MASS-CUSTOMIZATION IN COMMERCIAL REAL ESTATE: HOW THE AVIATION INDUSTRY CAN HELP US CREATE BEAUTIFUL BUILDINGS THAT ADD VALUE

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Submitted to the Department of Architecture and
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ABSTRACT

The term *"mass-customization"* in the Architecture, Engineering and Construction (AEC) industry refers to architectural elements that have similar purpose but are completely different from each other. Architects use mass-customized elements to give diverse design to different parts of a building. Mass-customization derives from three developments in computational technology: *Building Information Modeling (BIM)*, the implications of programing in graphical representation, and the progress of computer-controlled manufacturing machines.

However, the promise held by these technologies has not been fulfilled. While mass-customization is implemented in projects with large budgets, they are rarely employed in mainstream real estate.

This thesis examines two multi-family projects: *The Project on 8 Spruce Street* and the *Porter House*, both located in Manhattan, to outline the challenges of executing commercial real estate projects that employ mass-customized envelope systems and makes suggestions as to how to overcome them.

The thesis then examines the aircraft manufacturing industry, which is proficient in the use of *Building Information Modeling* and has advanced logistical expertise in transporting large-scale elements. The thesis examines its use of design and assembly processes such as *Concurrent Engineering* and *Lean Manufacturing*, and suggests that these techniques can be incorporated into the project delivery methods of the AEC industry.

The thesis focuses on the production of fuselage and metallic wing skin panels, distinguishing between fabrication technologies that are used for the manufacturing of *single-curved* and *double-curved* panels. The thesis proposes ways in which these processes can be adapted to the standards of the Architecture, Engineering and Construction industry, and suggests that such adaptation could reduce fabrication costs.

The thesis concludes by outlining the incentives for the aircraft industry to transition part of its operation into the fabrication of mass-customized envelopes for commercial real estate, pointing to the potential markets for such systems in the growing economies of China, Latin America and India.

This thesis attempts to demonstrate the potential of utilizing features of the aircraft manufacturing industry so as to improve cooperation between all parties involved in the process of commercial real estate development and to create more beautiful and valuable buildings.

Thesis Supervisor: George Stiny
Title: Professor of Design and Computation

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TO MY MOTHER

INTRODUCTION

1

1.1
PROBLEM STATEMENT

The term “mass-customization” in the construction industry refers to a large number of architectural elements that have a similar purpose but at the same time are completely different from each other. Mass-customized components should be seen in contrast to mass-produced components, which are completely identical. While a facade with mass-produced elements has exactly the same windows, a facade with mass-customized elements will have windows that are entirely different from each other in shape and size. Architects use mass-customized elements to give a unique and diverse design to different parts of a building in order to avoid boring repetition. Mass-customization in architecture derived from the development of three key areas: Building Information Modeling (BIM) software, the implications of programing in graphical representation, and the progress of computer-controlled manufacturing machines.

However, the promise held by these innovative technologies has not been fulfilled as expected. Until now, the use of mass-customization in construction has been limited to buildings with generous budgets such as private villas, museums and airports; mass-customized elements have not been widely employed in common residential buildings. At the present time, the number of apartment buildings that utilize mass-customized elements in the United States can be counted on less than ten fingers . The main difficulties in endorsing mass-customized elements in architectural scale can be divided into two types. The first one lies in technical constraints, or more precisely, the fabrication costs of mass-customized elements, which are still far higher than for mass-produced elements. The second arises from the cultural and organizational conventions in the mainstream construction industry, which remain a significant barrier to the widespread use of mass-customization in commercial real

[i] The focus of this thesis is mainly multi-family buildings. The research came up with the following projects:

1. The Aqua Tower in Chicago designed by Studio Gang.
2. The Macallen Building in Boston designed by NADAAA.
3. HL23designed by Neil Denari.
4. The Project on 8 Spruce St. designed by Frank Gehry.
5. The Porter House designed by SHoP Architects.
6. The Project on 290 Mulberry St. designed by SHoP Architects.
7. The Project on 40 Bonds St. designed by Herzog and de Meuron.
8. The Project on 100 11th Avenue designed by Jean Nouvel.
9. The Project on 166 Perry St. designed by Asymptote Architects.

estate.

Commercial real estate projects that employ mass-customized elements are often eliminated in their early stages because of the financial risks, which are rooted in the lack of technical ability of today's construction industry to complete these types of buildings. Developers may be reluctant to take on projects that may be difficult to execute, and banks and other investors may be reluctant to lend money for such projects because of the difficulty to estimating the associated risk of this type of projects. Lenders prefer to invest in the type of buildings that they are familiar with and have invested in in the past, rather than risk putting money into buildings with innovative design, particularly if it is not clear if there is a market for these or not. [1]

However, there is a clear need for new commercial real estate, and there is a strong argument for using mass-customized elements in the production of that real estate. The rapid expansion of the world's population, particularly in developing and emerging markets such as China, India and Latin America, where in the next 12 years an addition of tens of millions of people will live in cities, establishes a clear need for an extensive new urban development. The use of mass-customization, especially in building envelopes, can help to mitigate the density effect in upcoming urban developments, and also enable architects to realize unique designs that can relate to local and cultural contexts.

1.2
WHY IS THE USE OF MASS-CUSTOMIZED ELEMENTS IN COMMERCIAL REAL ESTATE IMPORTANT?

The thesis will present three arguments to explain the importance of the implementation of mass-customization in commercial real estate. First, the architectural argument will review the role of technological advances in construction and show how these have influenced changes in architecture. It will also attempt to

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[1] Gregg Pasquarelli, *"Versioning"*, Harvard Graduate School of Design, Harvard University,YouTube. Accessed June 2, 2013. http://www.youtube.com/watch?v=CGF63pr4h64&list=WL0C26508EE4ED282E.

explain the failure of the digital movement in architecture to find its way into mainstream real estate. Second, the real estate argument will attempt to show that the use of mass-customized elements in facades will not only raise the value of the building itself, but also mitigate the risks that are associated with the development phase of real estate investment. Third, the urban planning argument will explain how the use of mass-customized envelope systems can contribute to mitigating the extreme density in the rapid urban development in emerging markets.

In order to illustrate the unique challenges to using mass-customization in the commercial real estate market, the thesis will look into two case studies. The thesis will report on the Project on 8 Spruce Street in Manhattan (2006-2011) and the Porter House also in Manhattan (2002-2003). Next, the thesis will offer suggestions for dealing with these challenges by looking into the design for manufacturing and design for assembly processes in the aircraft industry. By examining fabrication methods used in producing the fuselage and wings of aircrafts, the thesis will suggest ways in which the commercial real estate developers might adapt some of these methods to construction industry standards and thus cut costs. Finally, the thesis will conclude by making suggestions as to what kind of expertise the aircraft companies can provide to the construction industry and what the incentives are for the aircraft companies to penetrate that industry. Moreover, the thesis will argue that both real estate and aircraft industries will benefit from the integration of the aircraft industry in the construction industry as a manufacturer of envelop system made of mass-customized elements.

THE ARGUMENTS FOR THE IMPORTANCE OF IMPLEMENTING MASS-CUSTOMIZATION IN COMMERCIAL REAL-ESTATE

2

2.1
THE ARCHITECTURAL ARGUMENT: THE FAILURE OF THE "DIGITAL ARCHITECTURE" MOVEMENT TO FIND ITS WAY INTO THE MAINSTREAM OF THE CONSTRUCTION INDUSTRY

Throughout history, technological developments have played a key role in shaping our buildings and promoting new styles in architecture, both by enabling innovative constructions methods and materials and by providing new representation tools for architecture. The most vivid example is the influence of the Industrial Revolution in the development of the Modern Movement in architecture. With the widespread use of mass-production in manufacturing in the first decades of the 20th century, architects such as Le Corbusier, Walter Gropius and Mies van der Rohe asked themselves how architecture might express the novel values and accommodate the new programs of the emerging industrialized era. Modern architects argued that the buildings of the industrialized era should be as functional as machines; they thus eliminated thousands of years of classical ornamentation. The resulting buildings were constructed using duplicated spaces and repetitive elements that were prefabricated in factories and assembled on site.

Figure 2-1: The Bauhaus in Dessau designed by Walter Gropius,1925-1926. The curtain wall with the repetitive cast iron elements frames was prefabricated and assembled on site.

During the 1990s, with the development of representation software for CAD (Computer Aided Design) and animation uses, and with the emergence of computer controlled manufacturing machines such as laser cutters, water-jets, CNC routers and CNC bending machines, architects such as Greg Lynn, Mark Goulthorpe and Lars Spuybroek began to explore the new design possibilities offered by these computer-based technologies. This movement in architecture, known also as " Digital Architecture," argued that computer-controlled manufacturing machines could produce a large number of elements which were completely different from each other, at almost the same cost and time it took to produce those that were exactly the same, thus introducing the notion of mass-customization. The ability to produce a large number of elements that are completely different from each other enabled the return of the architectural ornament that had been abandoned by the modern architects, this time with a progressive twist. Although expressive geometries were not a goal in themselves, the combination of mass-customized elements together with the return of the ornament usually resulted in a design of buildings with complex geometries.

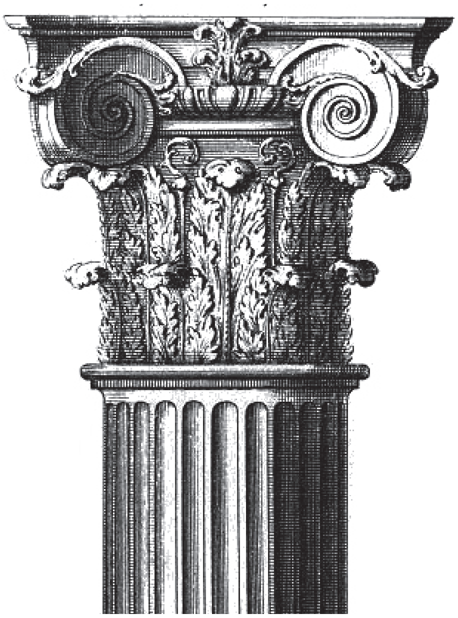


Figure 2-2: A Corinthian Capital. An example of classical ornament which was eliminated by the modern architects of the 20th century.

