabled translation of Gehry's ideas directly into the forms for the prefabricated concrete elements, which could then be produced on the right schedule and within the strict cost limits (Mathewson, 2007, p.343). The walls themselves consist of pre-cast concrete blocks that were molded using Styrofoam formwork cut by milling machines using digital model data (Szalapaj, 2005, p.209). The end result of many of Gehry's buildings is the construction of forms previously thought to be impractical and unbuildable.

Figure 6.4.2.1 Various façade materials.

Figure 6.4.2.2 Window application on steel façade.

7. A Laboratory for Experimentation…

> "In Toronto, an unusually large number of high-rise apartments poke above the flat landscape many miles from downtown….this is a type of high density suburban development far more progressive and able to deal with the future than the endless sprawl of the US…."
>
> Richard Buckminster Fuller, 1968 (City of Toronto, 2008)

7.1 The Mayor's Tower Renewal

Many of the modern concrete towers constructed in North America during the 1960s and 70s were experiments in modern planning during the period of post-World War II growth, and have now reached the end of their life cycle and are deteriorating rapidly. Currently in place is the idea of the tower renewal, which is investigating building skin consciousness, and how a facade might be renewed to improve the environmental performance of a building. It is valuable to investigate the adaptive re-use possibilities of these towers; as this will be an ongoing process as buildings inevitably reach the end of their life span. It is also vital given the vast amount of people currently occupying these towers.

In general, more Canadians per-capita live in high-rise dwellings than Americans, and of the top twenty cities in North America with the greatest number of high-rises, seven are Canadian (Emporis, 2009). Furthermore, a significant proportion of this high-rise stock in Canadian cities is made up of the post-war, modern high-rise residential towers. Toronto alone contains more high-rise buildings than any other city in North America other than New York, and they make up approximately 40% of the housing stock, representing about 1,000 buildings (City of Toronto, 2008).

Because it was believed that significant apartment housing was needed in peripheral regions in order to achieve employment, transit, and social objectives, the modern apartment tower played a prominent role in the shape of the Toronto Region (Kesik; Saleff, 2009). Furthermore, they have provided affordable living for countless numbers of people over the past 50 years, and the high-rise condo tower is still a popular form of city living. With the turn of the century, we experienced a condo boom much like that of the mid century apartment boom (Figure 7.1.1).

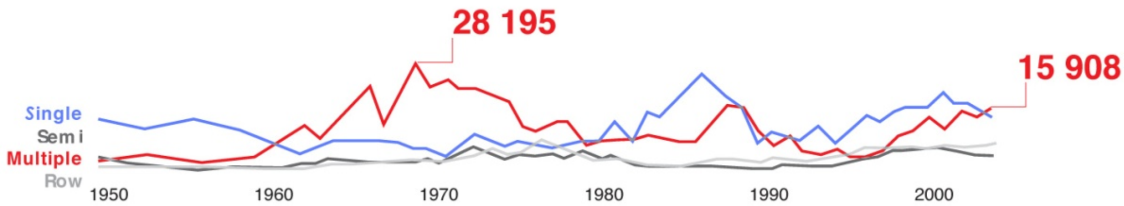


Figure 7.1.1 The graph above depicts housing developed in the GTA over the past 50 years, illustrating the turn of the century condo boom, and mid century apartment boom.

Toronto's developers favoured modern concrete towers for their efficiency of construction and popularity within the booming housing market. The local invention of the 'flying form' technique of concrete construction made building these towers remarkably fast and cost effective. The city is littered with a variety of tower typologies, all made up of concrete shear walls spaced at six metres, providing bays that were easily adapted for one, two, three, and even four bedroom configurations (Figure 7.1.2). The size was ultimately limited in length by the maximum distance allowed between fire stairs, and in height by the structural limitations of the chosen concrete framing system; about 36 storey's (City of Toronto, 2008). The building envelopes consist of brick masonry from slab to slab.

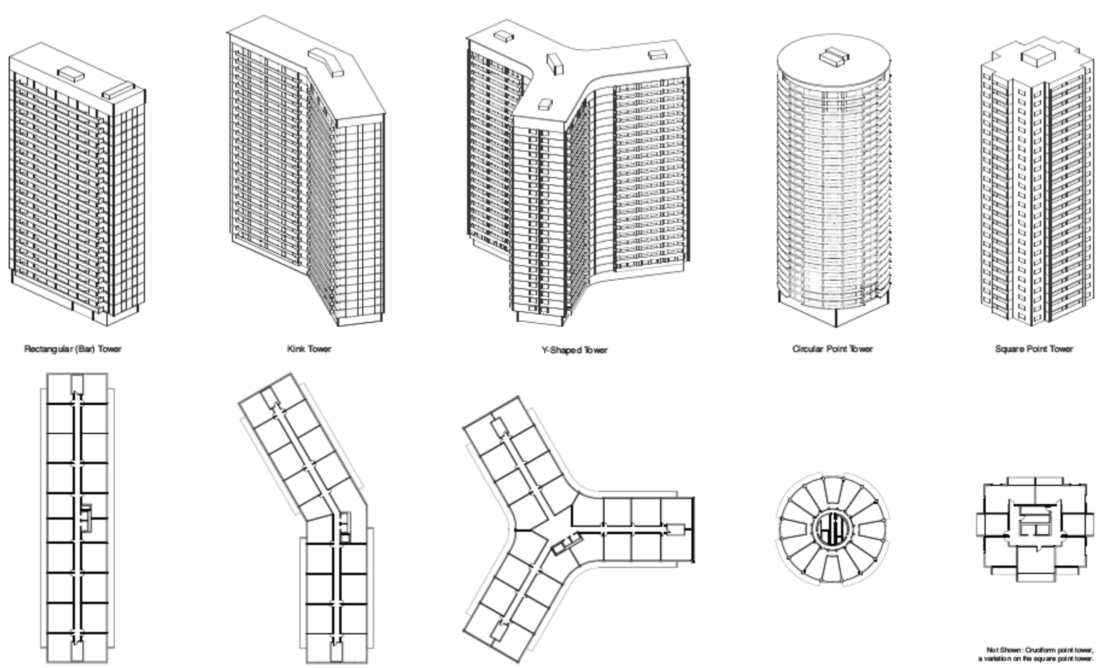


Figure 7.1.2. Commonly observed tower typologies of the 1960s and 70s.

As these communities approach their fifth decade, many are showing signs of disrepair, neglect and decline. Through a complex combination of factors, Toronto's postwar communities have become its most impoverished. These apartments have become among Toronto's most wasteful and ecologically irresponsible building types (City of Toronto, 2008). Although density is generally thought to aid sustainability, this stock of concrete slab apartments demands more energy per square metre than any other housing type, current data suggesting up to 20 per cent more than a contemporary single detached house (Kesik; Saleff, 2009). They require attention.

Figure 7.1.3. Arial view of St. Jamestown, Toronto.

Figure 7.1.4. Examples of deteriorating building components.

In the current Tower Renewal the city is implementing, the existing masonry walls are intended to stay, and act as a base on which today's green standards can be applied (thermal over-cladding, clean energy installations, grey water recycling, etc.) (Figure 7.1.5). The goal of this initiative is to have zero displacement of occupants, limited intrusion into the day-to-day lives of tenants, with minimal impact on vacancy rates. The images below demonstrate the current techniques that are being implemented for the retrofit of these towers.

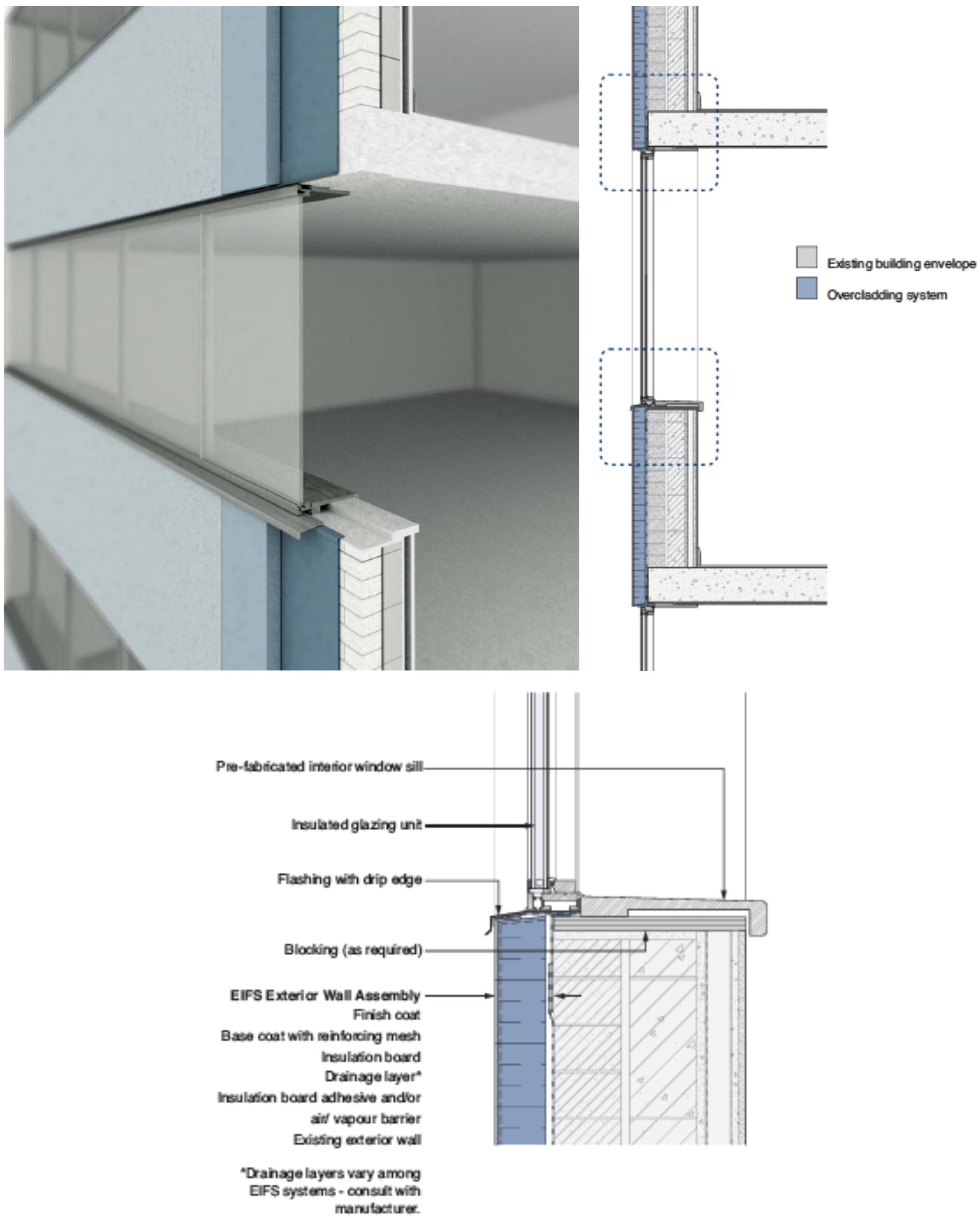


Figure 7.1.5. Overcladding system for masonry walls (Kesik; Saleff, 2009. p.A-8).

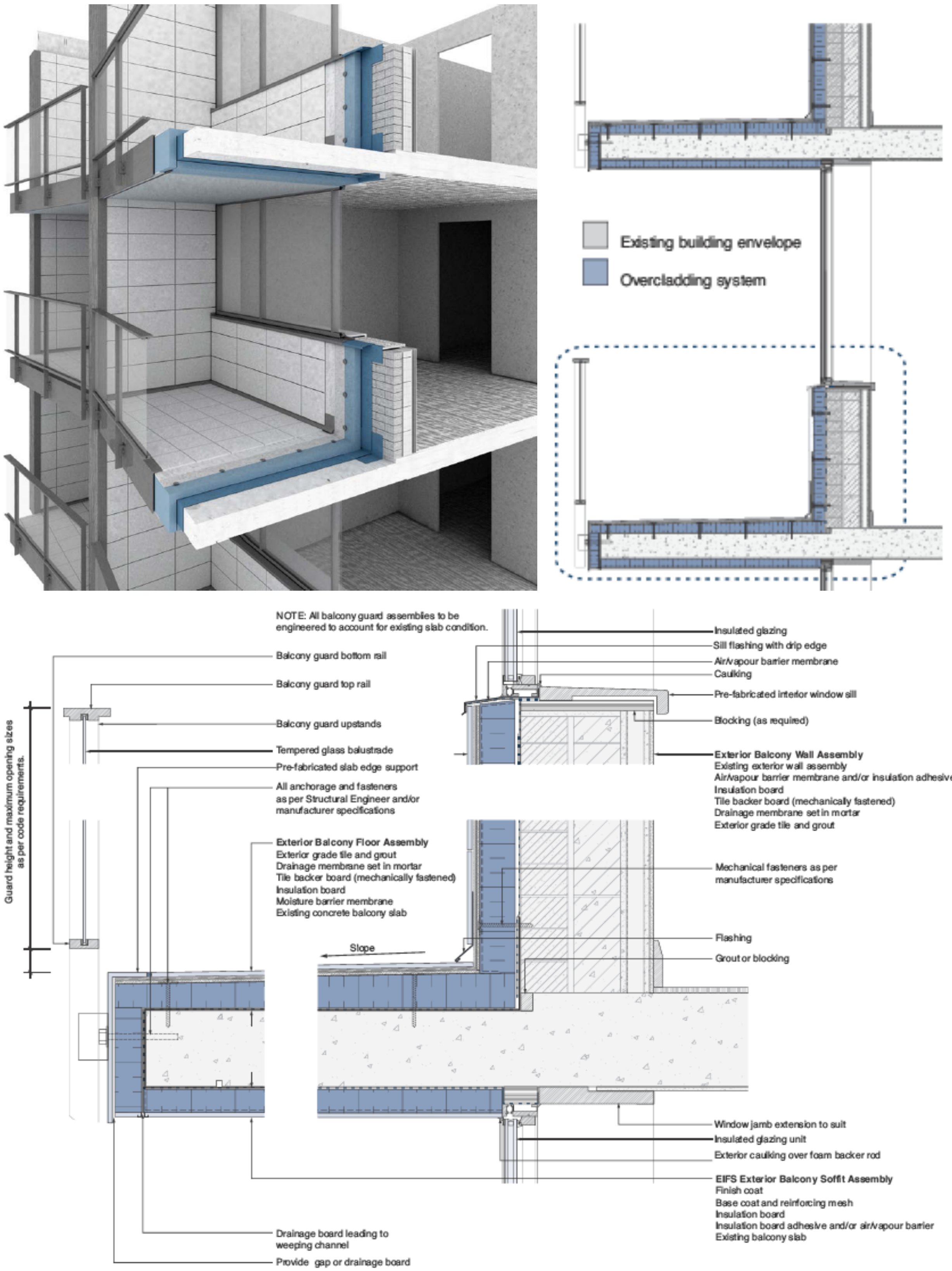


Figure 7.1.6. Overcladding system for balcony slabs (Kesik; Saleff, 2009, p.A-14).

7.2 Opportunity for Toronto

Toronto's aging modern towers may be it's greatest urban resource, as these tower communities provide high densities, and a mix of housing types and options for renters. These building types were not all failures, and the high-rise building type is still desirable. As we continue to erect high-rise condos today, it is still important to still consider the thousands of existing towers that desperately need attention. In doing so, there is the chance to create stronger communities, along with increased social and cultural benefits, while enhancing local economic activity, and sustainability (Figure 7.2.1.). Furthermore, with potential implication of production technologies, there are opportunities for variability in unit size and types, along with retrofitting the building while occupied, and potentially having interchangeable components which could be replaces individually as time passes. There is also the opportunity to create a solution that will continuously be developed as technologies and needs change, to upgrade and retrofit buildings and communities and they come to the end of their life cycles.

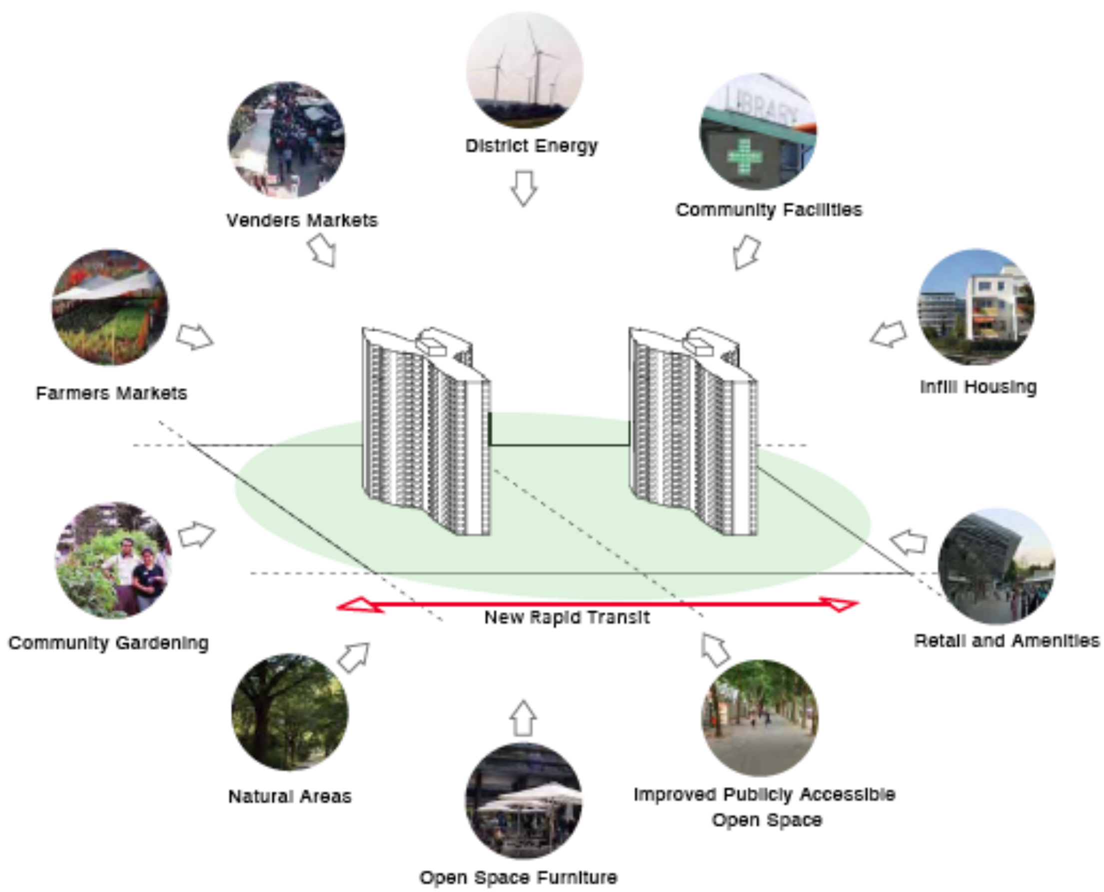


Figure 7.2.1 Opportunities for creating complete communities.