Figure 2-3: Michael Hansmeyer, *Subdivision: Ornaments Columns*, 2012. An example of re-introducing the architectural ornament by using algorithmic based design. A 3D cylinder was folded using and algorithm that changed the position of the folding each time. The final result was cut using a laser cutter into thousands of slim slices that were stuck on top of each other.

The completion of the Guggenheim Museum Bilbao in 1997, designed by world-renowned architect, Frank Gehry, was used by architects as a proof that building with complex geometries could be realized in the real world, and that humanity was on the verge of a new era in architecture.[2] However, this "Digital Architecture" has been limited to projects which enjoy the exceptionally high budgets that usually come from generous donations or taxes; it has not yet found its way into commercial real estate. One must wonder why "Digital Architecture" has failed to penetrate into the mainstream of construction industry while the Modern style can be found everywhere.

Figure 2-4: The Guggenheim Museum Bilbao , designed by Frank Gehry,1997.

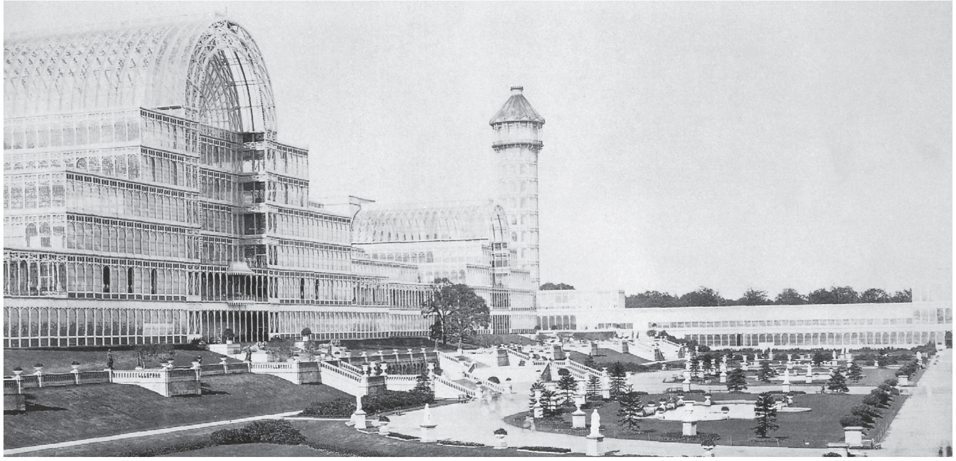
Historically, advances in building technology have been linked to major changes in architecture. The construction methods that ultimately allowed the inception of the modern movement in architecture were used in practice even before the clean Modern style came to be. For example, in 1854, the architect and landscaper, Joseph Paxton, designed a 990,000 square foot temporary structure for the first Great Exhibition in London, known as the Crystal Place.[3] The Crystal Place was made from prefabricated glass panels and repetitive cast-iron elements. Paxton designed the structure together with William Henry Barlow, a famous engineer who was involved in many projects of the Midland Railway; the cast-iron elements were

[2] Preston Scott Cohen, *"Museum as Genealogy- with Responses by Nicolai Ouroussoff"*, Harvard Graduate School of Design, Harvard University, YouTube. Accessed May 25, 2013. http://www.youtube.com/watch?v=V5Ij6laoMbQ.

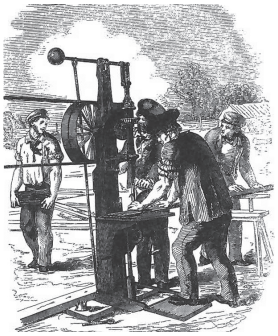
[3] John McKean. *Crystal Palace: Joseph Paxton and Charles Fox*. 1st Ed. Phaidon Press, 1994:60.

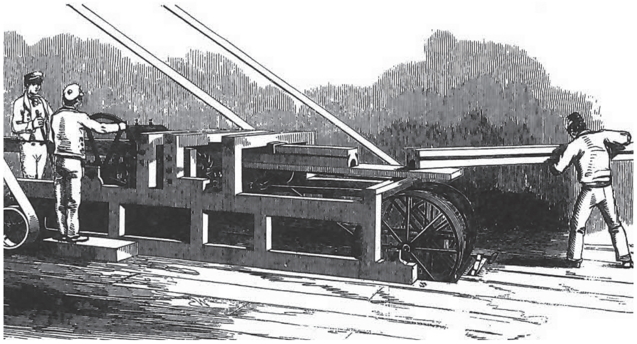
manufactured by railway equipment manufacturers named Fox and Henderson. Paxton knew that in order to be able to complete the ambitious project under budget and within a tight schedule, he had to collaborate with railway equipment manufacturers, since they had an experience working with cast iron, a knowledge which construction companies at the time lacked. [4] This is an example of how manufacturing and assembly technologies find their way into the construction industry.

Figure 2-5: The Crystal Palace, London, designed by Joseph Paxton, 1854.



Figures 2-6 & 2-7: Fox & Henderson workers fabricating cast-iron components. On the left, workers are using a drilling machine. On the right, workers are using the gutter-cutting machine.





In 1903-1904, the French architect Auguste Perret designed an apartment building in Paris whose structural system was made out of reinforced concrete columns and beams which at the time were still considered experimental, but which allowed flexibility in the organization of the floor plans. The facade was covered with ceramic tiles decorated with Art-Nouveau patterns. [5] It was not

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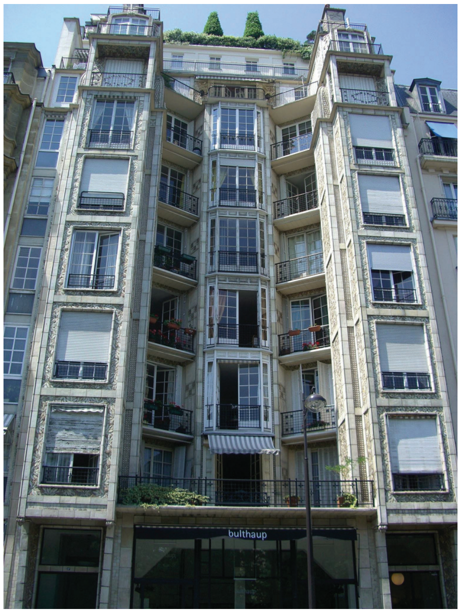
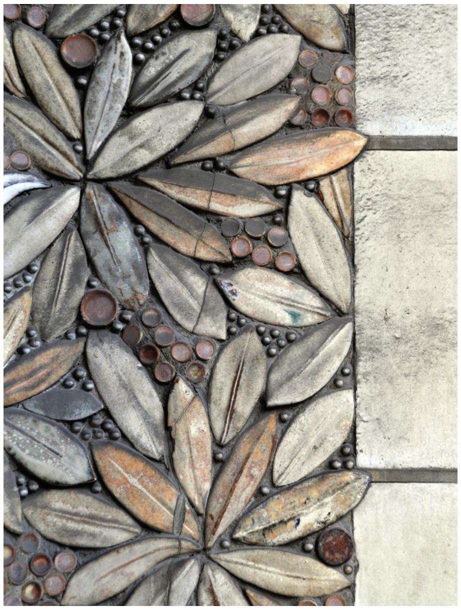
[4] Ronald S. Ely, *Crystal Palaces: Visions of Splendor*, Ronald S. Ely, 2004:22-23.

[5] Karla Britton, A*uguste Perret,* Phaidon Press, 2001:138-142.

Figure 2-8: An apartment building at 25 Rue Franklin, Paris, designed by Auguste Perret, 1903-1904.

Figure 2-9: The ceramic tile with the Art-Nouveau patterns.





until years later, in the 1920s and 1930s, that such clean geometric shapes characteristic of the Modern style in architecture came to be. However, the Modern movement in architecture could not have been conceived without the technological advancements introduced by Paxton, Perret and many other engineers and architects.

Similarly, 3D modeling software gave architects the tools to design and even produce construction and bid drawing sets for buildings with complex geometries. The use of these new technologies has thus far been limited to cultural and institutional buildings that have almost unlimited budgets, budgets that come from donations or tax money. However, no current building technologies are being employed to realize such complex architectural shapes under the budget frame of commercial real estate. One of the purposes of this thesis is to find ways to lower the cost of production of mass-customized metallic elements in architectural projects by looking into the fabrication and assembly process in the aircraft industry and adapting them to the standards of the construction industry.

2.2
THE REAL ESTATE ARGUMENT

The implementation of mass-customized elements in building facades can open the door for new design opportunities that can add unique artistic and esthetic value to buildings, value which in turn can add to the buildings' commercial value. Research has shown that renters of class A office space are willing to pay the premium of 20-22% for a better architectural design. [6] Moreover, the use mass-customized elements in envelope systems can also mitigate some of the risks which are associated with the development phase of buildings. In order to understand how this might work, we first need to explain what type of risk is associated with each phase of the development process, what the conditions for redevelopment are within cities, and what effect externalities have on urban economics.

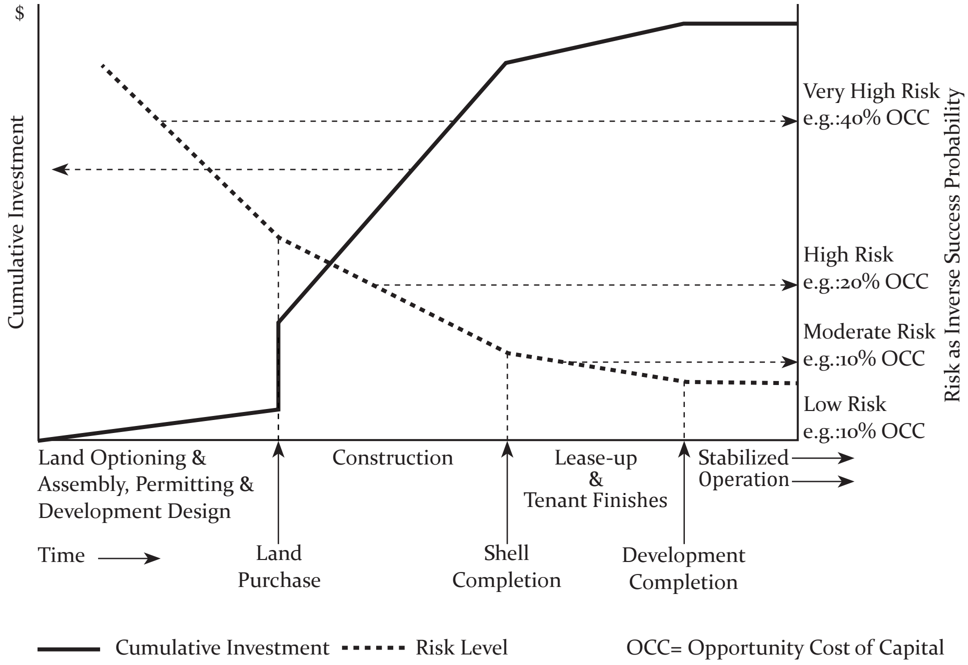
2.2.1
THE DIFFERENT RISK LEVEL OF EACH DEVELOPMENT PHASE

There is a great difference between the levels of risk associated with real estate investment in a stabilized asset, where the level of risk is relatively low, and the level of risk associated with real estate investment in a development venture. When an investor acquires a stabilized asset, the construction phase is over; the only risk the investor faces is to find tenants to occupy the completed units. On the other hand, a development process begins with finding land to build on, obtaining the ownership rights on the parcel, retrieving permits and entitlements from the local planning authorities, navigating the construction phase, and then eventually finding tenants who will be willing to pay the expected rents. Many things can go wrong during a real estate development investment; the risks are almost unquantifiable. However, it is also important to mention that the higher the risk an investor takes upon him or herself, the higher the expected return from the investment. [7]

[6] Kerry D.Vandell and Jonathan S. Lane. "The Economics of Architecture and Urban Design: Some Preliminary Findings." *Real Estate Economics 17*, no. 2 (1989): 235–260. doi:10.1111/1540-6229.00489.

[7] David M. Geltner, Norman G. Miller, Jim Clayton, Piet Eichholtz: *Commercial Real Estate Analysis and Investments 2nd Edition*, 2005:758-759.

Figure 2-10: Development project phases : Typical cumulative capital Investment and investment risk regimes.



2.2.2
THE CONDITIONS FOR REDEVELOPMENT WITHIN URBAN AREAS

The first condition that must be met in order for redevelopment to occur within an urban area is that the parcel (and the structure on it) must show that it has a Highest Better Use (HBU) value so that a new building can be built on top of it. Higher Better Use value can be established by showing that the asset suffers from depreciation, that there are changes in the asset's neighborhood, or that market demands are now different. For example, storage structures may be turned into loft buildings. [8] The second condition necessary order to make it financially profitable for a developer to acquire an asset, tear down the old structure and develop a new building instead, is that the FAR (Floor Area Ratio) of the new development will need to be, in most cases, significantly higher than that defined by current density on the site. However, the increase of density on the parcel might give rise to opposition from the owners of the surrounding buildings, and this might delay the receipt of permits and entitlements from the planning authorities. Such opposition might also force the developer to reduce the number of square feet that he or she planned to build. [9]

[8] David M. Geltner, Norman G. Miller, Jim Clayton, Piet Eichholtz: *Commercial Real Estate Analysis and Investments 2nd Edition*, 2005:64.

[9] Denise DiPasquale, and William C. Wheaton. U*rban Economics and Real Estate Markets. 1st Edition*, Prentice Hall, 1995: 81-86.

2.2.3
MASS-CUSTOMIZED ENVELOP SYSTEMS AS EXTERNALITIES IN URBAN ECONOMICS

The value of commercial real estate is not only determined by the quality of its design and the trends of market supply and demand, but also by the urban context in which it is located. The units in a residential building which faces a green park will be more highly valued than those in a building that does not. [10] This is where mass-customized features can play a key role. As mentioned above, the use of mass –customized elements on building facades can open the door for unique designs that can add an artistic and esthetic value to building. Moreover, a new building that will project beauty can also raise the value of the surrounding buildings. Realizing that there is a possibility that the value of their own property may increase, owners of the surrounding buildings may avoid raising objections in zoning board meetings or in other ways delaying or obstructing construction. Understanding that this type of building can have a positive effect on the image of a neighborhood, local planning authorities may be encouraged to give entitlements to developers as quickly as possible. Thus, by undertaking beautiful projects that will contribute to their surroundings, developers can cut down the development time period of their project and significantly reduce the level of risk that they take upon themselves. In short, mass-customization may contribute to the creation of beauty, and beauty may hasten development.

However, a statistical analysis that will depict a positive correlation between rents and prices of properties that are located around commercial real estate projects that employ mass-customized envelope systems is not yet available. Such studies will need to show that if there was an increase in the prices and rents of properties facing buildings with mass-customized envelope systems, this increase was not primarily a result of market trends. As mentioned in the introduction of this thesis, the number of

[10] Denise DiPasquale, and William C. Wheaton. U*rban Economics and Real Estate Markets. 1st Edition*, Prentice Hall, 1995: 348-357.

commercial real estate project that employ mass-customized envelope systems can be counted on less than ten fingers; moreover, most of those project were completed in the late 2010s and therefore not enough time has passed to conduct this analysis.

2.3
THE URBAN PLANNING ARGUMENT

For centuries, cities have played a key role in national economic growth; there is a strong positive correlation between economic prosperity and urban development. Cities attract skilled labor, productive business and at the same time are places where most consumption takes place, therefore the move to urban living generally increases the level of income for millions of people around the globe. In 2007, $30 trillion, which was more than half of the global GDP, was generated by the 1.5 billion people who lived in the 600 top tier cities all over the globe. By 2025, two billion people -- 25% of the world's population-- will live in 600 cities and will be responsible for $64 trillion, which will be more than half of the global GDP. Moreover, by 2025 the mix of the 600 top tier cities is going shift towards emerging markets such as China, Latin American, India and south Asia, as a result of the overwhelming urbanization processes which are expected to happen in those countries. [11]

In 2011, 260 million people were living in across Latin America. However, by 2025, 84% of Latin America population will live in 198 cities and is expected to reach 315 million. By 2040, the work force in Latin American cities will reach 470 million people, 80% of which will be young people who will immigrate to the cities from rural areas. The local authorities will need to prepare for these waves of migration by creating work places, building housing and investing massively in urban infrastructure. [12]

In 2008, India's urban population was 340 million people and is expected to reach 590 million people by 2030, twice the size of the

[11] "Urban World: Mapping the Economic Power of Cities | McKinsey & Company, "March 2011. Accessed June 6, 2013. http://www.mckinsey.com/insights/urbanization/urban_world.

[12] "Building Globally Competitive Cities: The Key to Latin American Growth | McKinsey & Company," August 2011. Accessed June 6, 2013. http://www.mckinsey.com/insights/urbanization/building_competitive_cities_key_to_latin_american_growth.

entire population of the United States today. India will have 68 cities of more than one million inhabitants, 13 cities with more than 4 million residents and 6 megacities with a population of more than 10 million people: cities like Mumbai and Delhi will be among the five largest in the world. In order to meet the expected market demands, 700-900 million square meters of commercial and residential real estate will need to be constructed annually. To better realize what this might mean, we can imagine that there will be a need to build a city in the size of Chicago every year. [13]

The rapid urbanization experienced by China between 1990 and 2005 increased the amount of developed area in China by 150%. Thus many local governments are about to run out of arable land. The goal of the Chinese authorities is to develop only 5-7% additional land in the next 15 years. In order to meet this target, upcoming urban developments will have to become much denser. This density also comes from the need to dramatically cut the costs of mass transit systems and urban infrastructure, attract more skilled labor, and mitigate pollution. Therefore, planning authorities in Latin America and India will also prefer to design dense urban patterns instead of sprawls.

Since 1990, China has gone through a rapid urbanization process that is expected to continue for at least the next 20 years. Between 1990 to 2005, 103 million people emigrated from rural areas to cities. This trend is expected to continue, as the urban population will grow from 572 million (in 2005) to 926 million in 2025, which is more than the entire population of the United States today. Out of 354 million people that will be added to urban areas, 240 million will come from rural areas. By 2025, an addition of 450-500 million job positions is expected to attract this massive labor force. Out of 900 Chinese cities, 221 cities will have more than million people, 115

[13] "India's Urban Awakening: Building Inclusive Cities, Sustaining Economic Growth | McKinsey & Company," April 2010. Accessed June 6, 2013. http://www.mckinsey.com/insights/urbanization/urban_awakening_in_india.

midsize cities with a population of 1.5-5 million, 15 big cities of 5-10 million inhabitants and 8 megacities with a population of more than 10 million people.   By 2025, forty billion square meters will be built in five million buildings, of which 50,000 buildings will be skyscrapers. This number of the skyscrapers is equivalent to 10 times more than the current inventory of high-rise buildings in New York City. [14]

The rapid urbanization that China went through from 1990 to 2005 increased the amount of developed areas in China by 150%. It is thus not surprising that many local governments are about to run out of arable land. The goal of the Chinese planning authorities is to develop only 5-7% additional arable land in the next 15 years. In order to meet this target, upcoming urban developments will have to become extremely denser. Denser urban planning also comes from the need to dramatically cut the costs of mass transit system and urban infrastructure, attract more skilled labor, and even help to control pollution nuisance.15 For the same reasons, planning authorities in Latin America and India will also prefer to design dense urban patterns instead of sprawls.

Figure 2-11: A collage of promotional signs next to construction sites across China during the 1990s, which demonstrates the ubiquity of repetitive modern urban scheme.

[14] "Preparing for China's Urban Billion | McKinsey & Company," March 2009. Accessed June 8, 2013. http://www.mckinsey.com/insights/urbanization/preparing_for_urban_billion_in_china

[15] "Preparing for China's Urban Billion | McKinsey & Company," March 2009. Accessed June 8, 2013. http://www.mckinsey.com/insights/urbanization/preparing_for_urban_billion_in_china

2.3.1
ROLE OF MASS-CUSTOMIZATION IN FUTURE URBAN DEVELOPMENT

Many cities around the globe use zoning regulations to enforce setbacks in high-rise buildings in order to mitigate the density effect which tall buildings have on streets and urban spaces. Building envelopes which will employ mass-customized elements can help to mitigate the perception of density by enabling architects to realize designs which convey diversity in the facades and which allow more sophisticated breaking of the buildings' mass than do simple setbacks. Moreover, mass-customization can provide architects and urban planners a richer palette of geometries and shapes: instead of copying and pasting from the predictable scheme of urban planning that has characterized the Western world -- a scheme which was already criticized for its flaws in the 1970s -- architects and planners can relate to the local cultural contexts in which they are operating.