At the regional scale, a tower renewal offers opportunities related to growth and transport. As many of these communities are connected by existing and proposed rapid transit (Figure 7.2.2), Toronto's apartment neighbourhoods could emerge as zones of new growth and investment. If the proper tools are utilized, these clusters of neighbourhoods throughout the city could evolve into vibrant, mixed-use communities. There is also immense opportunity for the redevelopment and rejuvenation of the vast amounts of open, underutilized green space, which surround the towers (Figure 7.2.3).

Figure 7.2.2 Toronto's Rapid Transit Plan intersecting with several of the region's underserviced high-density Apartment Neighbourhoods.

Figure 7.2.3 Network of dense Apartment Neighbourhoods and major natural open space systems. Tower Renewal offers several opportunities at the regional scale.

Figure 7.2.4 Cluster of towers at located in St. Jamestown, downtown Toronto.

Figure 7.2.5. Fenced in tower blocks located at St. Jamestown, downtown Toronto.

Figure 7.2.6. Underutilized open space located at Jane and Finch, Toronto.

Figure 7.2.7. Underutilized paths between towers located at Jane and Finch, Toronto.

7.3 The Kleiburg Housing Block: Lessons from Abroad…

Architect: Form Architects, Greg Lynn
Location: Amsterdam, Netherlands
Completion Date: Competition, 2005
Material Use: Metal
Form of Production: CNC technologies

Across the world, reinvestment has transformed tower block neighbourhoods into models for vibrant communities and urban sustainability. There are many international projects that give us the opportunity to learn and apply in our Canadian urban context and climate. This particular international project is the transformation and renewal of the Kleiburg housing block in the Bijlmermeer, the Netherlands, similar to those we see throughout North America (Figure 7.3.1). The developers of the housing project planned to renovate an existing building to include 250 market units, and 250 rentable units.

This particular project was a competition to give a facelift to the honeycomb apartment building Kleigurg; a typical Bijlmer block from the early 1970s with 500 rental dwellings on ten floors. Greg Lynn made the best plan and received a further commission to translate his ideas into a feasible plan. A partnership between artist and architects, the team was asked to consider energy-saving measures, solar energy and 'special forms of insulation' (Jolles, 2001). Within this scheme, Lynn divides Kleiburg into eleven different neighbourhoods each with its own entrance and circulation system. That ensures a wide variety of views, lighting conditions, spatial relationships, and forms.

Lynn explores these ideas of form and curvilinearity in this social housing project, where form variations were made possible as they engage different social, material, and contextual issues (Figure 7.3.2). He wanted to break the architectural monotony and the social segregation between the demographic groups to give them identity (Lynn, 2003, p.72). Lynn points out in his article from *The State of Architecture in the Beginning of the 21st Century*, that "the forms used are directly linked to a new type of social organization as well as to a new image for the building" (Lynn, 2003, p.72). The convex skin of the facade creates a complex and continuous, yet differentiated pattern across the elements, which provide a thoughtful reorganization of block and dwellings (Figure 7.3.2). There are 154 of these truss elements, all of which were welded, assembled, galvanized, painted, and clad in the factory, then shipped to the site.

Figure 7.3.1. Kleiburg housing block.

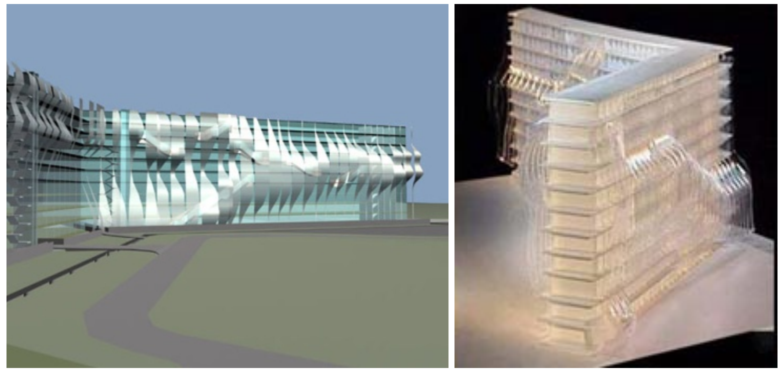


Figure 7.3.2. The convex skin of the proposed façade.

Similar to the thesis this project was a renovation of an existing building, and using CAD and CNC technologies, he created mass-produced art, allowing everyone to have a one-of-a-kind object. Similarly, this project attempts to provide mass-produced elements that can be arranged to create a unique composition, were no square foot of which is the same. Although the project seems inspirational, not much has been published about the efficiency.

So where do we go from here?

The fact that the investigation and application of renewal of these concrete towers is already underway provides a basis for the argument of using these tower blocks for a potential site for the purpose of the thesis. But given that the issue presented in this document is that the craft and customization in architecture has been lost through the original construction of these towers, further investigation will be given into how these towers can be rejuvenated using current technologies and design trends, which will also assist in the environmental updates, economical feasibility and ease of construction. It is stated in the Tower Renewal guidelines that: “it is hoped this modest beginning will inspire others to take up the challenge of maintaining the vitality of our built environment, so that is not a liability but a legacy to future generations” (Kesik; Saleff, 2009, p.iv). Therefore, the thesis is building upon the research previously done, but taking a different, bolder approach.

8. Design Introduction

8.1 Summary

Is there room for new technology in our current construction industry?

Throughout the modernist movement, architects fully embraced the technological innovations of their time, using them to their full potential. But today, we are not using our technological advances to their full potential, and we are still constructing our cities under modernist philosophies. In terms of digital design we are seeing a variety of innovative and custom form, with a wider exploration of materials, proving that we are using our digital design tools to they're full capability. Although when it comes to fabrication of these forms, we are still using traditional methods of constructing them.

Today, in our mainstream construction industry, we can clearly see that construction technology lags behind these available computer design technologies. New 3D software allows architects to conceive and design freely and easily, but ultimately, existing building methods do not allow the full potential of the new design software to be achieved. Despite the availability of construction machinery, the building industry is currently reliant on the manual interventions of professional builders who are the hands that operate the machinery.

Figure 8.1.1 Inquiring here the potential of new technology in construction.

Also, existing materials such as reinforced concrete and masonry is expensive and inflexible. Building a complex concave-convex surface, for example, would require the prefabrication of expensive formworks and cages, and the mounting of complicated scaffolding. As a result, these artistic and expressive forms are not readily available due to the high expense and customization, and the limitations of our industry appear to be the single most hindering factor. Ultimately, the mindset of the industry must be changed in order to incorporate and make these ideas reality.

Therefore, through the design process, not only was digital design explored as a way of form making, but also digital fabrication techniques were explored as a way to utilize our technology in the mainstream construction industry. In doing so, 3D printing was explored. We need to look past this mid - 20th century way of building, and imagine a new future of construction and what that picture may look like – moving us to a post-fordian way of building and designing.

8.2 3D Printing

Earlier it was said that with our digital technologies it is not a question of whether a particular form is buildable, but rather what new instruments of practice are needed. In search of this, the concept of life size 3D printing is what was explored for the application of the design and a mode of digital fabrication that has potential in our construction industry. Although this technology is very new, it offers enormous potential for the notion of mass production for mass customization. Essentially, this machine called d_Shape can create full-size sandstone structures without human intervention, using a stereolithography 3D printing process. This technology allows architects to use digital design software to its full potential, as with this the limitations of conventional construction will no longer hinder the architect's vision. Specifically, this machine enables architects to directly make the buildings they design using a robotic building machine that utilizes CAD-CAM design technology, with a direct link between the design and production, creating a fast, yet energy-and cost-efficient process to create freeform construction scale objects (Figure 8.2.1).

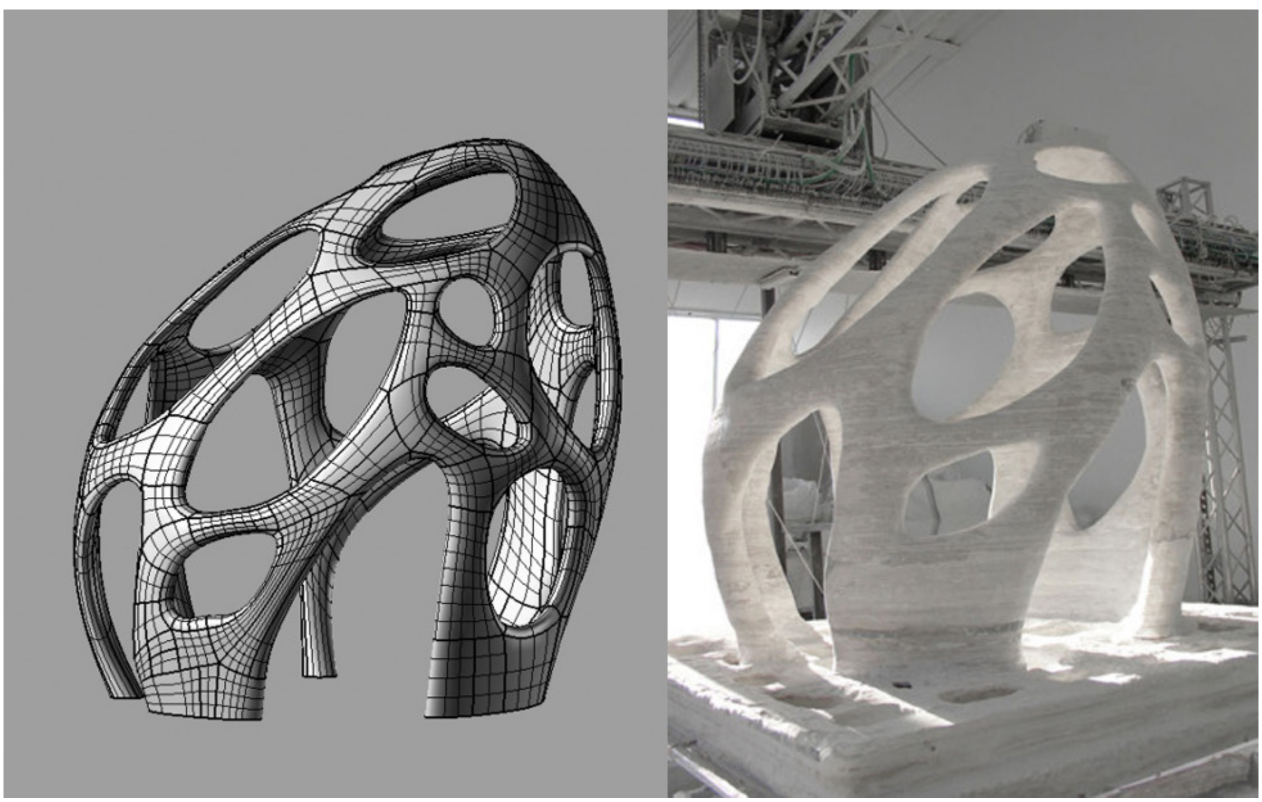


Figure 8.2.1 Process of digital 3D model to printed sandstone structure.

Essentially, the machine consists of a six by six metre plan that lifts along the four columns and can go to a height of nine meters (Figure 8.2.2). Adding high tensile strength reinforcing fibers to a mixture of granular sands makes the material, and effectively, this process returns any type of sand, dust or gravel back to its original compact stone state (Abrahams, 2010). The end result is a sandstone material similar to concrete in strength and properties.

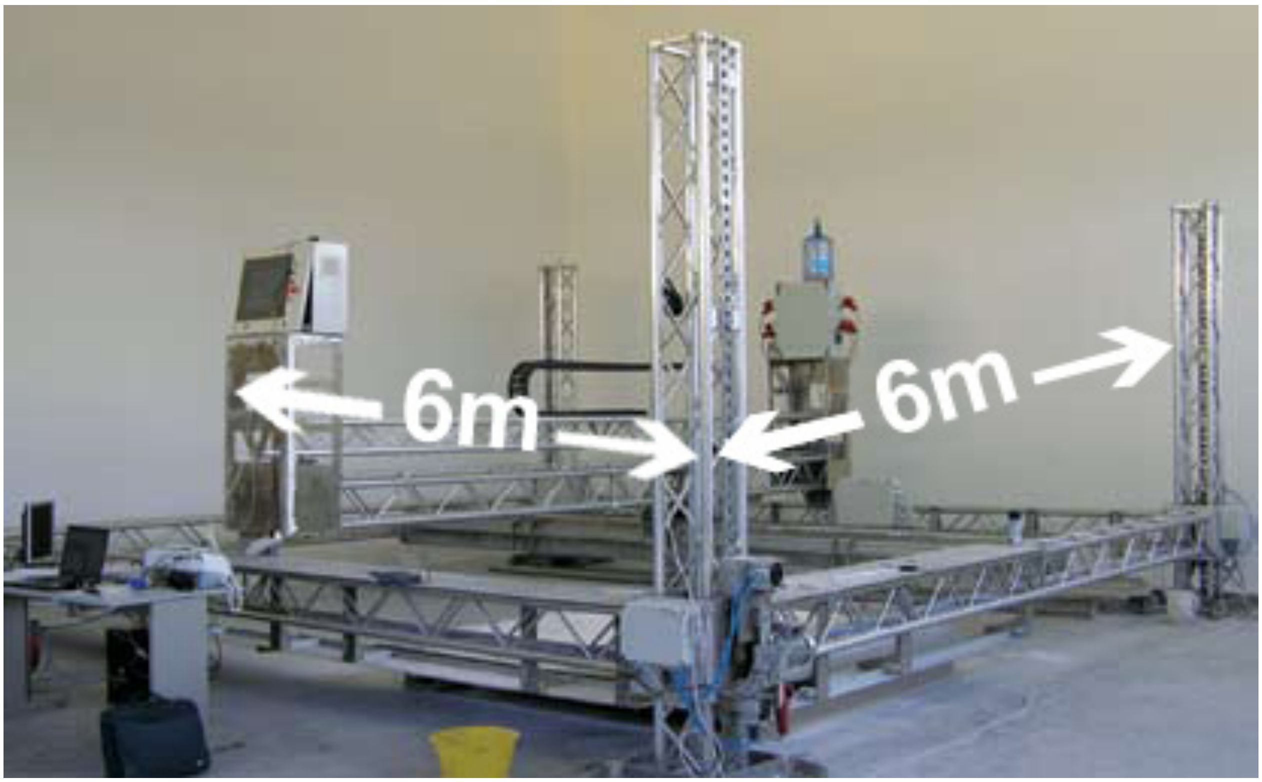


Figure 8.2.2. D_Shape's 6m x 6m printing bed.

Given this experimental technology, we can now begin to see the potential for mass-producing unique customized objects as easily as identical ones. Therefore, if keeping within the limitations of the machine, we can begin to imagine constructing full-scale building components printed with this technology.

8.3 The Process

The process of producing a design with this technology appears to be relatively uncomplicated, requiring little energy. A breakdown of the process is as follows:

1. Architect designs using 3D computer technology.

2. The design is then downloaded into an STL file (stereolitography) and is imported into the computer program that controls the printer head.

    The d_shape building process is similar to the ‘printing’ process much like what an inkjet printer does on a sheet of paper. This process is exactly that of the popular 3D printers used to create small plastic 3D models, like those seen in the shop at Ryerson.

3. The “printing” process takes place in a non-stop work session, starting from the bottom of the construction and rises up in sections of five to ten millimetres (Abraham, 2010).

Figure 8.3.1 Printing of sandstone structure in one continuous session.

With the implementation of this technology, we are ultimately achieving the main goal of this thesis, which is to have mass production of mass customization, at a feasible cost. With this, we are getting thousands of customized, unique objects that are mass-produced as easily as if we were producing a thousand identical objects.

Each of these individual building components is produced within the limits of the machine. With the technology being so new, the current printer capacity is six by six metres, which are ideal dimensions for creating one component per suite on our existing tower structure, using shear walls at 6m off center as a guideline.

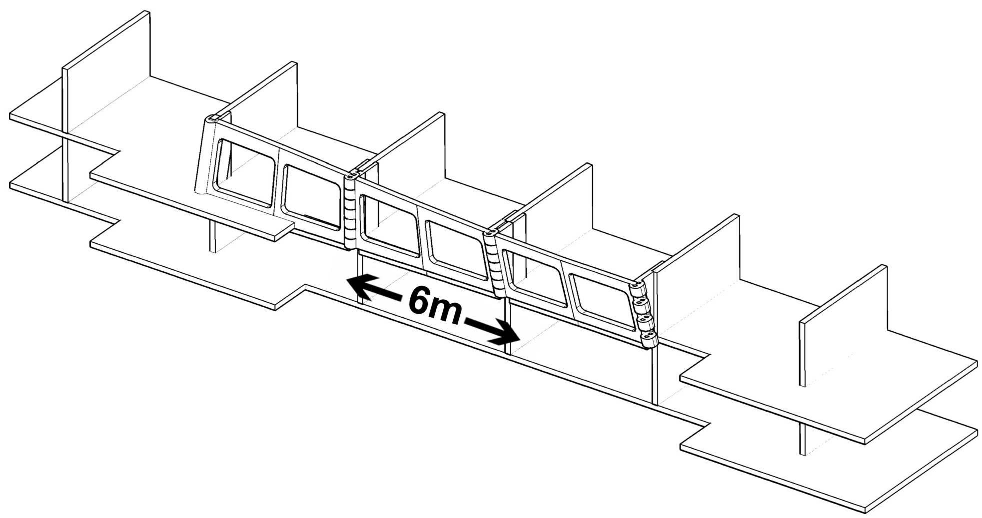


Figure 8.3.2 Due to limitations of technology, building components will be printed to fit between shear walls of existing structure.

Back in March 2010, in an article printed in Blueprint Magazine, and the creators of d-shape claimed that the cost of production with this machine is 30% - 50% less than conventional construction (Abraham, 2010), with the entirety of the building being printed off site. Therefore, it is claimed to be four times faster than conventional building, as no assembly is required besides piecing components together on site, consequently creating little waste, which is ultimately better for the environment. Having said that, though, this machine is not yet a commercial product and is still under investigation, and no building to the extent of what I am proposing has been built. Nonetheless, it demonstrates what can be done if we push the envelope of digital design and fabrication. With this there are infinite possibilities, hopefully pushing us in the direction of a post-fordist future. The proposed design will be testing the potential of this technology and its application in our North American construction industry, eventually speculating its opportunities and challenges in addressing the goals of this thesis.