It is a matter of urgency to find technical solutions to accommodate all these millions of people, but these solutions must also provide some sort of delight. If we wish to avoid the repetitive apartment block, which was introduced by modern architecture and was the basic component of the infamous "projects," we need to push forward the abilities to create apartment buildings that have uniqueness and beauty, but at the same time will be financially feasible.

CASE STUDIES

3

In order to understand the unique challenges that developers and architects in a harsh real estate market climate face when they wish to execute a building that employs mass- customized elements, this part of the thesis will describe two case studies. As mentioned in the introduction, not many commercial real estate projects that employ mass-customized elements have been completed; therefore, it made more sense to look into the few projects that have succeeded in being realized rather than into the numerous projects that have not. The two selected projects are the Project on 8 Spruce Street in Manhattan and the Porter House, also in Manhattan, which were designed by Frank Gehry and SHoP Architects, respectively. By tracing the development of these two projects, we can both understand the unique obstacles to the implementation of mass-customization in commercial real estate, and also examine what can be done to overcome them. Moreover, the success of these two projects lies not only in the fact that they were actually realized, but that they were also a huge financial success.

3.1
THE CRITERIA FOR CHOOSING THE CASE STUDIES

There were three conditions for choosing the two case studies. First, they had to be buildings whose construction phase was over and were occupied by tenants. Second, the mass-customized elements had to have played a key role in the design of the projects. Third, the two buildings had to be residential buildings, making them budget-driven projects. Both buildings-- the Project on 8 Spruce Street in and the Porter House--met those conditions.

3.2
THE PROJECT ON 8 SPRUCE STREET, MANHATTAN

Construction: 2006-2011
Architect: Gehry Partners, LLP
Developer: Forest City Ratner Companies
Structural engineer: WSP Cantor Seinuk
General contractor: KBF General Construction Company
Stainless steel panels engineering consultant: Permasteelisa Group
Concrete structure contractor: Sobara Construction Corp.
Location: 8 Spruce Street, New York
Height: 876 ft
Parking palace: 175
Stories above ground: 76
Floor area: 1,100,000 sq ft
Dwelling units: 903

3.2.1
GENERAL BACKGROUND AND THE CONDITIONS THAT LED TO THE COMMENCEMENT OF THE PROJECT

Designed by the world renowned-architect, Frank Gehry, the Project on 8 Spruce Street, is "the tallest residential building in the western hemisphere." [16] The building is located in the financial district of lower Manhattan. The project's main characteristics are the seventy-six-story high stainless steel wavy facades, which are placed on top of a six-story podium covered by a brick facade. This podium contains the first public grammar school to be built on private property, and a 25,000 square foot ambulatory

Figure 3-1: A view on the 8 Spruce Street Project from Brooklyn.

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[16] Mark Lamster, "22: Eight Spruce Street.," The Architectural Review, April 2011:66.

care center for the nearby New York Downtown Hospital. There are also two public plazas on either side of the building. Originally the one-acre lot was used as parking area for the hospital. The hospital management was on the verge of bankruptcy and had to auction the parcel to the highest bidder. [17]

Figure 3-1: The covered with bricks podium.

Ten developers competed for the site. Headed by one of the most prominent real estate developers in the United States, Bruce Ratner, Forest City Ratner Companies (FCRC), were able to obtain the site by offering $100 per square foot. [18] However, a deal between the developer, Forest City Ratner Companies (FCRC), and the local authorities created this strange combination between private and public functions in one tower. [19] According to an anonymous source, the fact that FCRC promised to build the brick envelope of the public school and the local health center, enabled them to win the bid over the other competitors for the desired lot. Moreover, the original Floor Area Ratio (FAR) of the lot was 800,000 sq ft.; 200,000 sq ft. were added to the building [20] in return for the creation of the two public plazas. One must understand that while the construction costs

[17] Mary Anne Gilmartin, "What Are Tomorrow's Buildings Today?", Columbia University, Columbia Graduate School of Architecture, Panning and Preservation, 2011. http://www.youtube.com/watch?v=UQPT391Q9EI&feature=youtube_gdata_player

[18] Ibid,

[19] Nicolai Ouroussoff, "Downtown Skyscraper for the Digital Age," New York Times, February 9, 2011, http://www.nytimes.com/2011/02/10/arts/design/10beekman.html?_r=2

[20] Chlloe Malle, "Cheek to Cheek with Frank Gehry" The New York Observer, November 23, 2011, http://www.observer.com/2010/11/cheek-to-cheek-with-frank-gehry/

of a building's top levels are more or less the same as for its lower levels, the upper units are sold for a much higher price, thus creating additional revenue for the developer.

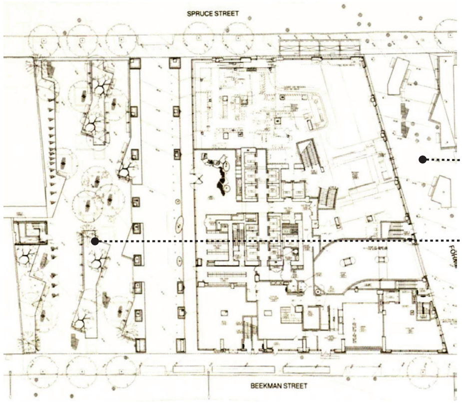

Figure 3-3: On the left. Street level Plan.

Figure 3-4: On the top right. The plaza in front of the public school.

Figure 3-5: On the bottom right. The plaza in front of the lobby entrance to the apartments tower.

After the 9/11 attacks in 2001, the authorities wanted to encourage the rehabilitation of Manhattan. Therefore, they initiated a "Liberty Bonds" plan, which meant tax exemptions were given for development projects in Manhattan. Out of the $875,000,000 cost, the project enjoyed $204,000,000 tax benefits in federal, state and city levels. [21] These tax reductions, together with the agreement which was settled with the authorities to build an extra 200,000 sq ft, in exchange for the two public plazas, were the incentives for FCRC to go ahead with the project.

3.2.2
THE BUILDING FACADES NEW INTERPRETATION OF THE "BAY WINDOW"

The main characteristic of the Project on 8 Spruce Street is its rippled metallic facades, which are made from stainless steel pre-fabricated panels. The geometry of the facades may seem arbitrary, but in fact the design process of the panels was budget-driven and took into consideration fabrication and assembly constraints. When Frank Gehry received the commission to design the building, in 2003, his initial concept was to give a new interpretation to the traditional "bay window" by implementing it in a high-rise building. Gehry used the bay window not only to create bumpiness

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[21] James S. Russell, "Gehry's $875 Million Tower Ripples High Above Brooklyn Bridge," Bloomberg, February 12, 2011, http://mobile.bloomberg.com/news/2011-02-11/gehry-s-875-million-tower-ripples-over-lower-manhattan-james-s-russell

in the building facades, but also to give the building's tenants a breathtaking, panoramic view of New York, which could not be achieved if the building had a flattened envelope. [22] Some of the bay windows have a view on other apartments, which some might perceive as a violation of privacy, but in a city in which next door neighbors often do not even know each other's name, Gehry wanted to create informal situations that would promote solidarity.


Figures 3-6 & 3-7: Gehry's interpretation to the "Bay Window".

3.2.3 THE DESIGN PROCESS OF THE STAINLESS-STEEL PANELS

The 427,734 sq ft building facades were covered with 10, 911 pre-fabricated stainless steel panels. [23] According to Emily Carr, the responsible engineer on the project in Permasteelisa North America (PNA), Gehry collaborated with them from the initial stages of the panels design, taking into consideration technical and budget constraints. [24] PNA was chosen to be the envelope engineering consultant of the project, because of their previous successful experience working with Gehry on projects such as the Guggenheim Museum in Bilbao, the Disney Hall in Los Angles and the Experience Music Project (EMP) in Seattle, and also because PNA was familiar with CATIA™, a Building Information Modeling (BIM) software, an alteration of which, called Digital Project, is used in Gehry's office. [25] Later on, the thesis will elaborate on the crucial role that BIM played in the successful realization of the Project on 8 Spruce Street.

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[22] dbox, " New York By Gehry," http://www.youtube.com/watch?v=NYTti5FkOjE

[23] Nadine M. Post, "New York's Tallest residential Tower Is Frank Gehry 'Demystified' Team Uses Collaboration and Digital Tools to Produce Architect's Most Expensive Draped Façade," Engineering News Record, 29 March 2010: 29.

[24] Emily Carr, interview by Shaul Goldklang, April 4, 2012.

[25] Nadine M. Post, "New York's Tallest residential Tower Is Frank Gehry 'Demystified' Team Uses Collaboration and Digital Tools to Produce Architect's Most Expensive Draped Façade," Engineering News Record, 29 March 2010: 28.

From the early stages of the design process of the project, architects from Gehry’s office had working sessions with the engineers from PNA. Those sessions had several purposes: the first was to outline the technical requirements of the stainless steel panels in terms of waterproofing, wind loads, and the dead load of the panels themselves.[26] Initially, Gehry wanted the panels to be made out of titanium, the same cladding material which was used for the Guggenheim Museum in Bilbao, but since the panels needed to carry a window- cleaning cart, they had to be of a thickness that would be extremely expensive to manufacture from titanium. Therefore, stainless steel was chosen instead. [27]

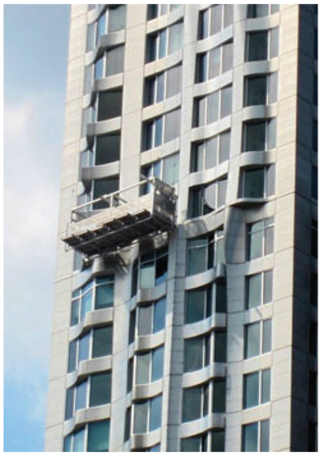

Figure 3-8: Housekeeping Cart windows of the project.

Figure 3-9: Frank Gehry inspecting the first mock up of the stainless steel panels.

The second issue discussed between Gehry and PNA was the fabrication constraints of the panels. The panels were made from 20”X80” [28] stainless steel sheets which were imported from Japan.[29] The project architects at Gehry’s office used BIM to create a 3D model with all the panels and sent it to PNA, which conducted a finite-element analysis in order to reduce the number of panels with double curvature. According to Dennis Shelden, Chief Technological Officer in Gehry Technologies, “the panels were curved in a way that a craftsman can lay them on like a sheet of paper” [30] with no need for special stamping process. On the other hand, panels with

[26] Emily Carr, interview by Shaul Goldklang, April 4, 2012.

[27] Jonathan Glancey,” Frank Gehry: Dizzy Heights,” The Guardian, 5 July, 2011, http://www.guardian.co.uk/artanddesign/2011/jul/05/frank-gehry-8-spruce-street

[28] Emily Carr, interview by Shaul Goldklang, April 4, 2012.

[29] Katharine Jose, “ New York’s Tallest apartment building, inside and out (and in between),” Capital New York, http://www.capitalnewyork.com/article/culture/2011/10/3817024/new-yorks-tallest-apartment-building-inside-and-out-and-between

[30] Frank Gehry’s Beekman Tower, 2011. http://www.youtube.com/watch?v=vaNoivBeG5I&feature=youtube_gdata_player.

double curvature are manufactured with warm bending, which is a much more expensive process. The use of BIM enabled Gehry and PNA to interactively examine the effects on the facades by replacing double curved panels with single curved ones. Eventually, only 10% of the surface was double curved. All the glass windows were flat but different in length.[31]

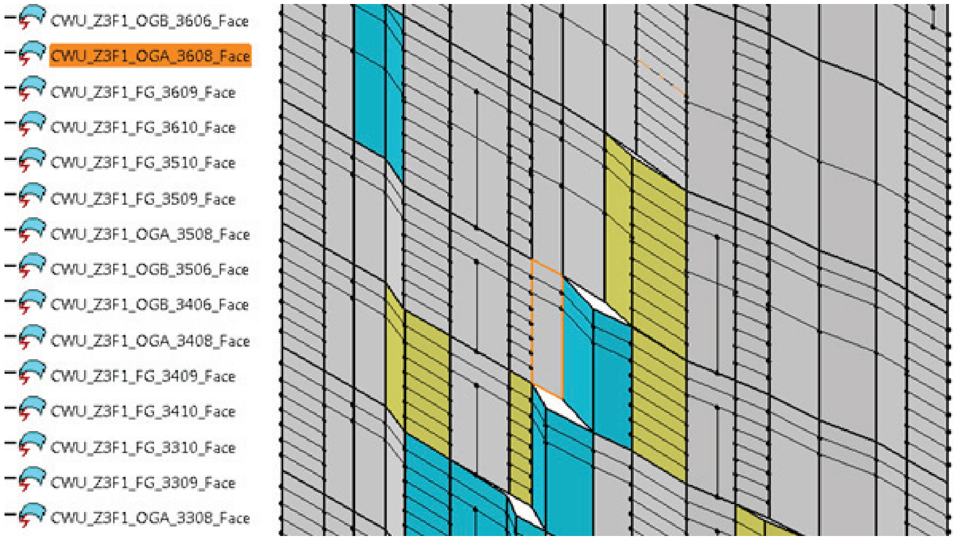

Figure 3-10: The analysis model of the curtain wall.

Because only 1,888 out of 10,911 panels were similar[32] it would have been impossible to produce thousands of 2D paper drawings so as to manufacture the panels. Instead, PNA engineers imported the BIM 3D model directly to Computer Aided Manufacturing (CAM) software that operated the Computer Numerical Control (CNC) machines which were used to fabricate the panel pieces. The use of BIM not only made the project possible to manufacture, but also cut down the amount of paper waste and prevented the kinds of mistakes that are usually made when transforming the 3D model into 2D drawings.[33]

The third issue that was raised in the working sessions between Gehry and PNA was that of how to assemble the panels on the concrete structure of the building. It was decided that the panels would work like a unitized curtain wall --i.e., while most of the

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[31] Nadine M. Post, “New York’s Tallest residential Tower Is Frank Gehry ‘Demystified’ Team Uses Collaboration and Digital Tools to Produce Architect’s Most Expensive Draped Façade,” Engineering News Record, 29 March 2010: 29.

[32] Ibid,

[33] Emily Carr,” Using Technology and Innovative Designs to Build Complex Architectural Envelops,” Techne 02 (2011): 153, ISSN: 2239-0243

panels were completely different from each other, all of them were connected to the concrete structure using a conventional system that was familiar to the workers on site. The stainless steel panels were connected to 14,000 aluminum embeds which were implemented in the edges of the concrete slabs; these embeds allowed flexibility in adjusting the panels. The panels were installed by PNA's local subsidiary, Tower Installation LLC, which also erected the curtain wall in IAC (InterActiveCorp) headquarters, Frank Gehry's first complete building in New York. This previous experience assisted in the rapid assembly of the project facades; one floor with panels was completed in one week. [34]

Figure 3-11: The installation of the stainless steel panels.

[34] Nadine M. Post, "New York's Tallest residential Tower Is Frank Gehry 'Demystified' Team Uses Collaboration and Digital Tools to Produce Architect's Most Expensive Draped Façade," Engineering News Record, 29 March 2010: 30.

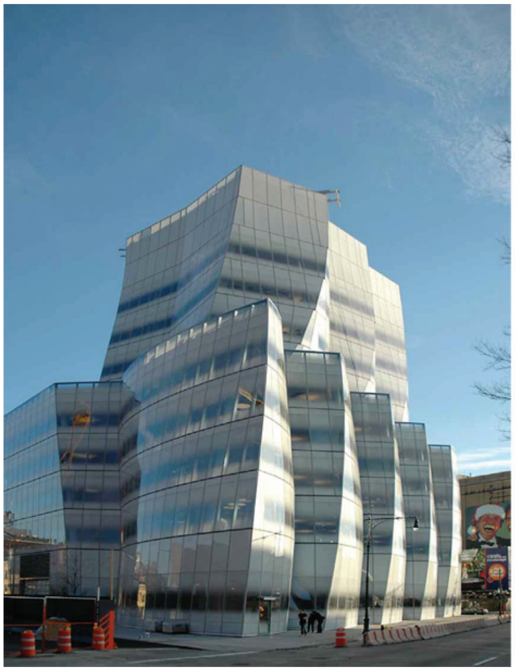

Figure 3-12: On the left. The IAC (InterActiveCorp) headquarters,New York City designed by Frank Gehry, 2007.

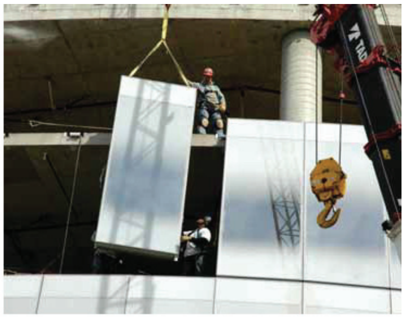

Figure 3-13: On the top right. The installation of the IAC curtain wall.

Figure 3-14: On the bottom right. An aluminum embedded for curtain wall installation, during the construction of the IAC headquarters.

3.2.4
THE BUILDING'S STRUCTURAL SYSTEM

While the building's facades were complex and executed with the aid of innovative technologies, the concrete structural system was designed using the "core-and-trigger" method in order to keep it as simple as possible. The concrete floors were mainly supported by the building's core, which contains the two staircases and the elevator shafts, and also by a series of columns in the edges of the slabs. However, as a result of Gehry's design, and mainly because of zoning regulations which required that building floors be recessed in order to enable sunlight to reach the street level, all the floor perimeters are different from each other. Therefore, Silivian Marcus, the chairman

Figure 3-15: On the left. Floor plan of levels 9-22 with core and perimeters columns colored in red.

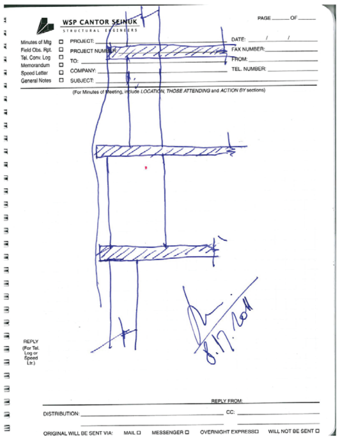

Figure 3-16: The sketch of "walking the columns" solution by Silivian Marcus.

of WSO Cantor Seniuk, the structural engineers of the project, came up with a solution which he called "walking the columns". [ii] In this method, the columns in the buildings perimeter go up to the 16th floor with no interruption and from the 17th to the 20th floor the thickness of the columns is tripled toward the building's interior. Tripling the columns' thickness allows the transfer of the vertical loads from the upper level columns. Using the "walking the columns" solution, Silivian Marcus managed to avoid "slop columns," which would have been very expensive. [35]

Figure 3-17: The concrete structure with the different perimeters in each floor with aluminum embeds for hanging the stainless steel panels.
One can notice that the columns are with changing thickness to reduce the lauds from the upper levels.

3.2.5
FLOOR CONSTRUCTION

As mentioned above, the perimeters of each floor are different from each other. Sobara Construction Corp (SCC), the concrete structure contractor, used the "flying foam" method to build the concrete floors -- i.e., a wood frame extended the actual length of the floor, which enabled the workers to nail to it flexible aluminum strips. The exact location of the aluminum frames was determined using an advanced survey system based on GPS technology. The aluminum frames were reusable. [36]

[ii] Slop columns are columns which lean diagonally

[35] Blair Kamin, "Gehry's Pleasantly Quirky Tower," Chicago Tribune, August 26, 2011, http://articles.chicagotribune.com/2011-08-26/entertainment/ct-ae-0828-kamin-gehry-spruce-street-20110827_1_frank-gehry-hotel-tower-skyscraper

[36] Nadine M. Post, "New York's Tallest residential Tower Is Frank Gehry 'Demystified' Team Uses Collaboration and Digital Tools to Produce Architect's Most Expensive Draped Façade," Engineering News Record, 29 March 2010: 30.