8.4 Application of Mayor's Tower Renewal

In response to the Mayor's Tower Renewal project, this thesis proposes an entirely new building envelope system, which will demonstrate the potential of mass customization using 3D printing. Given the current limitations of the machine, the existing structure will be used as an experimentation site for these new technologies to demonstrate how we can add a greater degree of irregularity, craftsmanship, thickness, weight, depth, and materiality to our skyline. In addition to experimenting with expressive form and technological advances in an economic way, this thesis presents an opportunity for the retrofit these buildings require, along with gaining variability in unit size, and better energy efficiency. Essentially, the tower renewal is about sustainability and energy efficiency, and although this thesis is not necessarily concentrating on that aspect, the increased efficiency will innately follow application. Therefore, this response to the tower renewal is strictly about form, program, and fenestration techniques – using these old buildings as a laboratory for the application of new technologies.

Using the Mayor's Tower Renewal as an experimentation site for the design proposal has provided the freedom to test the proposed technologies within their current limitations, while building on initiatives already happening in the City of Toronto, giving the thesis real world potential for application.

Currently, the typical building envelopes of the tower building typology are an example of simplicity and durability, but unfortunately not of energy efficiency and sustainability in the contemporary sense. The typical walls were constructed simply from a 4-inch clay brick as the exterior cladding, bounded by header courses to an interior 4-inch hollow concrete block, which subsequently supported the interior finish system (Kesik; Saleff, 2009). These masonry units simply sat above exposed concrete slab edges without base flashings or control joints to allow for movement, and the exposed balcony slabs have an adverse effect on heat transfer across tower building envelopes (Figure 8.4.1).

Furthermore, the window systems have poor thermal performance, as they typical are comprised of single glazed units in metal frames without thermal breaks. All of these combined factors have attributed to the increasing energy inefficiency of this building type.

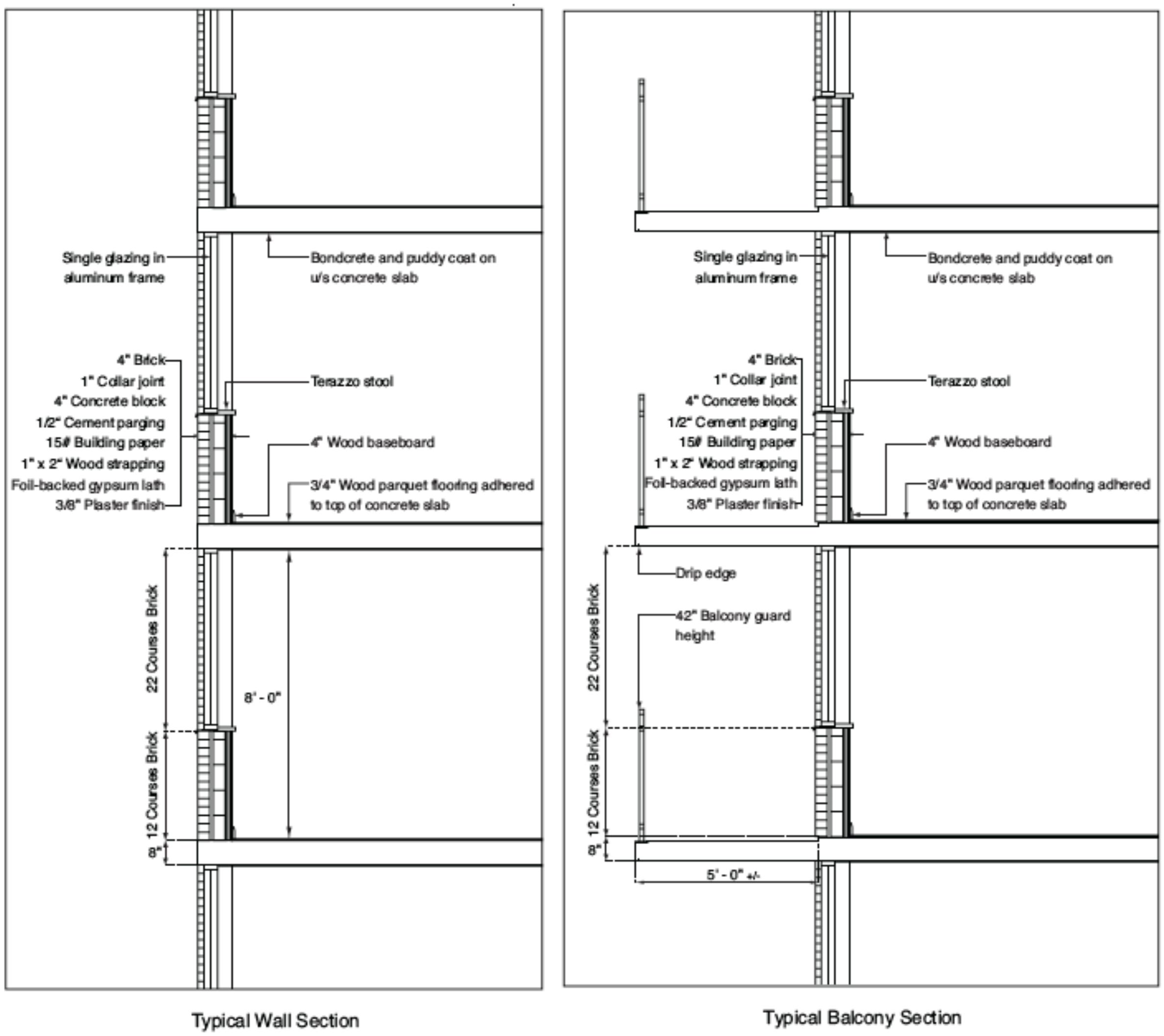


Figure 8.4.1 Existing structure of concrete towers: exposed slab edges (left) and balconies (right)

Throughout the research conducted for the Mayor's Tower Renewal, it was concluded that the most effective strategies for tower block renewal is thermal overcladding (Kesik; Saleff, 2009). The methodology here is that the improvement of the building performance can solve a majority of the major issues and concerns, therefore a 'new skin' is applied to the existing structure. Although there are several advantages, it is said that the process is lengthy, disruptive, and costly. But on the other hand, if new technologies in 3D printing are implemented, and construction time is quicker, the argument here is that demolition is the best solution. The durable concrete construction of these towers is sound and perfectly suited for upgrade to meet 21st century expectations of building performance and amenity (City of Toronto, 2008). Therefore, the structure of these towers will remain in tack, while the façade will be completely rethought using the presented technologies in digital design and production.

Figure 8.4.2 Existing tower.

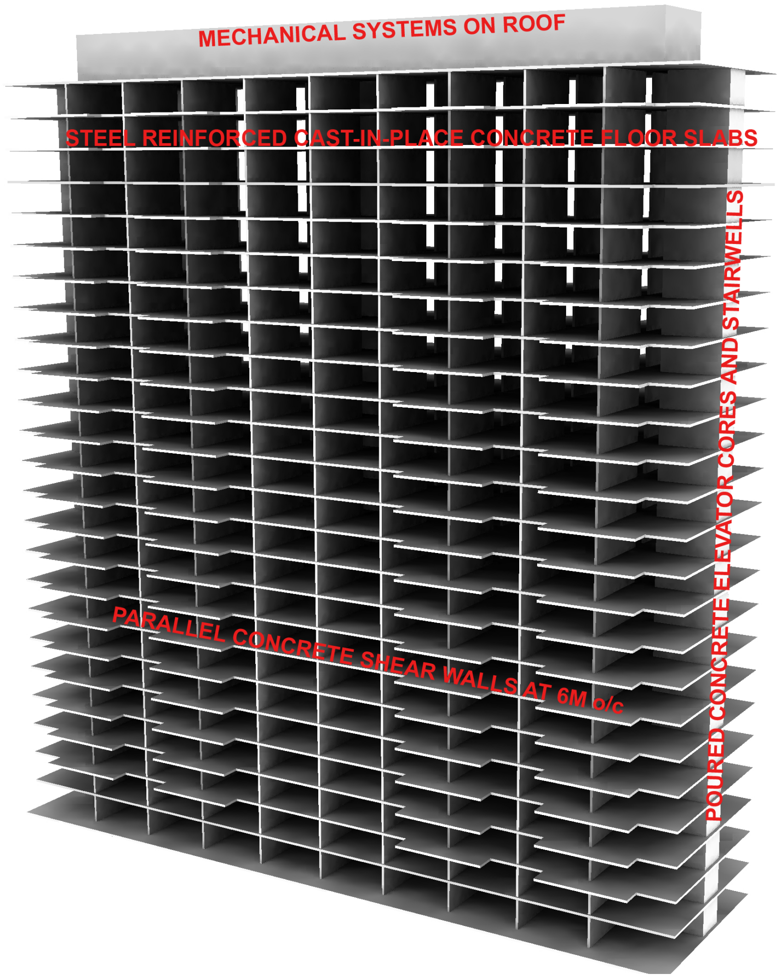
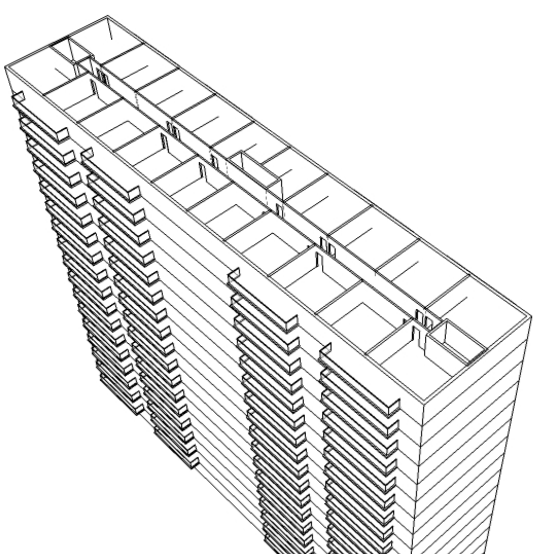


Figure 8.4.3 Existing structure after exterior façade is demolished.



A typical tower apartment buildings of the 1960s and 70s was symmetrical and repetitive, with structure consisting of the following elements:

- steel reinforced concrete floor slabs
- poured concrete elevator cores and stairwells
- series of parallel concrete shear walls 6m o/c
- double loaded corridors and a relatively shallow building plate
- solid non-load bearing masonry envelope which simply sat on top of the exposed exterior floor slab perimeter
- Mechanical system on roof.

8.5 The Concept

The concept of the final design is a diagram representing how we currently build, opposed to the system proposed, which is a future way of building. Here, building and constructing was looked at in comparison to the structure of a human bone. Our fordist way of building, and still how we are building today can be seen as a layering of elements, such as the skin, the fat, and the bone. These represent our conventional stick built layering technique of the exterior façade, insulation, and structure (Figure 8.5.1).

But imagining a post-fordian way of construction, we can begin to see construction as simply the bone, using this idea of printing buildings as constructing one piece where all layers are morphed into one. Here, there is the opportunity to "print" conduits, ducts, and other service voids, in addition to window frames, and potentially windows (Figure 8.5.2). With this, everything is built into the structure, as an organic integrated system of building. This can be seen as a way to transform conventional construction, looking at a way to push our boundaries and imagine a new way to construct buildings using the technologies that are available to us.

The potential form creation offered by this type of fabrication strongly takes on characteristics and behaviours of organic architecture, along with the integrated concept. This concept of constructing our building systems as our bone structures are built brings us back to elements found in nature and the idea of formulating architecture inspired by that. Using concepts of the human body to derive architecture is not a new concept, but one that has been prevalent throughout history, yet essentially lost in our mainstream construction. Vitruvius used the human body, with its modular construction, as an expression of nature. His homo quadratus – the figure of a man, with extended arms and legs, fits neatly into what were considered the most perfect geometrical figures – the square and circle (Pearson, 2001).

Now how can this concept be realized as a building component?

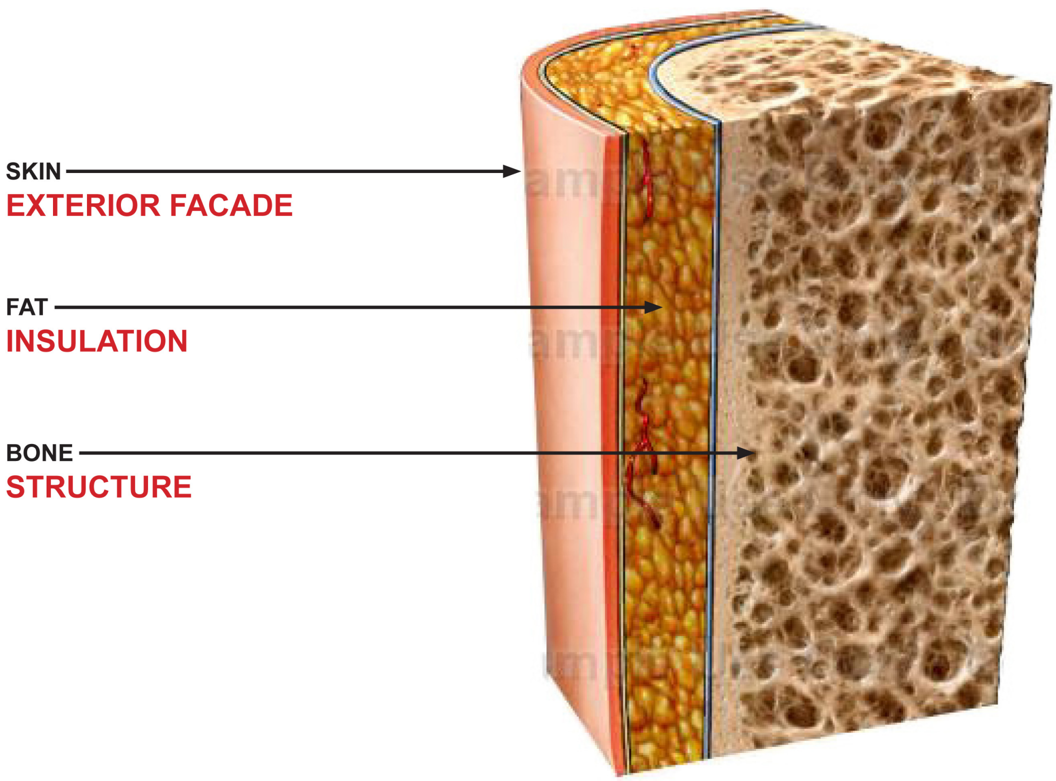


Figure 8.5.1. Bone Concept – fordist building technique (stick built / layering)

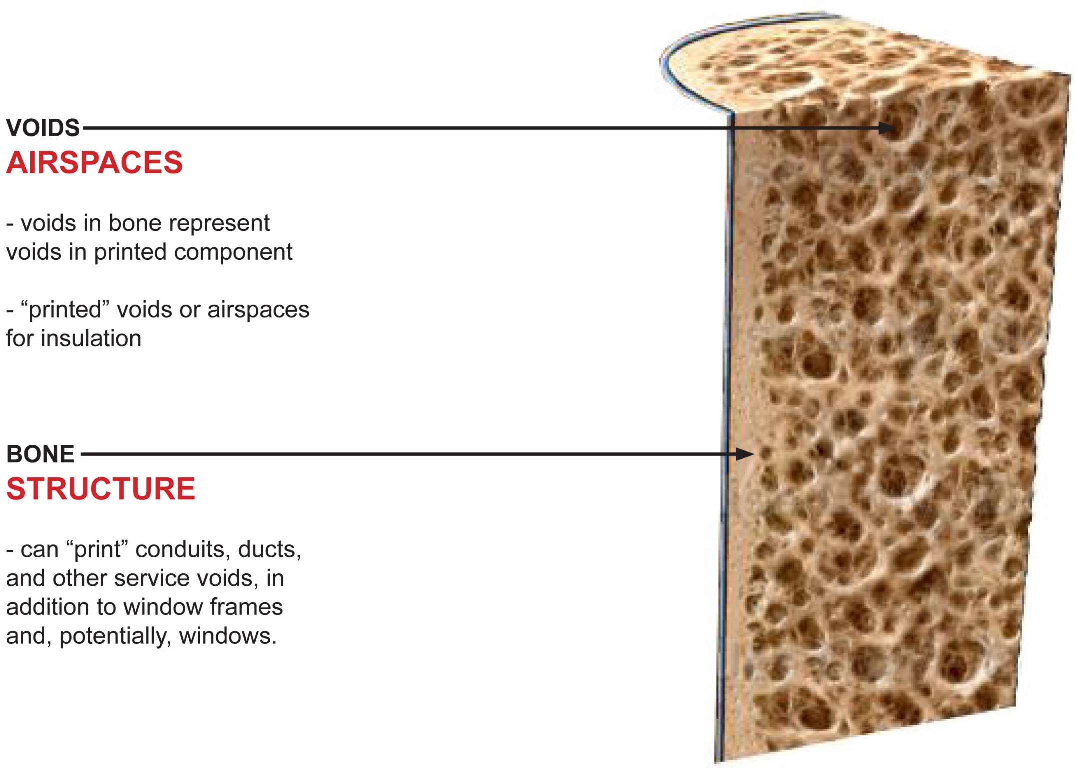


Figure 8.5.2. Bone Concept – Post-Fordian building technique (integrated system).

9. Design Project: Why Not Print Buildings?

Architecture as an art and craft can only advance when new ideas are tested against the possibilities of contemporary construction.

9.1 Design Objectives and Methodologies

The objective of the thesis is to bring forward the art and customization of organic and expressive forms in a way that can be economically incorporated into the standard North American construction practice. New technologies in digital design and fabrication will be used to create a building envelope system that will allow for a curvilinear, irregular, and expressive form which could then be applied to reskin the plethora of existing banal and energy inefficient high-rise residential buildings from the 1960 and 70s found throughout almost every North American city.

According to research done at the University of Toronto, the durable concrete construction of these towers is sound and perfectly suited for upgrade (University of Toronto, 2008); thus, the structure will remain, while the façade will be completely rethought using digital design and fabrication techniques, producing a system that introduces form, expression, variability, and meaning. Therefore, these towers were seen as a canvas for the implementation of technologies and design ideas to explore this idea of mass production of mass customization, as today, despite all the available technologies we are still seeing a predominance of rectilinear form and repetition. Having learned from past construction techniques, it is still important that prefabrication is optimized to maximize construction efficiency, but with the incorporation of digital design and fabrication, prefabrication of elements does not necessarily need to mean repetitiveness. Although it is important to note that repetitiveness is innately embedded in design and construction, this thesis also represents *apparent* customization. As will be seen through the final design, the entire notion of mass production is repetitiveness, and here we are mass-producing hundreds of building components. Although no two are completely identical, they are nonetheless a repetitive system of parts, which are arranged to create a customized from and collective whole. This is ultimately a solution to arrive at the given end form, whether that be organic or straight.

Ultimately, the design presented in the following section is but one example of the myriad of forms the proposed methodology affords with potential application to a variety of tower typologies. The final form was selected to best demonstrate the potential of the digital design technologies, showing what is possible and how we can fully take advantage of this manufacturing technique. The specific shape and detail of the end product can ultimately be customized and crafted to represent the actual local specifics of site, orientation, client desires, and identity.