3.2.6
THE EFFECT OF THE 2008 CREDIT CRISIS ON THE CONSTRUCTION OF THE PROJECT

The real-estate market is so volatile it is possible for the construction of a building to begin when the market is in one condition and end when it is in another. The initial design of the building in 2003 divided the building into 38 lower floors of rental apartments, and 38 upper floors of condominiums. [37] In 2006, Forest City Ratner Companies (FCRC) realized that the prices of condominiums in New York had peaked, but that they were expected to go down by the time that the construction of the building was completed. On the other hand, it was projected that rents in New York would continue to rise; therefore, the upper floors were converted into rental apartments and the layouts of all the floors were modified to contain more units. [38]

As a result of the credit crisis of 2008, FCRC had to find additional ways to cut construction costs. Therefore, FCRC forced the unions to re-negotiate new salary conditions for the project's on-site workers. In March 2009, when the building frame reached its 37th level, Bruce Ratner halted construction work for two months, threatening to complete the building at its current height. Since at the time, there was a very small number of construction commissions in the New York area, the unions agreed to a one-year wage freeze and to cut on their benefits, which led to a reduction of around 20% in constructions costs. [39]

3.2.7
THE FLAT FACADE FACING BEEKMAN STREET

Although the shiny rippled envelope is the most significant characteristic of the building, the facade that faces Beekman Street is completely flat. In an interview with the British newspaper, *The Guardian*, Gehry admitted that the initial design had wavy panels all over the building, but that he was asked to flatten one facade for marketing reasons. When FCRC saw the wrinkled apartments were more popular among the renters, they asked Gehry to return

[37] Ibid,

[38] Blair Kamin, "Gehry's Pleasantly Quirky Tower," Chicago Tribune, August 26, 2011, http://articles.chicagotribune.com/2011-08-26/entertainment/ct-ae-0828-kamin-gehry-spruce-street-20110827_1_frank-gehry-hotel-tower-skyscraper

[39] Nadine M. Post, "New York's Tallest residential Tower Is Frank Gehry 'Demystified' Team Uses Collaboration and Digital Tools to Produce Architect's Most Expensive Draped Façade," Engineering News Record, 29 March 2010: 30.

to the original design, but by then Gehry had fallen in love with the new version of the building and was reluctant to go back to the more rippled option. [40] In her article at the Engineering News Record, Nadine Post mentioned that as part of the efforts to reduce construction costs, PNA agreed to a deal in which they cut wage by $5 per hour. However, FCRC refused to disclose more details on this new agreement. [41] An anonymous source told me that PNA agreed to reduce in their fee, but in return they would produce the facade facing Beekman Street as a flat one.

Figure 3-18: On the left. A working model of the project with wavy panels on the façade facing Beekman Street.

Figure 3-19: On the right. The final result: The flat facade facing Beekman Street.

3.2.8 THE MARKETING AND FINANCIAL SUCCESS OF THE PROJECT

Equipped with all the amenities of a luxury tower, the main target market for the Project on 8 Spruce Street was the young brokers who work in Wall Street, which is six minute walk from the building. By October 2011 500 out of the 600 apartments that were offered for rent were occupied. The rents of the penthouses are expected to be $60,000 per month. In December 2012, one of the biggest pension funds in the U.S. --the Teachers Insurance and Annuity Association - College Retirement Equities Fund (TIAA-CREF) -- valuated the building at record high for a rental building at $1 billion. TIAA-CREF bought from FCRC 49% of the building equity for $250 million. [42]

[40] Jonathan Glancey," Frank Gehry: Dizzy Heights," The Guardian, 5 July, 2011, http://www.guardian.co.uk/artanddesign/2011/jul/05/frank-gehry-8-spruce-street

[41] Nadine M. Post, "New York's Tallest residential Tower Is Frank Gehry 'Demystified' Team Uses Collaboration and Digital Tools to Produce Architect's Most Expensive Draped Façade," Engineering News Record, 29 March 2010: 30.

[42] Craig Karmin,. "Skyscraper? Value of New York Tower Is High." Wall Street Journal, December 11, 2012, sec. NY Real Estate Commercial. http://online.wsj.com/article/SB10001424127887324339204578173712456078752.html.

3.3
THE PORTER HOUSE, NEW YORK, MANHATTAN

Construction: 2002-2003

Architect: SHoP Architects

Developer: Jeffrey M. Brown Associates and SHoP Architects

Structural engineer: Buro Happold

General contractor: Bethel Construction

Zinc panels fabricator: Maloya Laser, Inc.

Location: 66 Ninth Avenue, New York

Stories above ground: 10

Floor area: 51,460 sq ft

Dwelling units: 22[43]

Figure 3-20: The Porter House.

3.3.1
GENERAL BACKGROUND

Located in the Meatpacking District of Manhattan, the Porter House is a mixed-use building with nine stories of 22 condominiums and one street level floor of retail. The project was designed by New York based firm, SHoP Architects, which carefully restored the facades of a 1905 brick warehouse built for wine importer, Julius Wile, and was later owned and occupied by a furniture manufacturer. ShoP Architects added to the existing 30,000 sq ft of the warehouse another 20,000 sq ft in four new stories, which were covered with a

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[43] Architecture-page, Porter House, August 21, 2006, http://www.architecture-page.com/go/projects/porter-house__all

system of black zinc panels combined with rectangular light boxes and windows. The length dimensions of the panels, light boxes and windows were different from each other. This difference created a reaction to the heaviness of the warehouse, especially when accented by the dynamism of the zinc facades. [44]

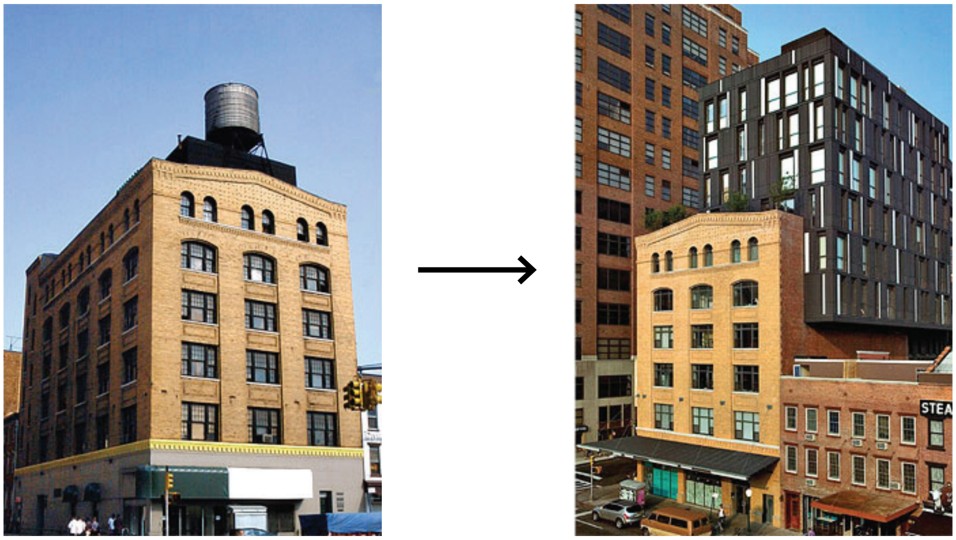

Figure 3-20: The Porter House. “Before & After.”

3.3.2
THE CONDITIONS THAT LED TO THE COMMENCEMENT OF THE PROJECT

The Porter House was the first project in which SHoP Architects acted not only as designers but also co-developers. In their book *Out of Practice*, SHoP Architects stated that architects “need to put their skin in the game” in order to reclaim their status in the construction industry, a status which had been deteriorating since the end of the Second World War. SHoP Architects make the case that by sharing the burden of the financial risk, architects can not only reclaim part of the project’s revenues and have a chance of dramatically increasing their income, they can also have more input on the projects they design. [45]

In his lecture in the California College of the Arts, Gregg Pasquarlli, a principal and one of the founders of ShoP Architects, described the process of how the purchase of the warehouse came to be. At the beginning there were twelve developers who wanted the property. Out of the twelve, only nine developers had the required

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[44] Josh Barbanel, ”Condominium Project in Meatpacking District; Modernistic Addition Rises over Century-Old Warehouse” New York Times, May 25, 2003.

[45] Christopher Sharples, Coren Sharples, William Sharples, Kimberly Holden, and Gregg Pasquarelli. SHoP: Out of Practice. New York: Monacelli Press, 2012

funding to buy and transfer the air rights from the two adjacent historic buildings to the warehouse. Therefore, they were able to offer a higher price for the property. However, zoning regulations required a certain height limit and a setback from the street, which limited the number of square feet that could be transferred to the top of the warehouse. From the nine remaining developers, only three were able to build a cantilever of four floors in the back side of the building, which would enable them to follow the zoning regulations and also to add more built area. The proposed cantilever increased the potential revenue of the project, which allowed those three developers to make a higher offer for the warehouse. However, the cooperation between SHoP Architects and the project's structural engineers from Buro Happold resulted in a structural solution that enabled a six-floor cantilever. This design also proposed a longer cantilever than the other developers. This small difference in built area created enough projected

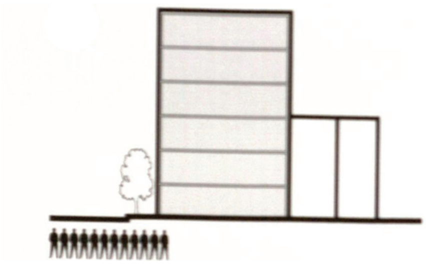

Figure 3-21: "Twelve developers proposed using the exiting building for condos."

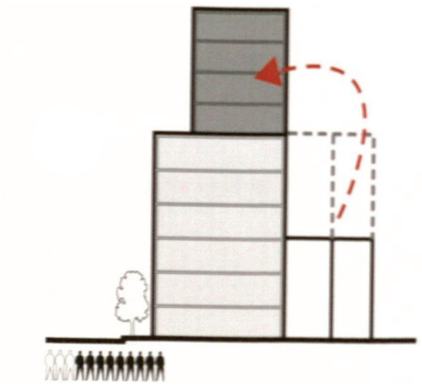

Figure 3-22: "Nine developers proposed a transfer of the adjacent air rights."

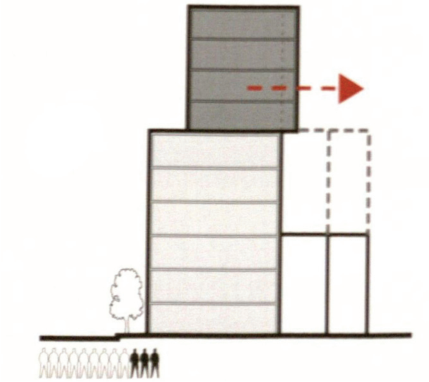

Figure 3-23:"There developers proposed modest cantilevering the new floors."

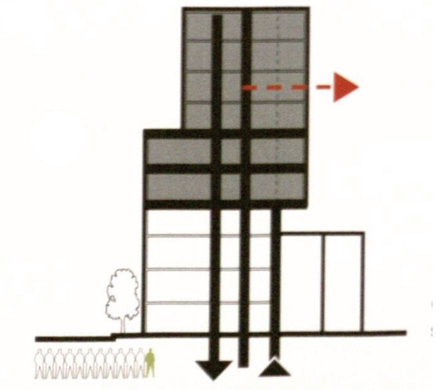

Figure 3-24: " Only SHoP Architects proposed a six-floor cantilever."

revenue to enable SHoP Architects to win the bid for the desired warehouse. Since initially SHoP Architects did not have the capital that was required for the project, they entered into a joint venture with one of their previous clients, Jeffrey M. Brown Associates, acting not only as the architects of the project but also as minority partners.[46]

3.3.3 THE STRUCTURAL SOLUTION

The structural aspects of construction are crucial when adding floors to an existing building, since the original structural system has not usually been designed to carry the extra load of the additional floors. This is especially true when dealing with an old building, when usually there is little information about the condition of its structural system. This uncertainty can sometimes lead to unexpected increases in construction costs, which can cause the termination of the project.

In an on-line interview which was conducted by the author of this thesis, Cristobal Correa, an associate principal in the New York office of Buro Happold, described the measures that were taken in the design process for the new structural system of the Porter House. In the first stage of the structural design," a review of the soil [on site] was conducted, the existing foundations were inspected, and the existing steel and the brick were tested."[47] However, as construction started, "the building began to lose its structural integrity," since the building had 22-inch-thick brick walls and 98-year-old wood beams.[48] Since the original wood piles of the building were found to be rotten, new foundations resting on 27 mini-piles had to be poured.

According to Cristobal Correa, the new design had a "completely new steel structural core in order to resolve lateral loads." The core location was determined primarily to accommodate the

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[46] Gregg Pasquarlli, the California Collage of the Arts(CCA) Architecture Lecture Series, the California Collage of the Arts, February 16, 2009, http://www.youtube.com/watch?v=Ht9Gkr5H358

[47] Cristobal Correa, interview by Shaul Goldklang, April 17, 2012.

[48] "The Porter House", Building Design+ Construction, retrieved February 29, 2012, http://www.bdcnetwork.com/porter-house

architectural requirements and also to avoid excessive torsion of the building. [49]

The last row of columns to the south acts as a three story high Vierendeel truss. [iii] The use of the Vierendeel truss did not interrupt the floor layouts, and at the same time enabled SHoP Architects to hang an eight-foot-long cantilever, which was longer than had been proposed by other developers. These extra feet of built area in each of the six floors of the new addition gave SHoP Architects the added value to win the bid for the warehouse. [50]

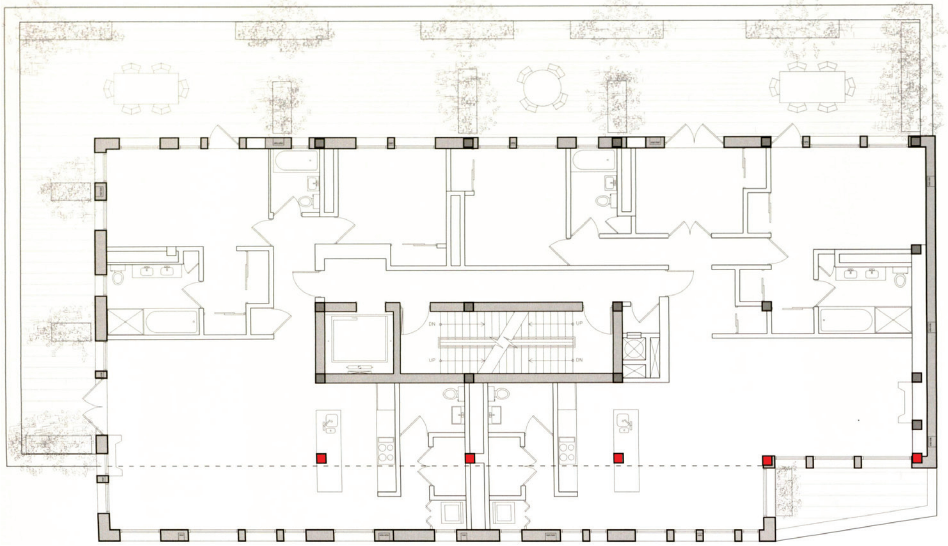

Figure 3-25: The plan of the addition first floor, with the Vierendeel truss's columns marked in red.

3.3.4
THE DESIGN PROCESS OF THE BUILDING ADDITION ENVELOPE

The four-story addition to the warehouse was covered with a system of 4,800 black zinc panels combined with light boxes and windows. From the early stages of the design process SHoP Architects collaborated with Maloya Laser Inc. (MLI), the manufacturer of the panels, taking into consideration the fabrication and assembly constraints. SHoP Architects approached MLI based on previous acquaintance between Jonathan Malle, the project manager at SHoP Architects, and Reto Hug, the president of MLI. Moreover, MLI had successfully fabricated graphic exhibition panels for the American Museum of Natural History in New York, proving that MLI understood the design requirements of architectural projects. [51]

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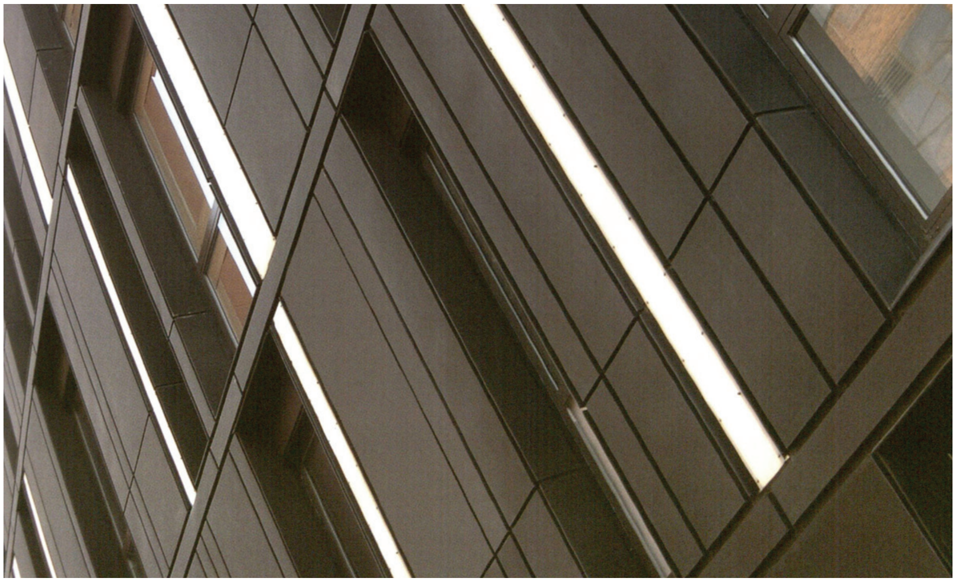
[49] Cristobal Correa, interview by Shaul Goldklang, April 17, 2012.

[50] Gregg Pasquarlli, the California Collage of the Arts(CCA) Architecture Lecture Series, the California Collage of the Arts, February 16, 2009, http://www.youtube.com/watch?v=Ht9Gkr5H358

[iii] A Vierendeel truss is a truss with rectangular voids.

[51] Reto Hug, interview by Shaul Goldklang, April 18, 2012.

Figure 3-26: A close up on the zinc panels system combined with light boxes and windows.



In an interview conducted by the author of this thesis, Reto Hug, the president of MLI, described the design process of the panels. SHoP Architects bought 1000 sheets of 3m X 1.5m alloyed zinc from VM Zinc, a company from France, where, at the time, most zinc came from. The type of material and the size of sheets were based on the technical capabilities of MLI to cut and bend the zinc, and also on the projected tolerance between the panels. Zinc is considered as a soft metal which is relatively easy to bend. [52] Moreover, "the zinc [sheets] were pre-weathered and did not require galvanizing or painting."[53] A larger size of the zinc sheets would have been extremely expensive, and would also have limited ShoP Architects to a small number of fabricators that would have charged an enormous fee for this unique commission.

Figure 3-27: On the left. A laser-cutter machine.

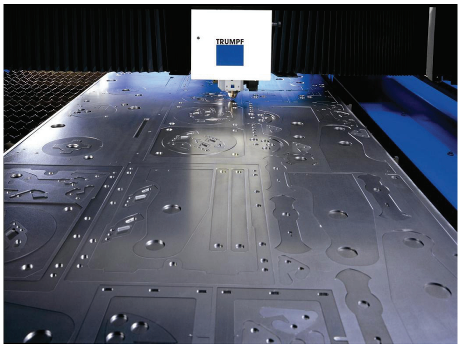


Figure 3-28: On the right. A CNC bending machine.