9.2 The Parametric Design and Form

Mies van der Rohe believed that architecture and technology should grow together and be an expression of one another in order to be a true symbol of the times. Through the design process this was kept in consideration, and digital design and fabrication tools were used so that construction of our buildings could be a representation of our available technologies.

Given the desire to have the mass production for mass customization, parametric design was used as a tool for creating a mass-producible form, while providing a versatile way to represent complex curves and surfaces. Using parametrics, designers could create an infinite number of similar objects, as sets of equations are used to express certain quantities as explicit functions of a number of variables. As seen below, a flat surface was placed over the existing structure and was used as the starting point for form creation. Within this, certain variables were altered throughout the process to achieve essentially any form desirable.

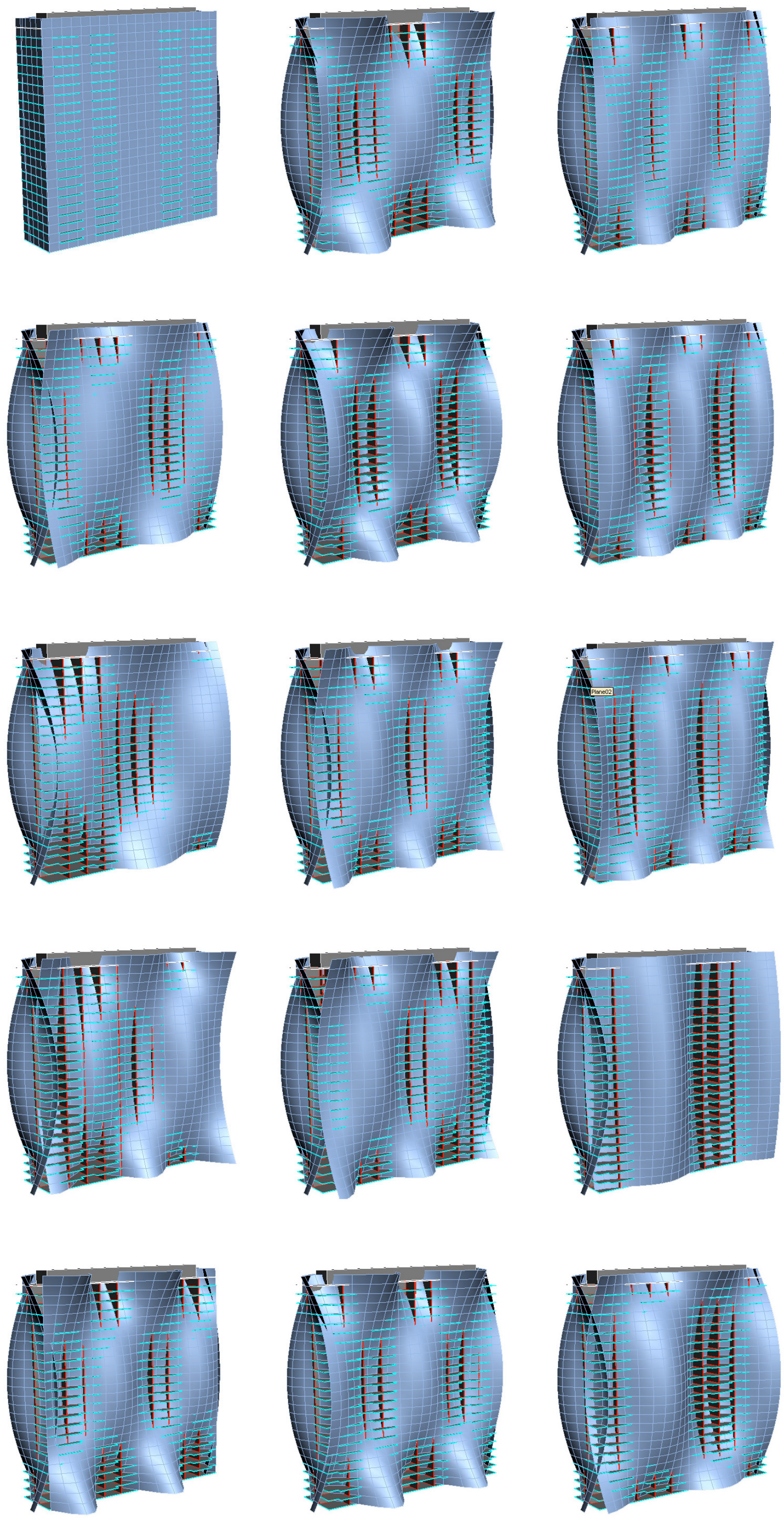


Figure 9.2.1 Variety of potential forms created with parametric design.

9.3 The Constraints

Any form is essentially *possible* when using parametric design, but not every form is *practical*. In this case, the final form is to be attached to an existing tower structure, therefore there were constrains on the design of the form.

a. The maximum cantilever from the existing structure is to be a maximum of four metres.
b. The form is to intrude in past the existing building envelope in some cases to achieve balcony conditions, but so much that is makes the suite unlivable as a 2-storey unit.

9.4 The Breakdown

Once the desired form is established, it can be translated into a variety of building components. The curvilinear form is broken down to its basic geometries to represent the various building components and divided up into three by six metre sections to accommodate the limitations of the printing machine. This incidentally equals the size of a suite: six metres between sheer walls, and three metre floor-to-floor height.

The digital technology allows the shape of one six by six metre component to flow along the entirety of the curved surface, demonstrating how design and fabrication techniques can be applied to an existing structure.

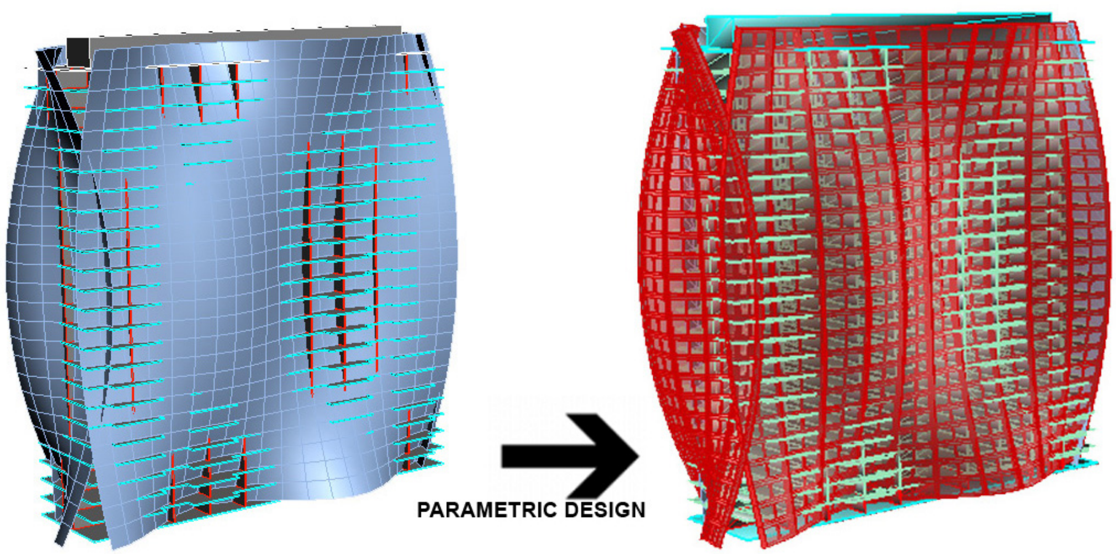
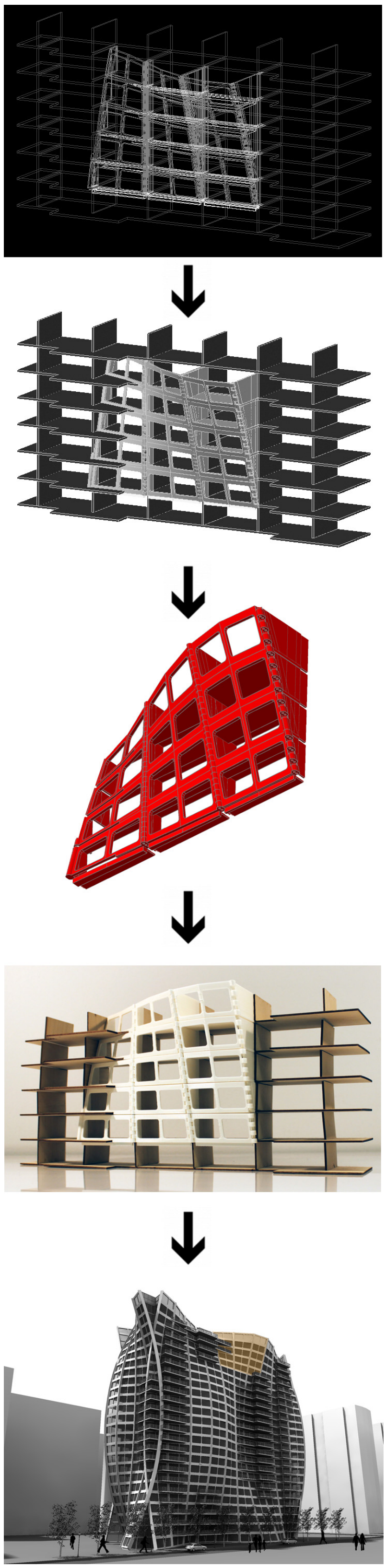


Figure 9.4.1 Desired form converted into printable 3d model.

9.5 The Fabrication



As seen above (Figure 9.4.1), the final form has been broken down into hundreds of building components (one per suite). Then each individual component can be printed using d_Shape; a machine that prints full scale sandstone structures.

a. 3D conceptual computer model of component is created.

b. Each component piece is converted to an STL file and sent directly to the printing machine to be printed in a non-stop session. Here components can potentially be mass produced 24 hours a day.

c. Once component pieces are printed, they can be attached to eachother much like a puzzle. Each piece is specially design with interlocking corners that connect directly to the piece beside it.

   Here we are producing hundreds of unique building components, all at the same rate and cost of producing hundreds that are exactly the same.

d. 1:100 scale mock-up of printed pieces, all attached to one another and slipped on to existing structure.

   Image here demonstrates where physical model is extracted from on the final form.

Figure 9.5.1 Fabrication process of individual components.

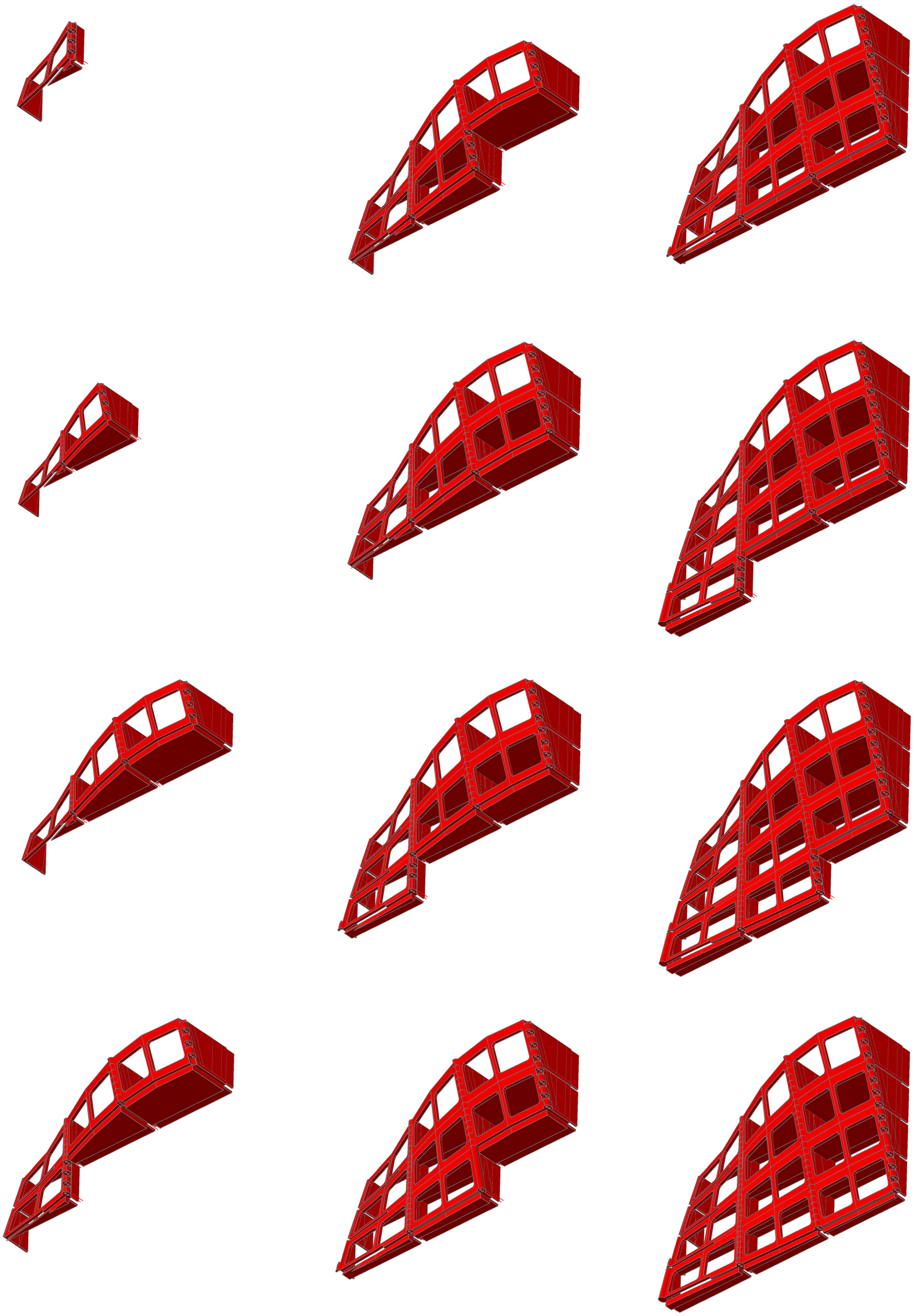


Figure 9.5.2 Connection of the final building pieces. As a whole make up overall form.

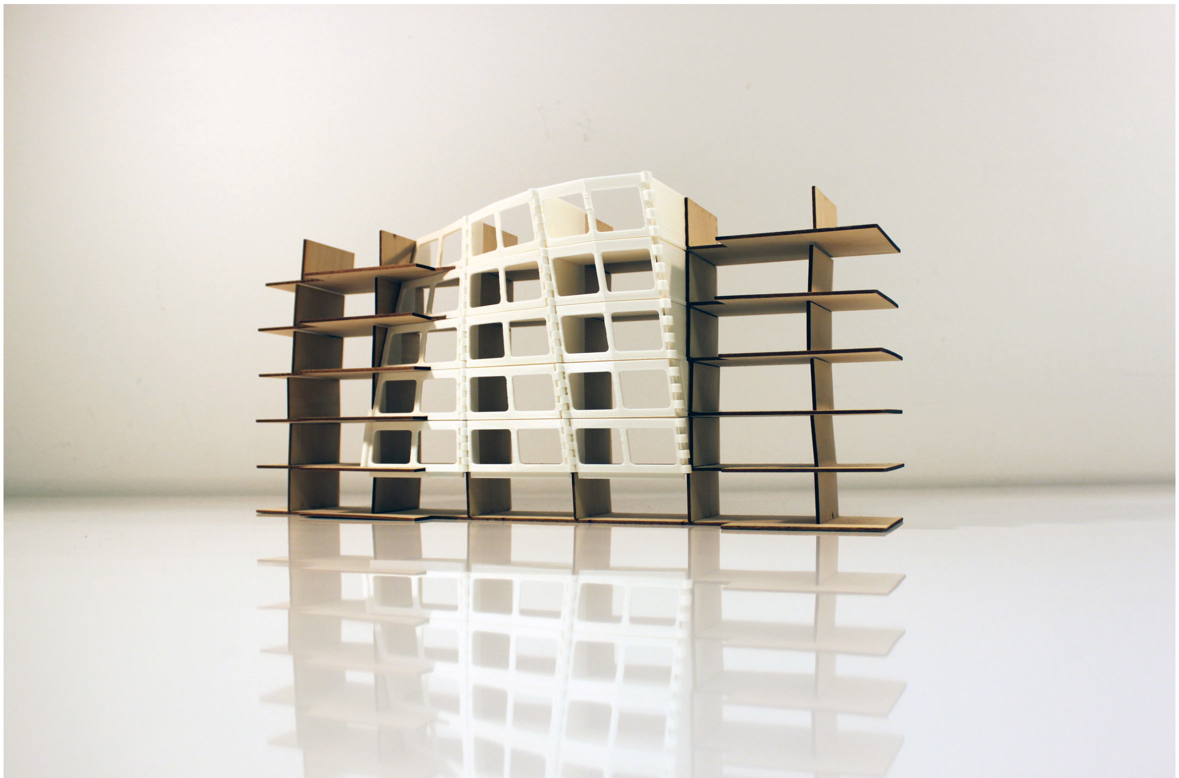


Figure 9.5.3 Photograph of 3D printed physical model (front view).

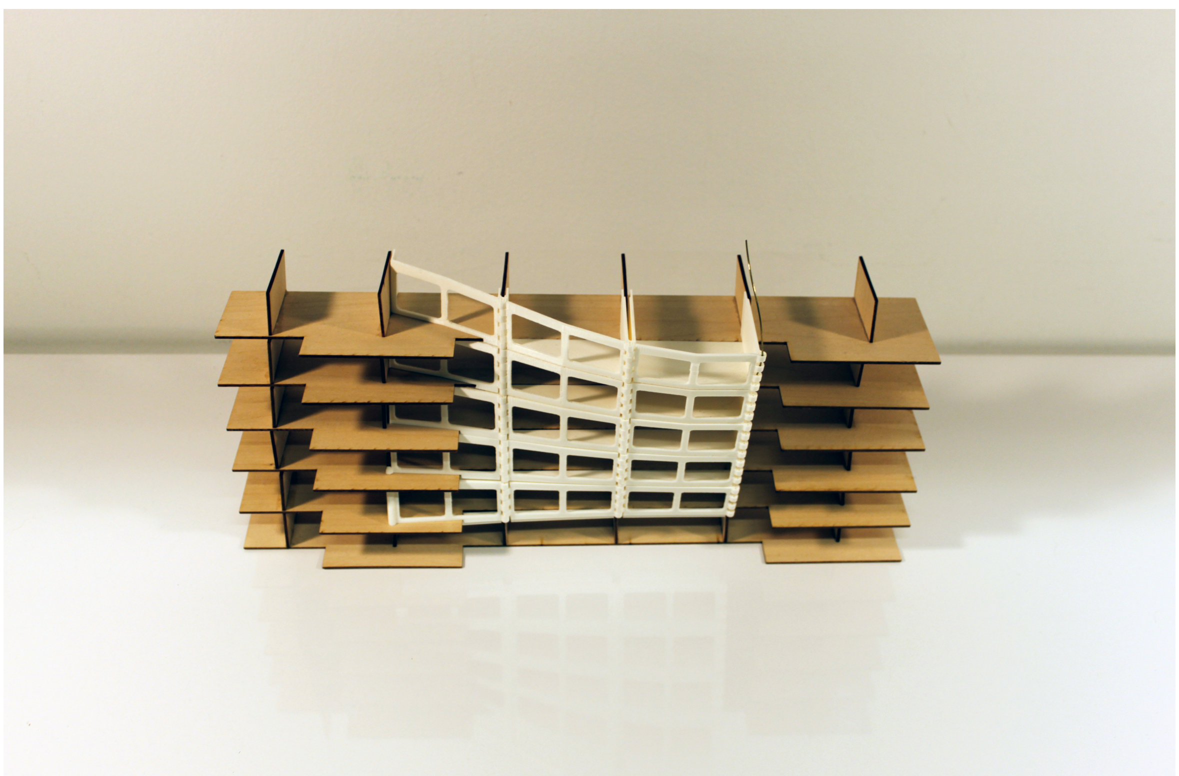


Figure 9.5.4 Photograph of 3D printed physical model (top view).

9.6 The Component

As mentioned earlier, given the current limitations of the printing machine, an existing tower structure was used as a laboratory for experimentation, where the facade could be broken down to three by six metre components (one component per suite). Below is one building component.

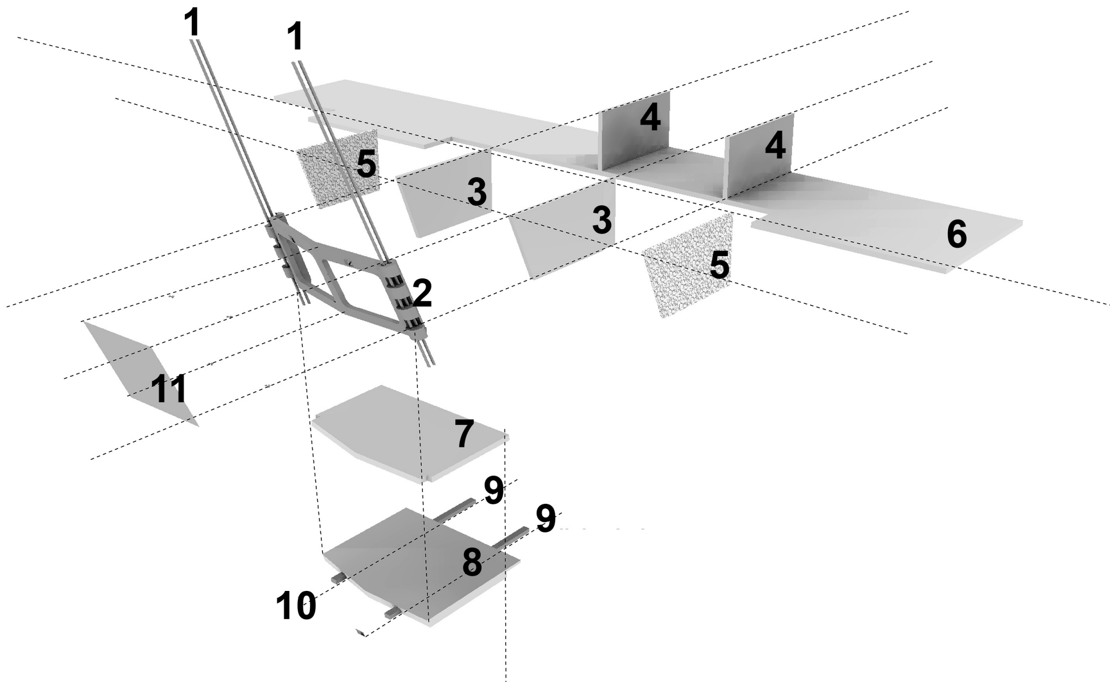


Figure 9.6.1. Exploded axonometric of integrated building component.

1. Structural tension cable running through joints where components connect.
2. Front face of component with interlocking corners.
3. Walls of components – when adjoined with connecting component it makes an airspace.
4. EXISTING TOWER SHEAR WALLS.
5. Insulation to be installed in airspace between components.
6. EXISTING TOWER FLOOR SLAB.
7. Additional floor space of component.
8. Roof of component below with voids printed into structure for insertion of mechanical ducts and other services.
9. Mechanical units run through voids in structure.
10. Mechanical Louvres installed on outside of structure.
11. Glazing installed on exterior of structure.

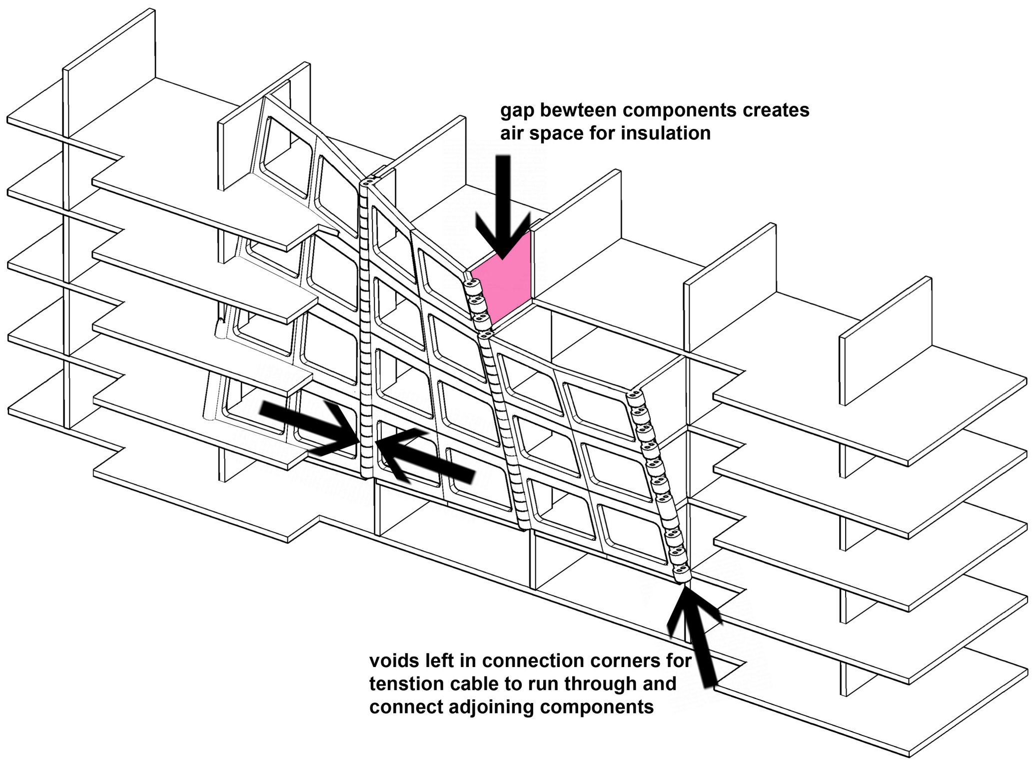


Figure 9.6.2. Diagram showing connection points of components – corner piece missing.

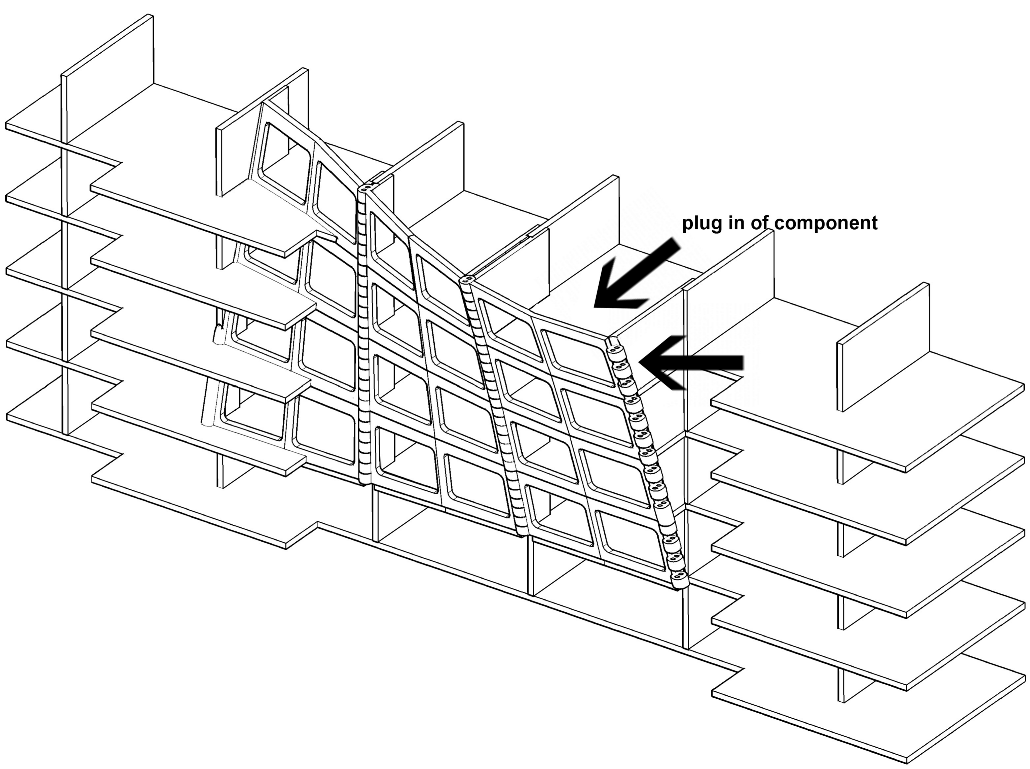


Figure 9.6.3. Diagram showing connection points of components – corner piece added.

Component

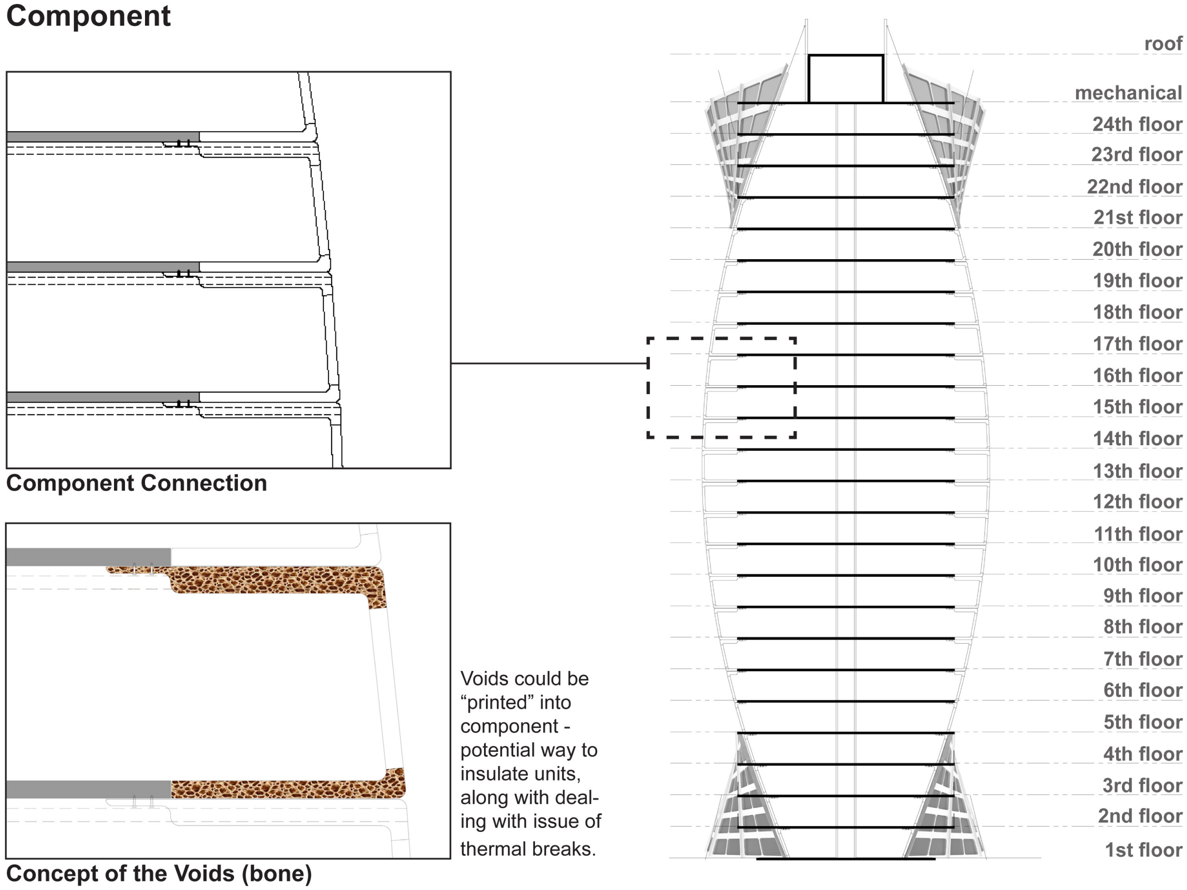


Figure 9.6.4 Detail showing printed in voids and connection of component to underside of slab.

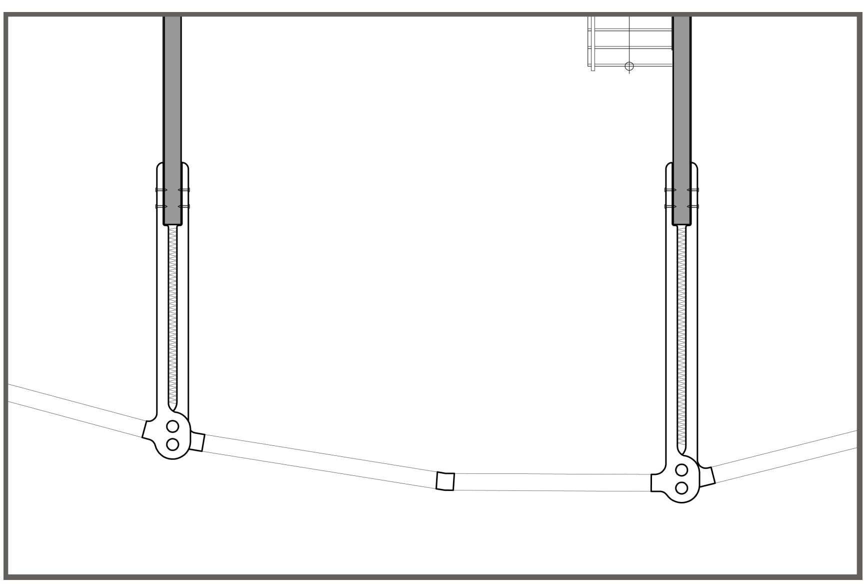


Figure 9.6.5 Detail showing where components connect to eachother and shear walls with airspaces between filled with insulation.

Figure 9.6.6 Photograph of 3D printed phyical model showing connections.

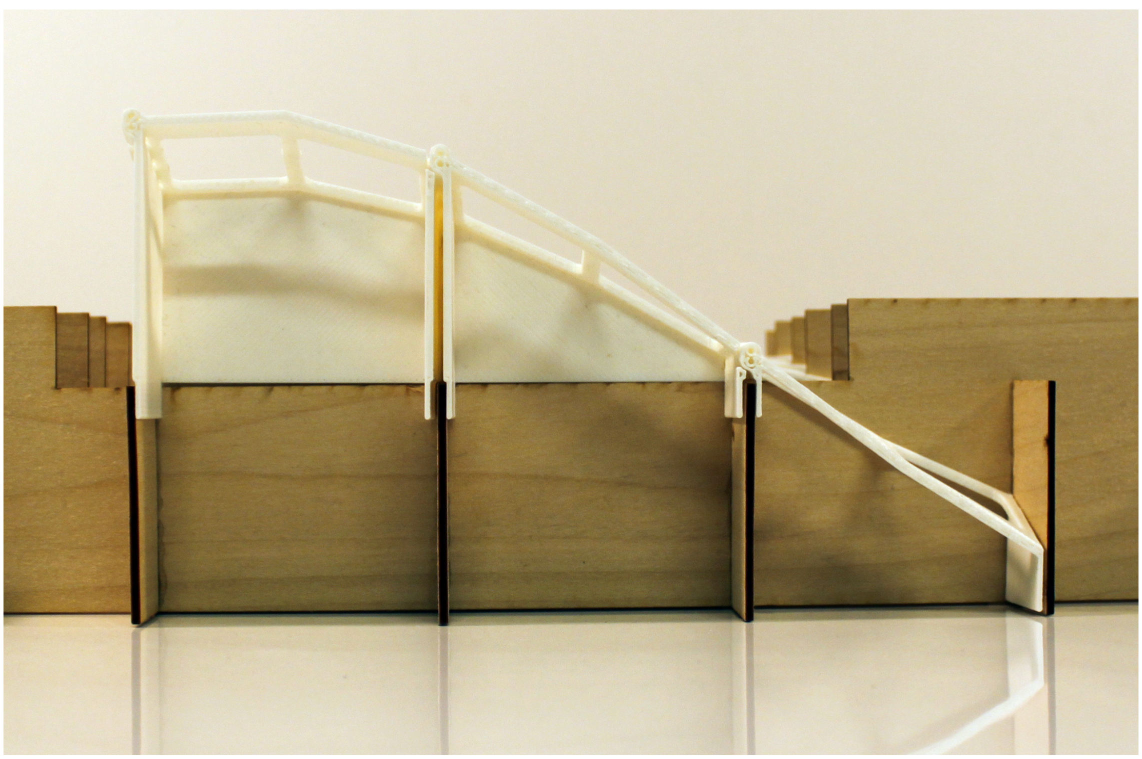


Figure 9.6.7 Photograph of 3D printed phyical model showing plan view.

9.7 The Construction

Essentially, the building components are efficiently fabricated off-site, then delivered and attached to the existing structure. In the case of a full façade demolition (which is the case here), the components could be printing off-site during the actual demolition. Then once the site is cleared, they are ready for installation, and turnover of the building could potentially happen in weeks.

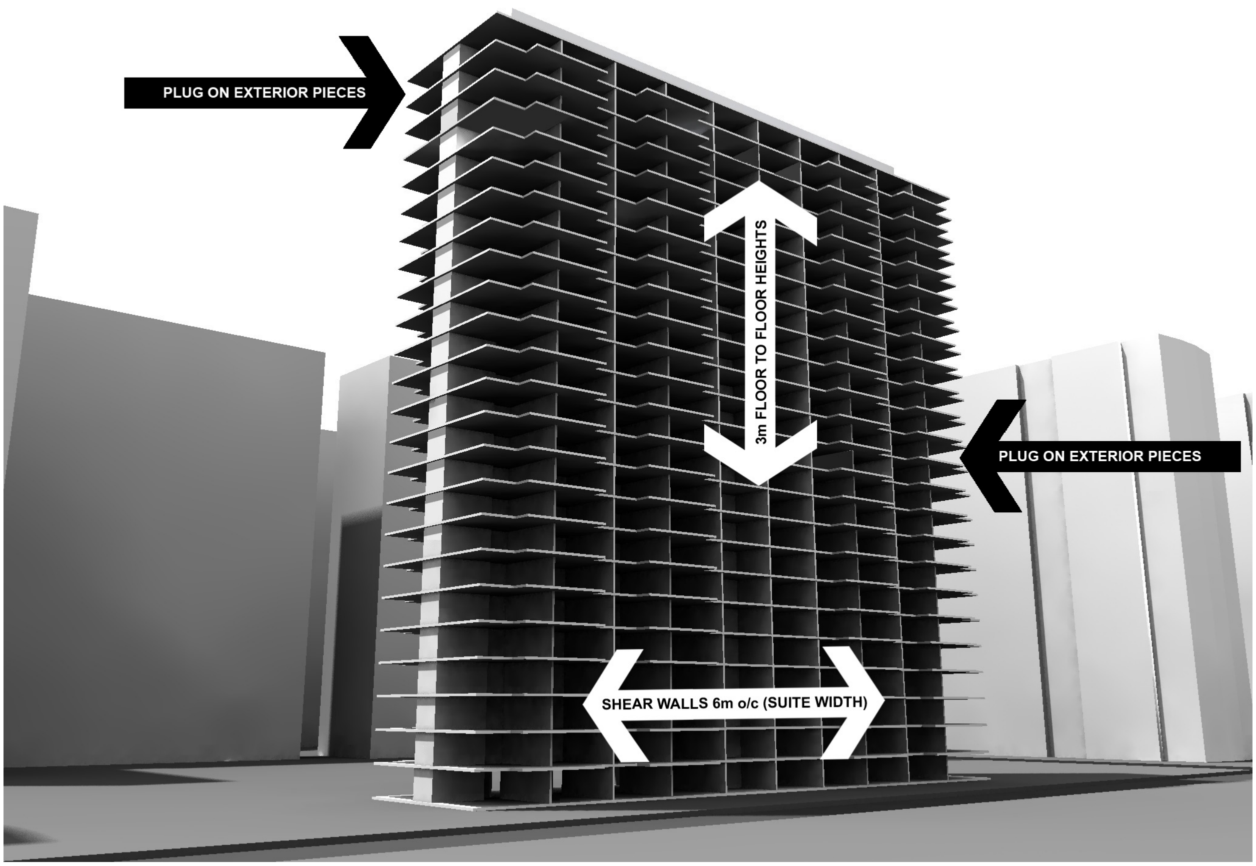
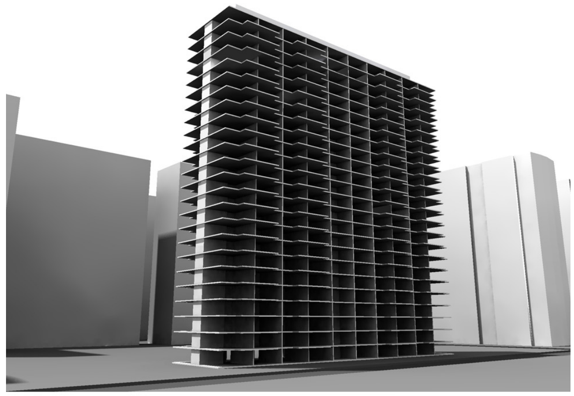
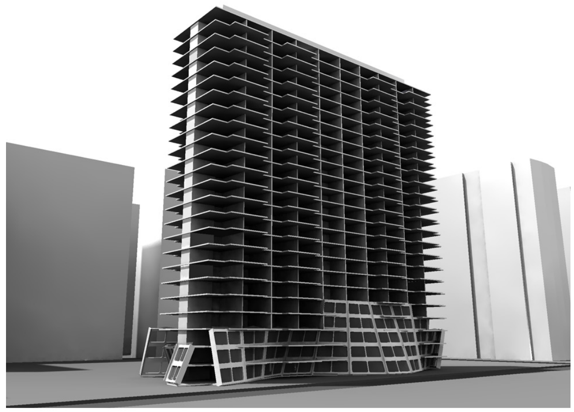
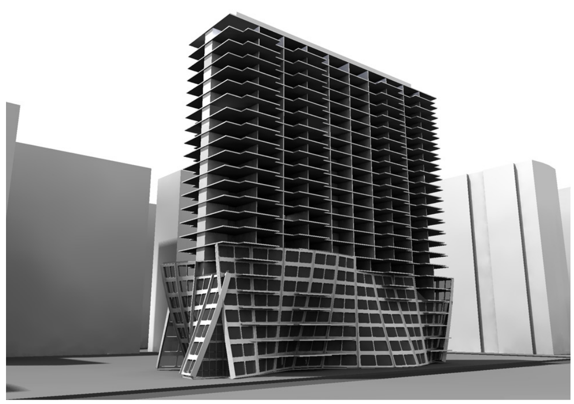
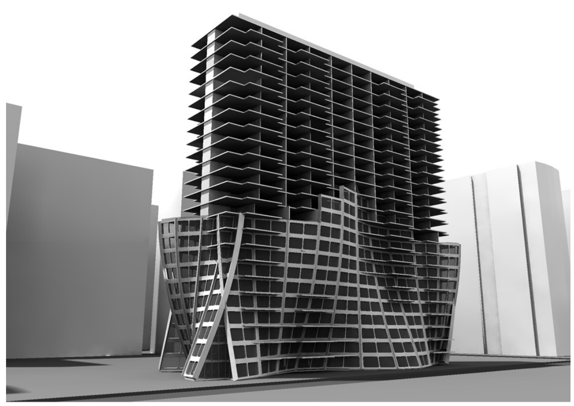


Figure 9.7.1 Existing structure.









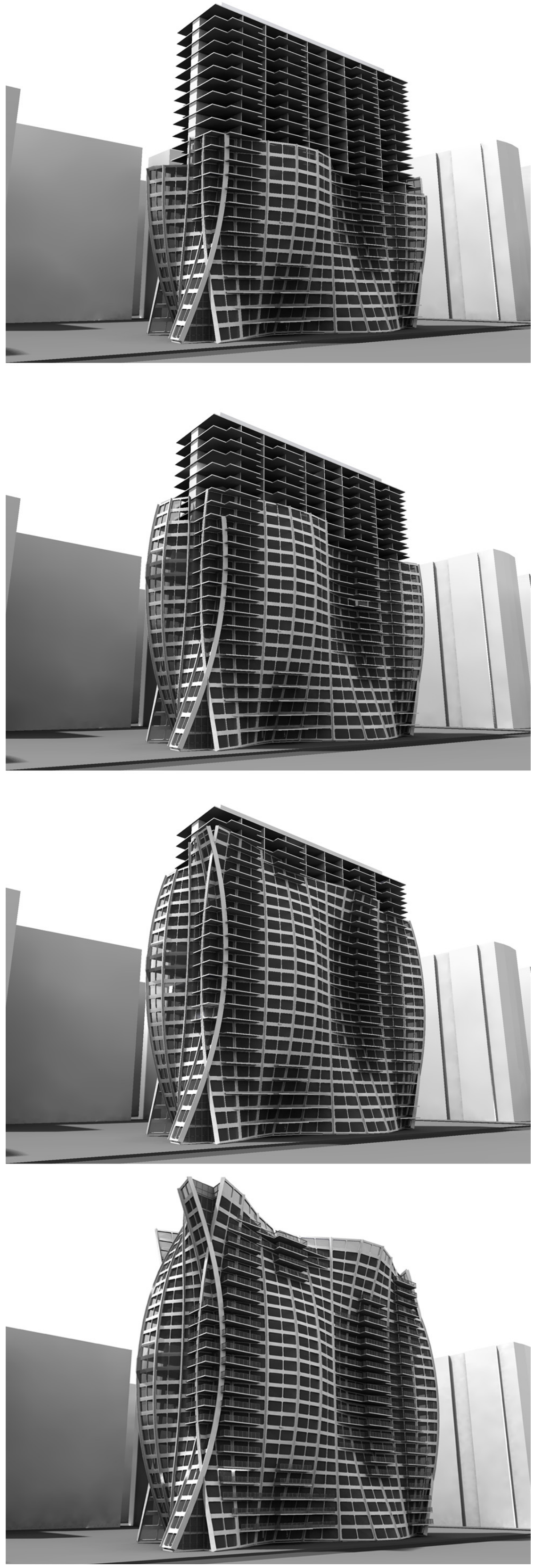


Figure 9.7.2 Gradual attachment of components.

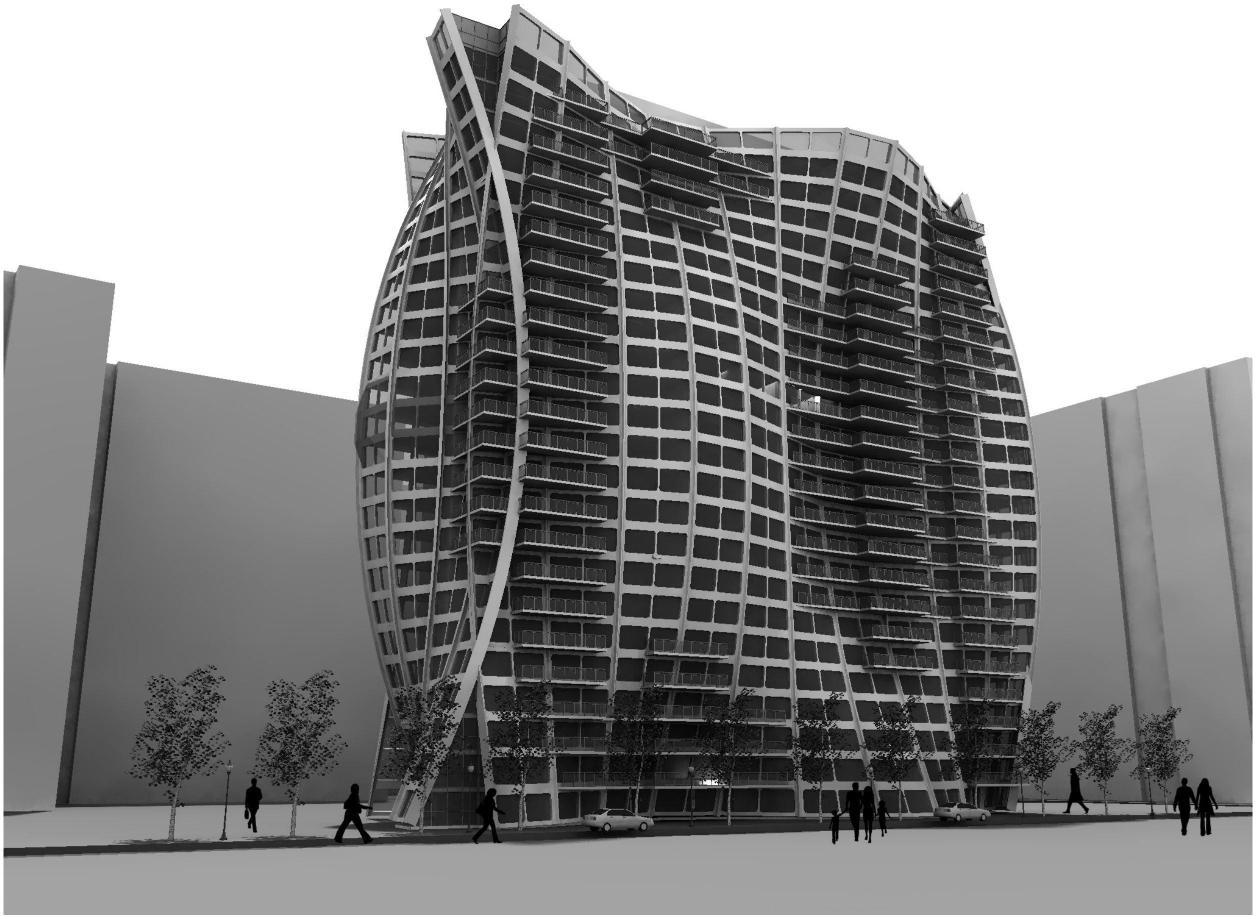


Figure 9.7.3 Final arrangement and placement of components.

MASS PRODUCTION + MASS CUSTOMIZATION

Just print + assemble component puzzle + install systems and exterior glazing

9.8 The Details

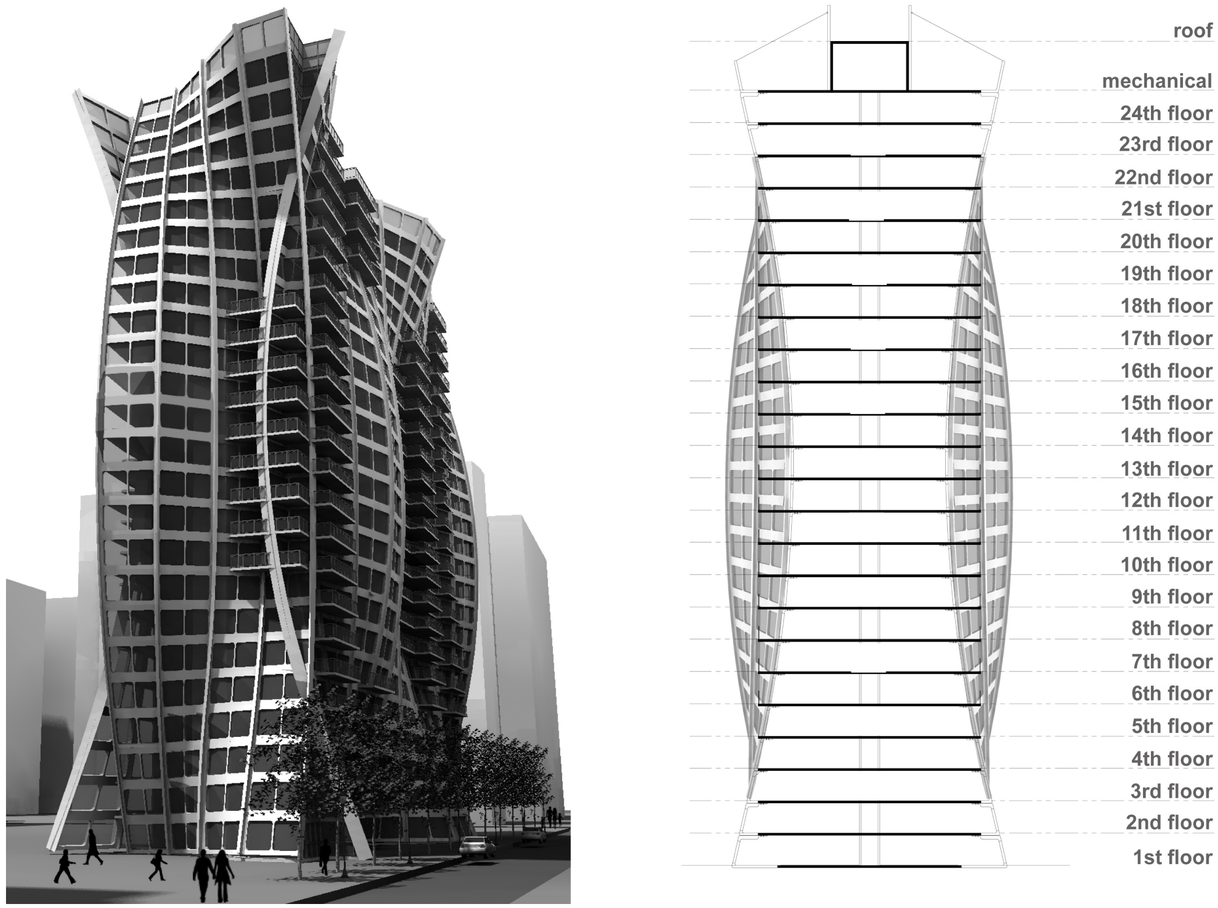


Figure 9.8.1 Builidng section through 'skinny' section of tower.

Given the pushing and pulling of the building façade to create larger units, and balcony conditions, there is the opportunity for a variation in unit types. In some cases the unit will remain the same and can be a range of one bedroom suites to three bedroom suites. In the cases where the builidng pulls in (Figure 9.8.1) and there is the potential to create two-storey suites. In doing so, the skip-stop system is utilized, where the elevator only stops on every other floor. Therefore, the outcome not only assists in the retrofit these buildings require, but the design also assists in the overall efficiency of the building, while addressing the desire to gain variablility in unit size.

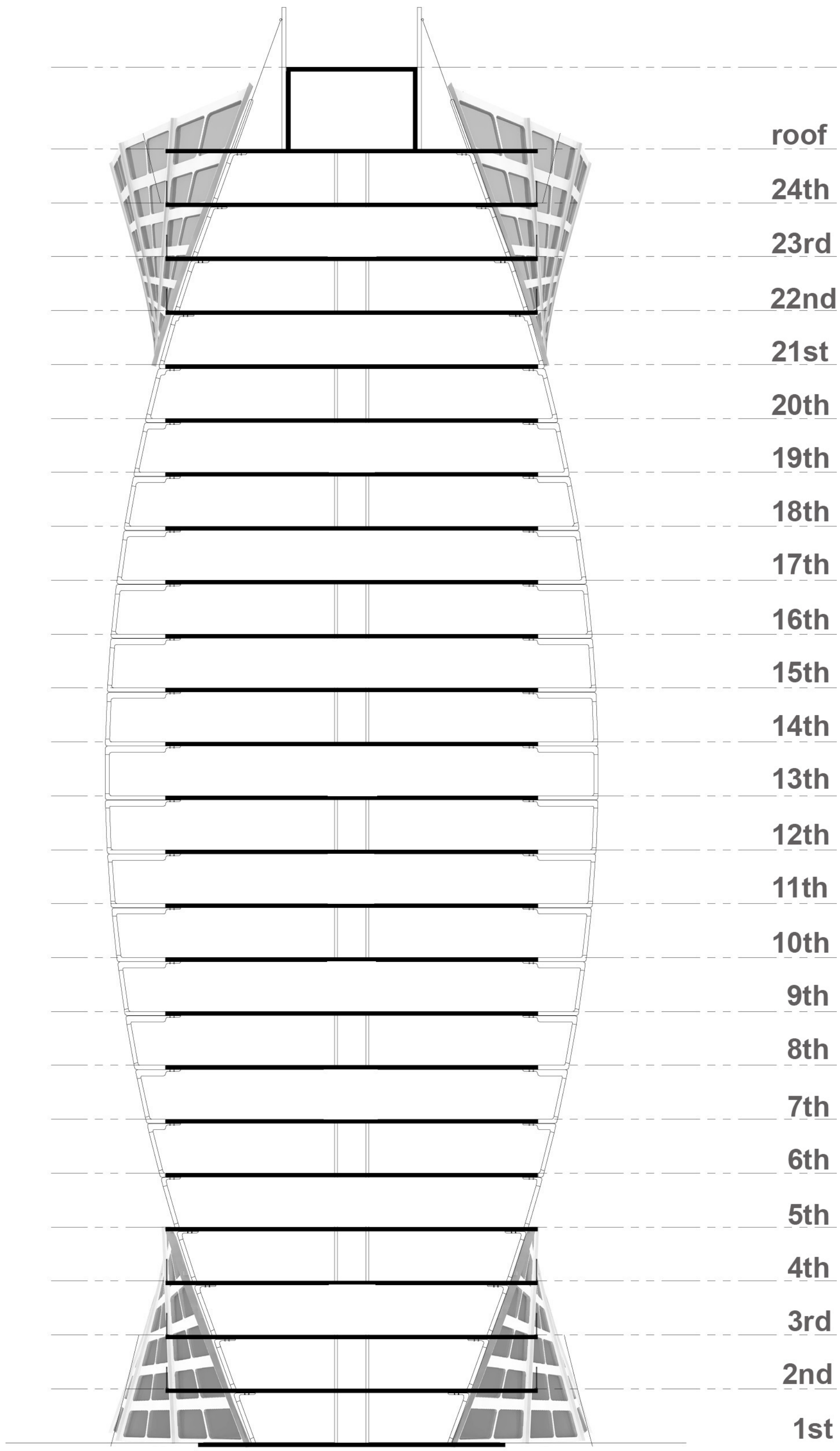


Figure 9.8.2 Builidng section through 'fat' section of tower

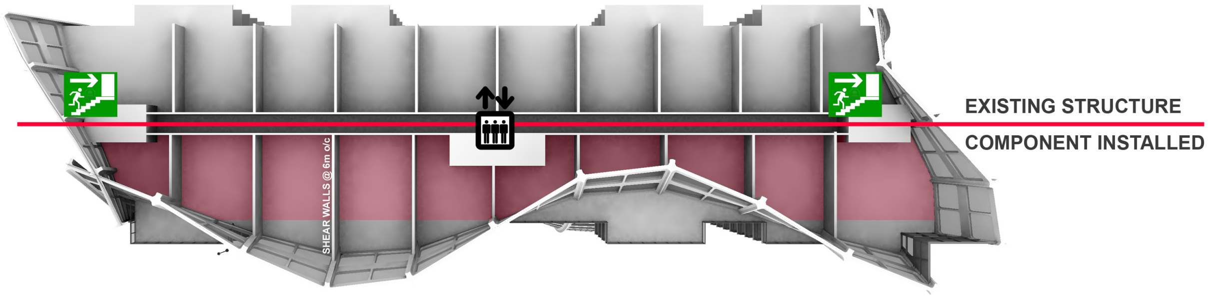


Figure 9.8.3 Existing floorspace of tower.

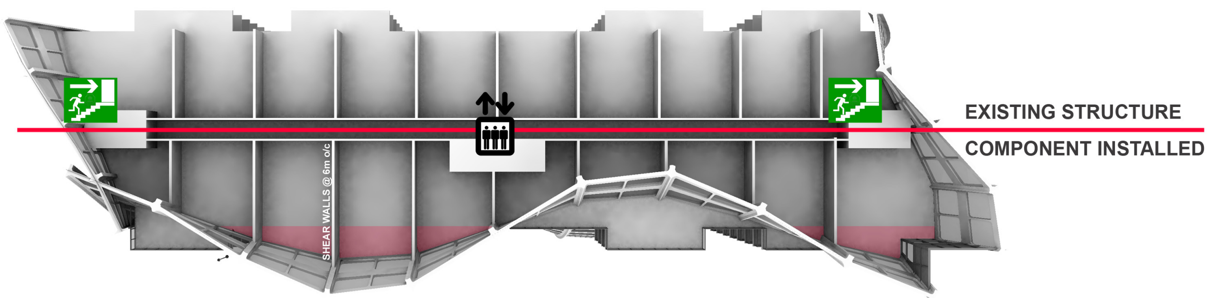


Figure 9.8.4 Additional floorspace gained once components attached.

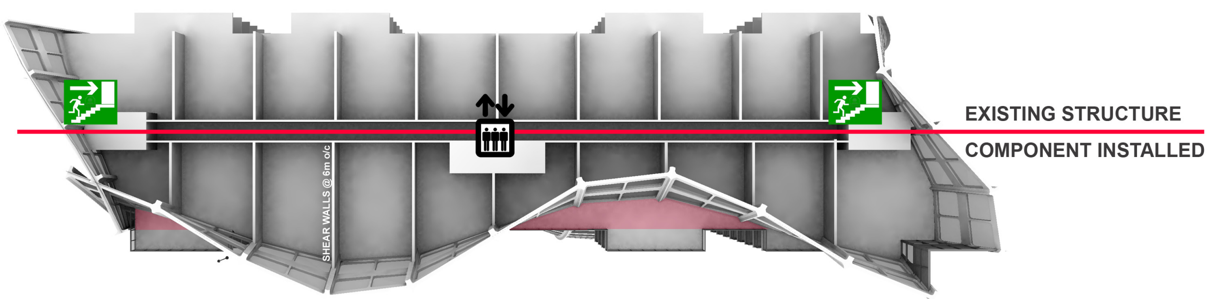


Figure 9.8.5 Floorspace lost once components attached.

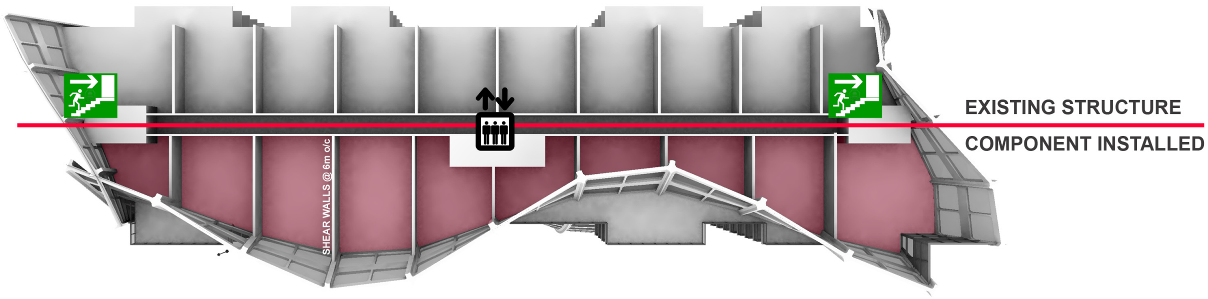


Figure 9.8.6 Overall floorspace of suites.

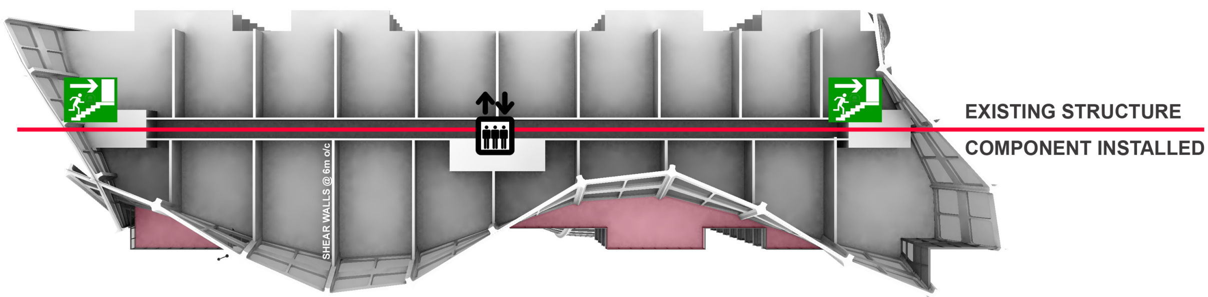


Figure 9.8.7 Balcony space.

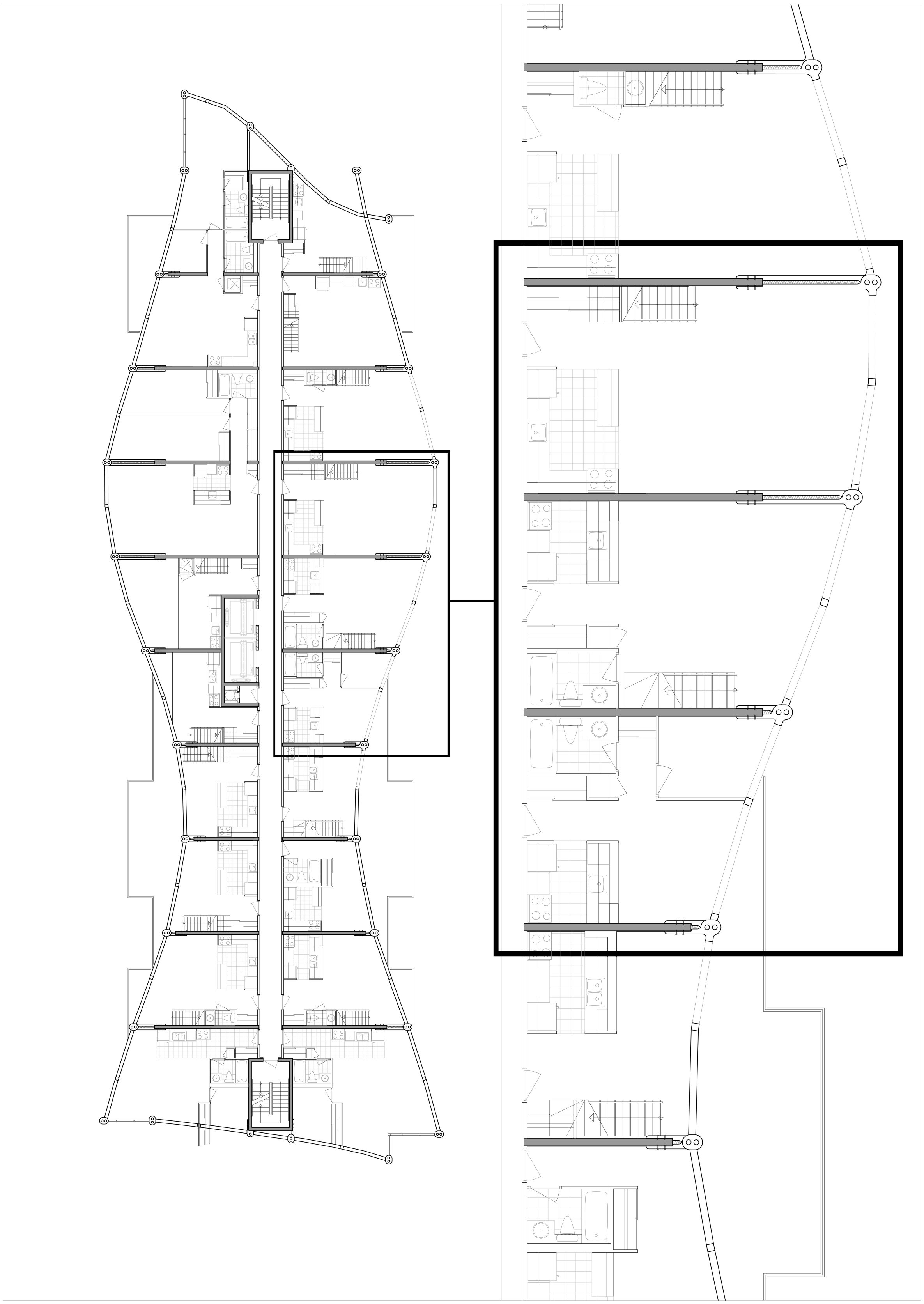


Figure 9.8.8 Lower level floorplan.

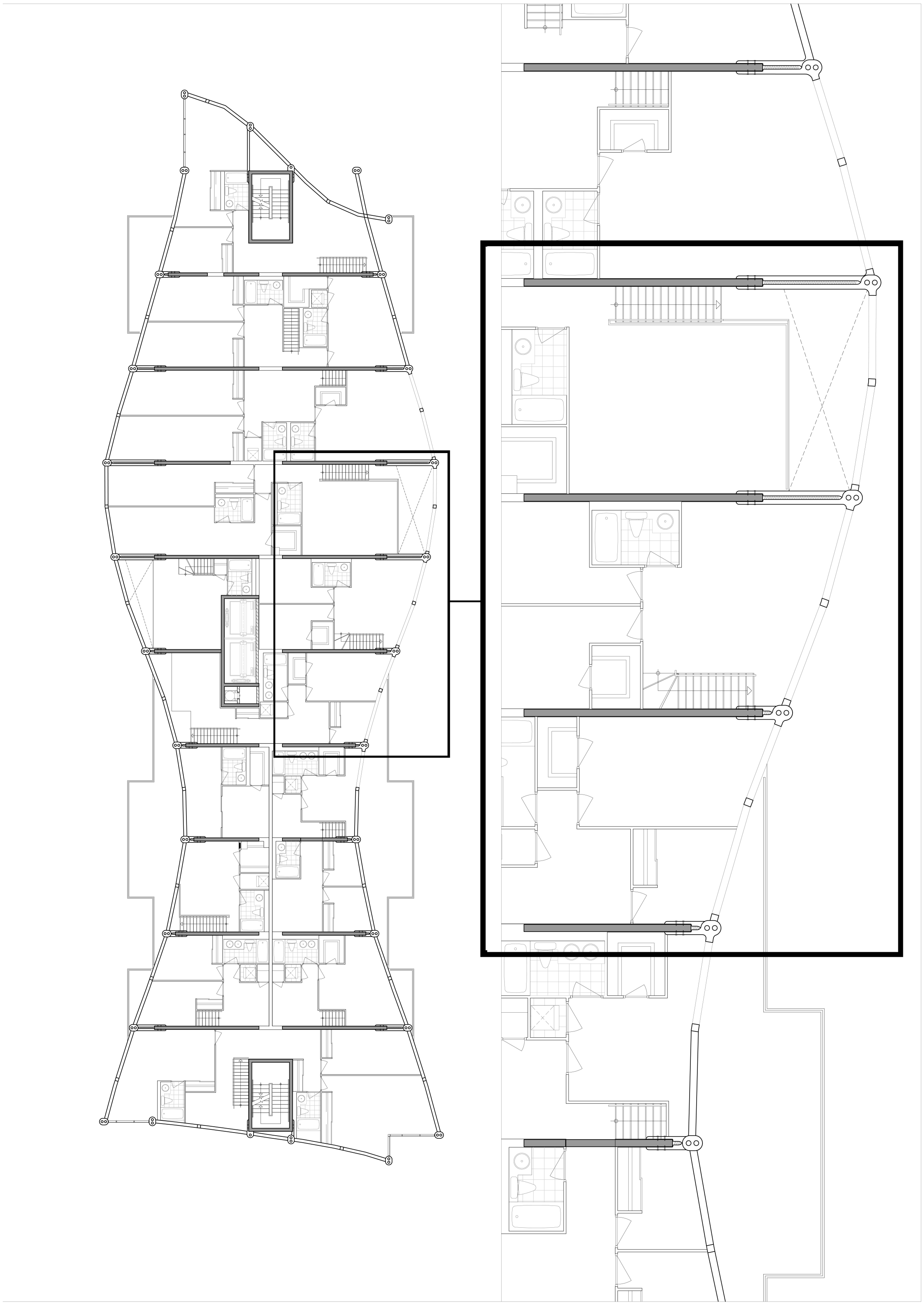


Figure 9.8.9 Upper level floorplan.

9.9 The Structure

All of the components have interlocking corners, which innately add strength to the exterior façade. Once the components are slipped on to the existing structure, a tension cable runs through the interlocking corner pieces, adding additional support and tying the overall exterior face back to the existing structure. This acts much like a bow and arrow (Figure 9.8.3). The tension cable is then anchored at the existing rooftop. Also, smooth curvilinear corners on component help avoid stress concentrations.

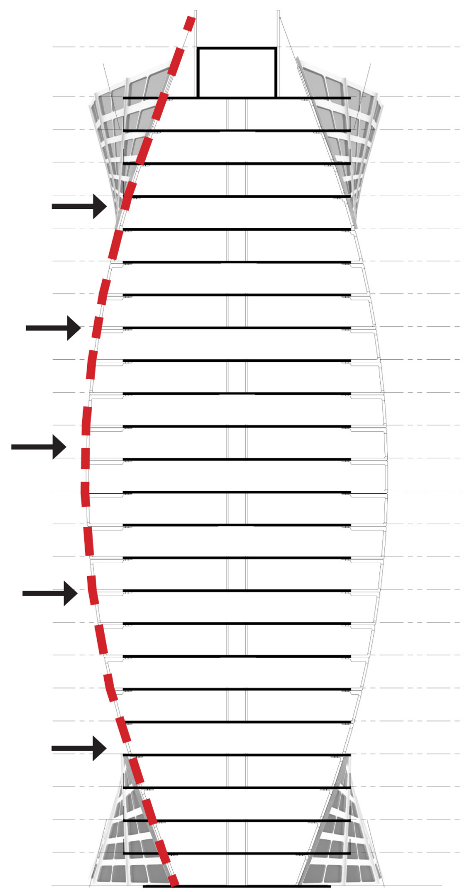


Figure 9.9.1 Structural Diagram

9.10 The Street

With the addition of street level retail there is a chance to create stronger communities, along with increased social and cultural benefits, while enhancing local economic activity, and sustainability.

Figure 9.10.1 View of main street retail of potential tower block.

Figure 9.10.2 Internal street view of potential tower block.

Figure 9.10.3 Internal street view of potential tower block.

Figure 9.10.4 View of rejuvinated open space surrounding potential tower block.

10. Opportunities and Challenges

With all our technologies in digital design and fabrication today, it is no longer a question of whether a particular form is buildable, but now rather what new instruments of practice are needed, and what opportunities are opened up by the digital modes of production. Through the research we can begin to truly understand that "the notion that uniqueness is now as easy to achieve as repetition, challenges the simplifying assumptions of Modernism and suggests the potential of a new, post-industrial paradigm based on the enhanced, creative capabilities of electronics rather than machines" (Kolarevic, 2003, p.27). Therefore, what are the opportunities and challenges for the future of architecture and construction if we do indeed embrace all of the technological innovations that are being presented to us?

10.1 The Impact of Printed Buildings

This technology in digital design and fabrication allows a level of precision and freedom of design unheard of in the past, and the limitations of conventional construction will no longer hinder architects' visions. Building elements entirely printed and assembled in a factory offers advantages similar to that of any industrial product. This process has the potential to save energy and reduces construction time while cutting building costs (Abrahams, 2010). In this scenario, not only do the building façade components have the potential to be printed, but the structure does also if implemented for new construction as opposed to a retrofit.

Furthermore, the prefabricated units arrive at the building site ready for quick and efficient installation. This requires far less workers on the construction site than traditionally needed, and each individual unit can be customized according to the owner's need and style. Each individual unit is also equipped with the necessary air spaces and voids for mechanical ducts, plumbing, and insulation. This again eliminates the amount of waste and traffic that is accumulated on site. With the design presented here, preassembled units are simply hooked to each other, resulting in the avoidance of additional materials, on-site waste, noise, and pollution.

Almost every product used today is the result of an industrial process and can be transported around the world, from cars and boats to computers and clothing, and factories are chosen for their ready access to materials, production technology, inexpensive labour, efficiency, and other conditions that result in high quality at a relatively low cost. But it appears as though construction, which is one of the leading sectors of the world economy, is also one of the most primitive. The concept of 3D printed building components represents the future of architecture, but this is just one small step. What are the implications for the construction industry as a whole?

10.2 The Future of the Construction Industry

Throughout the given research, we can see that digital technologies in design and production are being highly utilized, and offer enormous advantages for the construction industry, but we are not using them to their full potential. The mere idea of printing buildings is still a concept that has the potential to be realized, but not the likelihood as our mainstream construction industry is too far behind. With such advances in technology, we have the opportunity to transform the industry, but the mindset needs to change.

Embedded in the concept of printing buildings is the role of the computer to produce building elements. How about the idea of industrial robots in hard hats? Today robots are heavily involved in the fabrication side of construction, but is the time coming when they will take a more active role? In striving for a post-fordist future, we need to have innovation and technological improvements on all sides. We are futuristic enough to imagine a future where buildings are printed, and we have the technology to do so, but when it comes to putting the building together, we only know one way – that of sticks and planes, and people in hard hats manually building our skylines. Therefore, to truly move forward and have a post-fordist way of construction, if even at all possible, there needs to be a complete transformation of the construction process.

Most construction jobs are repetitious, labour-intensive, and dangerous – perfectly suited for robot automation, one would assume. Robots have the speed, dexterity, and power necessary to transform construction. Within this, construction could be a 24-7 process, having buildings built faster, safer, and cheaper. But is this truly an option in our society, to completely erase and rebuild this sector? This is most likely a far-fetched idea, but we can only advance so much with our digital technology in design and manufacturing without at least addressing the lack thereof in our construction industry. Sure, the speculation outlined here is just that, but without at least the acknowledgment of it, we will never move forward and fully embrace the technologies that are presented to us.

Ultimately, robots are invaluable workers when it comes to palletizing and packaging building products. Robotics is a highly developed technology, but its use in construction has been very limited. If a robot/machine can be used to economically produce all of the necessary building components, construction robots have the potential to lead to a new, innovative architecture, allowing for a complete new style of building.

There is logic for wanting to revolutionize the construction industry, but does the drive, ambition, and practicality of the idea have a real world application, or is speculation all that will come out such ideas? The full use of technology and robotics in the manufacturing process can still greatly enhance many aspects of construction, as demonstrated throughout this report, and if that is as far as we advance in the next few years, then there is still hope.

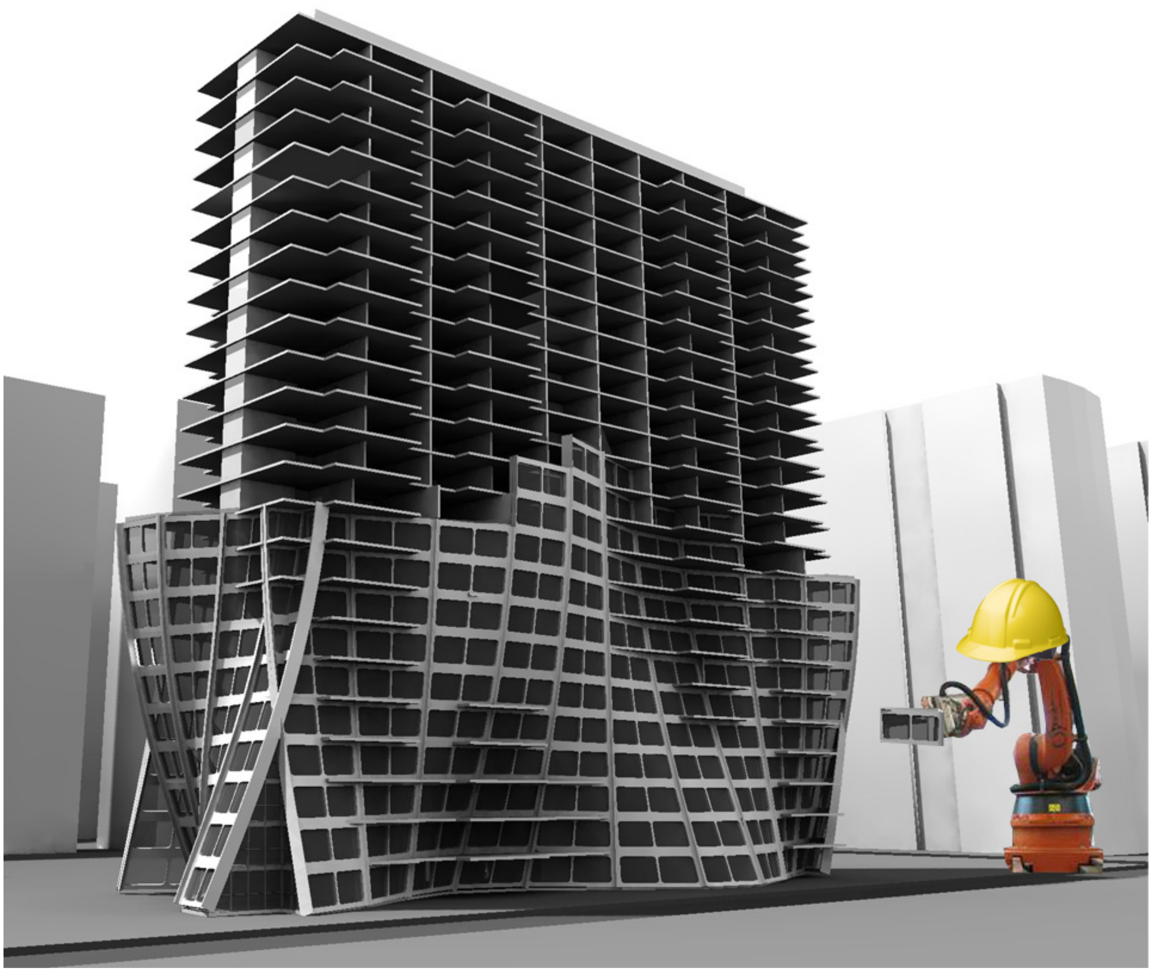


Figure 10.2.1 Speculation into the future of construction.

Does a Post-Fordist future mean robots in construction?

10.3 Challenges

As with any new technology or system that is being implemented into an industry with as much history as architecture and construction, there are inevitably going to be issues, concerns, and resistance. This is what we are seeing now, with the emergence of these digitally-driven processes of production, design, and construction. While it is opening up unprecedented opportunities for the building industry, it nevertheless faces a number of difficult, multifaceted challenges, which must be overcome for these processes to become a reality. Perhaps one of the biggest hurdles is as simple as communication and coordination. In this particular industry, obstacles arise from the long-established social and legal practices within it, particularly the clear definition of responsibilities. This could potentially stand in the way of new collaborative synergies that are emerging through the advent of numerous technological advances in all fields of design.

The sharing of digital data among various parties in the building process is currently discouraged by the current legal codes of practice. Under the current definitions of professional liability, if an architect transmits a digital model or drawing to a contractor or a fabricator, he or she becomes liable for any work resulting from the given model (Kolarevic, 2003). Thus, we have each participating party in the design and construction of a project creating its own digital data from scratch, creating a higher margin of error. However, attempting to unite all parties involved blurs the lines of responsibility, which have been drawn for ages. This requires radical restructuring of the industry. While it is technologically possible, it is an "enormous task given social and cultural inertia of the firmly entrenched traditions, developed slowly over several centuries" (Kolarevic, 2003, p.60).

Furthermore, there are general concerns regarding general forms that are afforded by these techniques. With all of the available technologies, there are immense opportunities for complexity in our building industry if these tools are used properly. If left in the wrong hands, we could see a skyline full of arbitrary forms, created 'just because we can'. Also, this idea of 3D printing could potentially generalize or simplify architecture, again questioning the role of the architect. With so much easily accessible customization, does the architect lose control of how a building looks? Therefore, it is clear that possibly the biggest obstacle of presenting these new ideas to the construction industry is simply acceptance. It is almost like 'teaching old dogs new tricks', and it is the hope that in the near future, we have these systems in place.

10. Conclusions

Today, with all our advances in digital technology, we can begin to see the potential for complex curvilinear or expressive forms being designed and produced with the same ease as these rectilinear and symmetrical geometries. Essentially, the possibilities of digital production and design can begin to change the notion that architecture operates most efficiently when buildings are constructed using a limited set of regular, uniform rectilinear and planar elements. Throughout the modernist movement, architects fully embraced the technological innovations of their time, using them to their full potential. Today, however, despite all the available technologies today we are still seeing a predominance of rectilinear form and repetition, which was addressed throughout the design process.

Through experimentation it has been demonstrated that uniqueness, not only in design, but also in production, is now potentially as economic and easy to achieve as repetition. In application of these methodologies and speculating through design, a new fabrication process was discovered that would push the boundaries of our current industry showing what is possible if we use some of these technologies to their full potential. Perhaps most importantly, presented here is an opportunity for our buildings to be a true representation of our time, while being able to evolve and customize appropriately as the times change.

Ultimately, this thesis was about testing the boundaries of our mainstream construction industry and introducing a new way of designing, thinking, and building that would accomplish all the same goals and aspirations of our current practices, but in a new, efficient and economical way, offering feasibility, variability, expression, and customization. Having learned from these past construction techniques, it is still important that prefabrication is optimized to maximize construction efficiency, but with the incorporation of digital design and fabrication, prefabrication of elements does not necessarily need to mean repetitiveness. Throughout the process of design and investigation, it was discovered that perhaps there is no way to truly erase repetitiveness in our buildings. In the final design presented here, although in many cases repetitive, the overall form presents mass customization, rationalized with components that are mass-produced through being printed. Through discovery and experimentation, and by fully embracing our technological advances, this method now has the potential to bring through detail, specificity, texture, and ornamentation, a new character, identity, and meaning to our cities.

11. References

Ábalos, I. & Herreros, J. (2003). *Tower and Office: from Modernist Theory to Contemporary Practice*. Cambridge: MIT Press.

Abrahams, Tim. (2010, March 8). The World's First Printed Building. *Blueprint Magazine*.

Beesley, P. & Bonnemaison, S. (2008). *On Growth and Form: Organic Architecture and Beyond.* Halifax: Tuns Press.

Barkow, F. (2008). Cut to Fit. In Kolarevic, B. & Klinger, K. (Eds.). *Manufacturing Material Effects: Rethinking Design and Making in Architecture.* (pp. 92-102). London: Routledge.

Bates, D. (2008). Different Differences. In Kolarevic, B. & Klinger, K. (Eds.). *Manufacturing Material Effects: Rethinking Design and Making in Architecture*. (pp. 160-174). London: Routledge.

Chu, K. (2003). Toward Genetic Architecture. In Tschumi, B & Cheng, C. (Eds.). *The State of Architecture in the Beginning of the 20th Century* (p. 62). New York: Monacelli Press, Inc.

Crosbie, M. (2005). *Curtain Walls: Recent Developments by Cesar Pelli & Associates*. Boston: Birkhäuser.

Dery, M. (2000, December). Retrieved on November 29, 2009, from *Soft House: Home Grown:* http://www.artbyte.com/mag/nov_dec_00/lynn_content.shtml

Doordan, D. (2002). *Twentieth-Century Architecture*. New York: H.N. Abrams.

Eisele, J. & Kloft, E. (2003). *High-Rise Manual: Typology and Design, Construction and Technology*. Boston: Birkhauser – Publishers for Architecture.

E.R.A. Architect, City of Toronto (2008). *Mayor's Tower Renewal: Opportunities Book*. Toronto.

Frampton, DK (2003). Organic Organ-i-city. In Gans, D. & Kuz, Z. (Eds.). *The Organic Approach to Architecture* (p. 75-87). Great Britain: John Wiley and Sons Ltd.

Franken, B. (2003). Real as Data. In Kolarevic, B. (Eds.). *Architecture in the Digital Age: Design and Manufacturing* (p. 122-138). New York: Spon Press.

Garvin, A. (2002). *The American City: What Works What Doesn't* (2nd ed.). United States: The McGraw-Hill Companies, Inc.

Gehry, G. (2003). Architecture and Intuition. In Tschumi, B & Cheng, C. (Eds.). *The State of Architecture in the Beginning of the 20th Century* (p. 52-53). New York: Monacelli Press, Inc.

Giencke, V. (2003). Work. In Gans, D. & Kuz, Z. (ed.). *The Organic Approach to Architecture* (pp. 75-87). Great Britain: John Wiley and Sons Ltd.

Gramazio, F & Kohler, M. (2008). *Digital Materiality in Architecture*. Baden : Lars Müller Publishers

Gramazio, F & Kohler, M. (2008). Towards a Digital Materiality. In Kolarevic, B. & Klinger, K. (Eds.). *Manufacturing Material Effects: Rethinking Design and Making in Architecture*. (pp. 101-118). London: Routledge.

Hall, P. (1996). *Cities of Tomorrow: An Intellectual History of Urban Planning and De-sign in the Twentieth Century.* Oxford: Blackwell.

Iwamoto, L. (2009). *Digital Fabrications: Architectural and Material Techniques*. New York: Princeton Architectural Press.

Jacobs, J. (1961). *The Death and Life of Great American Cities*. New York: Random House.

Johansen, J. (2003). Organic Process. In Gans, D. & Kuz, Z. (Eds.). *The Organic Approach to Architecture* (pp. 95-104). Great Britain: John Wiley and Sons Ltd.

Jones, P. (1999). *Hugo Haring: The Organic Versus the Geometric*. Sungnam: Daehan Printing & Publishing Co., Ltd.

Jolles, A. (2001, June 28). Retrieved November 3, 2009, from *Archined News: A Genuine Greg Lynn in Amsterdam South-East?* http://www.classic.archined.nl/news/0106/kleiburg_eng.html

Kesik, T; Saleff, I; Daniels Faculty of Architecture, Landscape, and Design; University of Toronto (2009). *Tower Renewal Guidelines: For the* Comprehensive *Retrofit of Multi-Unit Residential Buildings in Cold Climates*. Toronto.

Kieran, S. & Timberlake, J. (2004). *Refabricating Architecture: How Manufacturing Methodologies Are Poised to Transform Building Construction*. New York: McGraw-Hill.

Kolarevic, B. (2003). Digital Morphogenesis. In Kolarevic, B. (Eds.). *Architecture in the Digital Age: Design and Manufacturing* (pp. 13-28). New York: Spon Press.

Kolarevic, B. (2003). Digital Production. In Kolarevic, B. (Eds.). *Architecture in the Digital Age: Design and Manufacturing* (pp. 31-54). New York: Spon Press.

Kolarevic, B. (2003). Information Master Builders. In Kolarevic, B. (Eds.). *Architecture in the Digital Age: Design and Manufacturing* (pp. 57-62). New York: Spon Press.

Kolarevic, B. (2008). The Risky Craft of Digital Making. In Kolarevic, B. & Klinger, K. (Eds.). *Manufacturing Material Effects: Rethinking Design and Making in Architecture*. (pp. 120-128). London: Routledge.

Lalvani, H. (2003). Genomic Architecture. In Gans, D. & Kuz, Z. (Eds.). *The Organic Approach to Architecture* (pp. 115-126). Great Britain: John Wiley and Sons Ltd.

Lepik, A. (2004). Skyscrapers. New York: Prestel

Lynn, G. (1993). Architectural Curvilinearity: The Folded, the Pliant and the Supple. In Lynn, G. *(Eds.). AD Profile 102: Folding in Architecture* (pp. 8-15). London: Academy Editions.

Lynn, G. (2003). Calculated Variations. In Tschumi, B & Cheng, C. (Eds.). *The State of Architecture in the Beginning of the 20th Century* (pp. 72-73). New York: Monacelli Press, Inc.

Mathewson, C. (2007). *Frank O. Gehry: Selected Works: 1969 to Today*. Buffalo, New York: Firefly Books Ltd.

Mierop, P. (1995). *Skyscrapers: Higher and Higher*. Paris: Institut Francais D'Architecture.

Mies van der Rohe, L. (1950). A Speech to IIT. In Johnson, P. (1953). Mies van der Rohe, second edition. New York: Museum of Modern Art.

Mori, T. (2003). Materiality and Culture. In Tschumi, B & Cheng, C. (Eds.). *The State of Architecture in the Beginning of the 20th Century* (p. 30-31). New York: Monacelli Press, Inc.

Novak, M. (2000). *Archilab.com*. Retrieved November 19, 2009, from: http://www.archilab.org/public/2000/catalog/novak/novaken.htm#

Pearson, D. (2001). *New Organic Architecture: The Breaking Wave*. London: Gaia Books Limited.

Robinson, S. (1991). *The Continuous Present of Organic Architecture*. Cincinnati: Contemporary Arts center.

Rosa, J. (2003). *Next Generation Architecture: Folds, Blobs, and Boxes*. New York: Rizzoli International Publications, Inc.

Schoenauer, N. (2000). *6,000 Years of Housing*. New York: W.W. Norton & Company, Inc.

Sharples, C. (2008). Material Practice. In Kolarevic, B. & Klinger, K. (Eds.). *Manufacturing Material Effects: Rethinking Design and Making in Architecture*. (pp. 38-46). London: Routledge.

Simmons, M. (2008). Material Collaborations. In Kolarevic, B. & Klinger, K. (Eds.). *Manufacturing Material Effects: Rethinking Design and Making in Architecture*. (pp. 262-288). London: Routledge.

Spiller, N. (2009). *Digital Architecture Now: A Global Survey of Emerging Talent.* New York, NY: Thames & Hudson Inc.

Steadman, P. (2008). *The Evolution of Design: Biological Analogy in Architecture and the Applied Arts*. London: Routledge.

Szalapaj, P. (2005). *Contemporary Architecture and the Digital Design Process*. Burlington, Massachusetts: Architectural Press.

Unknown Author (2008, January 18). Retrieved November 5, 2009, from *arcspace.com*: http://www.arcspace.com/architects/hadid/nordpark/nordpark.html

Unknown Author (2009, November). Retrieved November 22, 2009, from *Emporis Commercial Real Estate and Construction Database:* http://www.emporis.com.

Wallick, K. (2007). Making SmartWrap: From Parts to Pixels. In Tanzer, K. & Longoria, R. (Eds.). *The Green Braid: Towards an Architecture of Ecology, Economy, and Equity* (pp. 223-233). Oxon: Routledge.

Waters, J. (2003). *Blobitecture: Waveform Architecture and Digital Design*. Gloucester: Rockport Publishers, Inc.