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[52] Ibid,

[53] Architecture-page, Porter House, August 21, 2006, http://www.architecture-page.com/go/projects/porter-house__all

There were eleven types of panels, and each type had hundreds of variations which summed up to a total number of 4,800 panels. [54] There were four types of floor-to-ceiling-height windows, and two types of light boxes, a thin one and a thick one. The light boxes are monitored by a timer, so they glow softly at dusk, and turn off at midnight. [55]

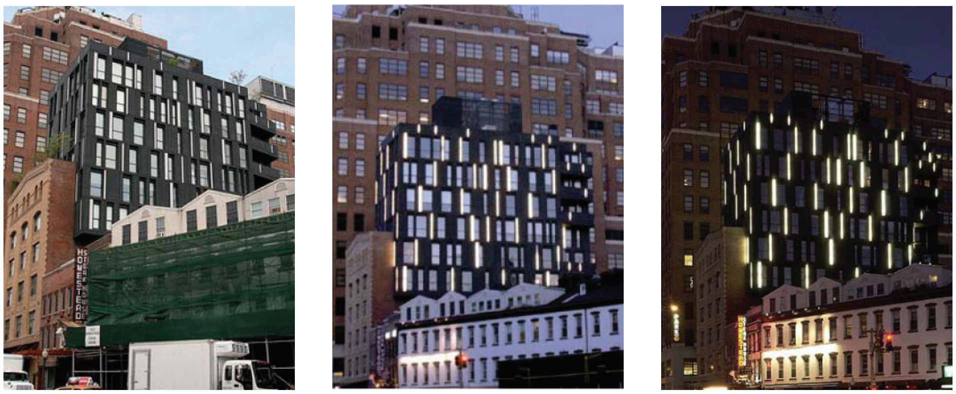


Figure 3-29: The Change in the intensity of the light boxes according to the time of day.

All the envelope segments were modeled in SolidWorks®, which enabled MLI and SHoP Architects to look for overlaps between the zinc panels. After the final version of the 3D model was approved, the dimensions of the panels were imported from SolidWorks® to Excel spread sheets. An algorithm was used to automatically arrange the panels on the zinc sheets in a way that minimized material waste. Once all the files were set, the fabrication process was relatively straightforward. The panels went directly to the laser cutter from the spreadsheets, avoiding the need to produce thousands of 2D drawings, thus saving on paper waste and eliminating mistakes that usually occur when transforming a 3D model to 2D shop drawings.

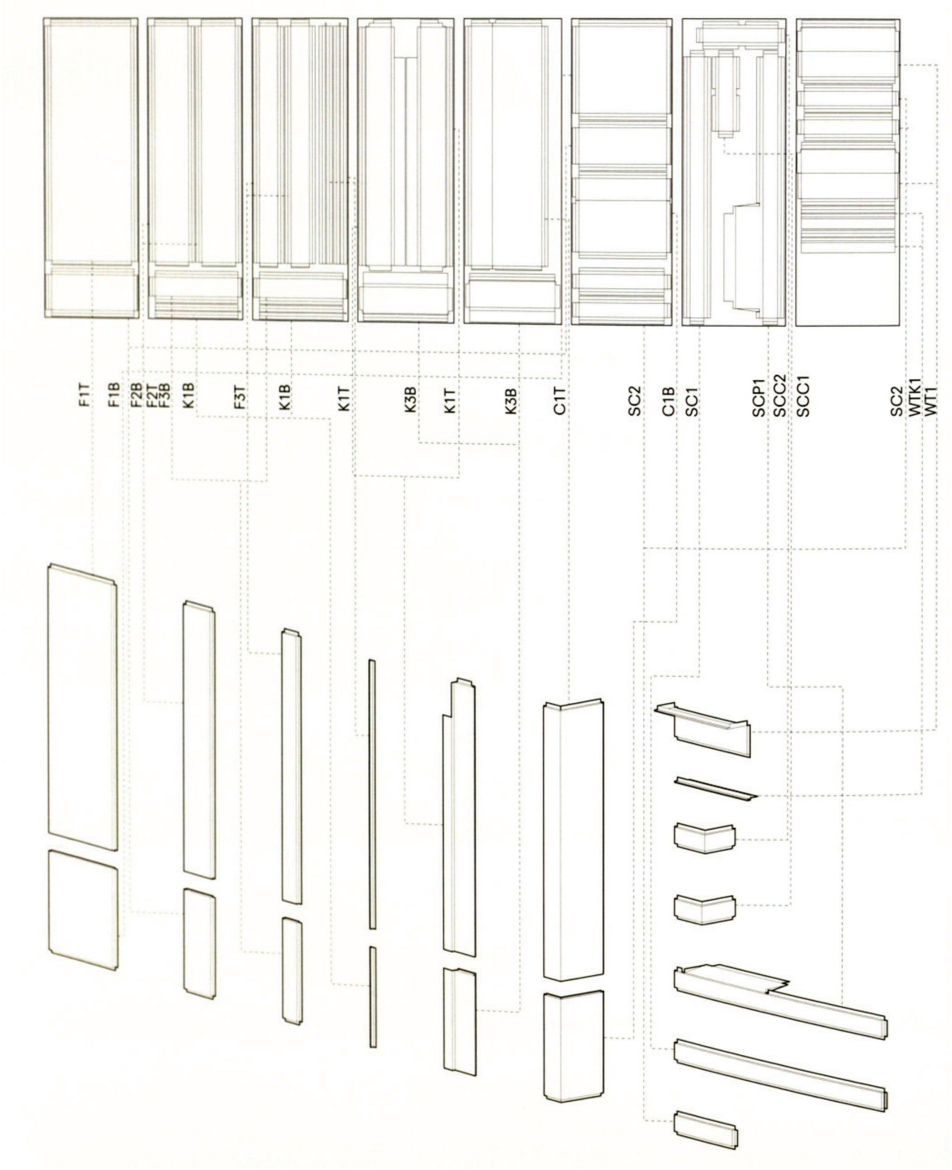
All the panels were labeled in order to mark where each one of them needed to be screwed into a system of aluminum rails, so that no special training was needed to assemble the panels system. However, according to Reto Hug, it took some time to find a sub-

[54] Reto Hug, interview by Shaul Goldklang, April 18, 2012.

[55] Gregg Pasquarlli, the California Collage of the Arts(CCA) Architecture Lecture Series, the California Collage of the Arts, February 16, 2009, http://www.youtube.com/watch?v=Ht9Gkr5H358

contractor who would agree to install the panels at a reasonable price, since the job was quite different from a common commission. The panel was assembled from the south facade to the east. [56] However, the building's corners were left off, and only after all the panels had been installed were final measurements taken and the last panels fabricated and assembled. By assembling the elements in this manner, there was no issue of dealing with the tolerances at all.[57] Because the panels were acting as a rain screen, there was no need to water-proof them. [58]

Figure 3-30: The panels as they were organized on the zinc sheets, and in their final formation.



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[56] Reto Hug, interview by Shaul Goldklang, April 18, 2012.

[57] Gregg Pasquarelli, "Versioning" 2013. Harvard University, Harvard Graduate School of Design, http://www.youtube.com/watch?v=CGF63pr4h64&feature=youtube_gdata_player.

[58] Reto Hug, interview by Shaul Goldklang, April 18, 2012.

3.3.5
THE MARKETING AND FINANCIAL SUCCESS OF THE PROJECT

By taking all the measures mentioned above, SHoP Architects managed to lower construction costs to $202.5 per square foot, which was 10% less expensive than an average residential project in New York, making the entire construction costs of the project $10,420,650.[59] I was not able to obtain the price that was paid for the warehouse itself. In his lecture at the Harvard Graduate School of Design, Gregg Pasquarlli claimed that all the 22 condominiums were sold in four weeks in a price 12% higher than the highest comp sold in the neighborhood until 2003.[60] In 2003 their prices ranged from $735,000 for one bed room to $4.15 million for the penthouse. [61] In 2011, even after the credit crisis of 2008, some tenants managed to sell their condos for twice the price they had paid for them. [62]

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[59] Jessie Scanlon, “Frank Gehry for the Rest of Us,” Wired Magazine , Issue 12.11, November 2004, http://www.wired.com/wired/archive/12.11/gehry.html

[60] Gregg Pasquarelli, “Versioning” 2013. Harvard University, Harvard Graduate School of Design, http://www.youtube.com/watch?v=CGF63pr4h64&feature=youtube_gdata_player.

[61] Josh Barbanel,” Condominium Project in Meatpacking District; Modernistic Addition Rises over Century-Old Warehouse” New York Times, May 25, 2003, http://www.nytimes.com/2003/05/25/realestate/postings-condominium-project-meatpacking-district-modernistic-addition-rises.html

[62] Sara Polsky, “Banker-producer Hopes for Big Profit on Porter House Condo,” Curbed New York, April 12, 2011, http://ny.curbed.com/archives/2011/04/12/bankerproducer_hopes_for_big_profit_on_porter_house_condo.php

LESSONS LEARNED

4

This section of the thesis will analyze the two case studies which were described in chapter three, and use them to highlight the factors that played a crucial role in the realization of commercial real estate projects that employ a mass-customized envelope system. It is important to note that the design and construction processes of these two projects do not represent the norm in the mainstream construction industry. Furthermore, this thesis argues that the design for manufacturing and assembly (DFMA) processes of the mass-customized envelope systems described in the two case studies needs to become the standard in the mainstream construction industry, not only in order to make mass-customized envelope systems more common in commercial real estate, but also to improve the quality of current construction processes in general.

One might assume that the obstacles to realizing mass-customized envelope systems in commercial real estate lie in the fact that current fabrication technologies of mass- customized elements in architectural scale are beyond the budget frame of typical commercial real estate projects, even in high-end class A office building or luxury condominiums buildings. While there might be some truth to this claim, analysis of these two case studies (and seven more projects which are not described in this thesis) shows that many of the challenges also lie in the cultural and organizational conventions of the mainstream construction industry. Gehry and SHoP Architects realized that they needed to disregard those conventions and come up with different design processes in order to successfully execute real estate projects that employ mass customized elements. In later chapters, the thesis will show that most of Gehry and SHoP Architects design processes for the projects in the two case studies are very similar to the Design for Manufacturing and Assembly methods which are used in the aircraft industry.

4.1

THE KEY ROLE OF BUILDING INFORMATION MODELING

Building Information Modeling (BIM) played a crucial role in the successful execution of the buildings described in two case studies. BIM is 3D modeling software that enables multiple users to create and work on the same project file. Each component of the model contains parametric attributes, thus the 3D model is not just a simplistic representation of the project, but also allows to the project team to conduct different types of analyses such as costs easements and climate analysis. The parametric attributes enable the project team members to update the drawings -- which can be revised automatically according to the 3D model -- more swiftly than with 2D CAD software. Often the BIM model is used to find conflicts between the various systems in the building -- for example, conflicts such as those between the air condition shafts and the structural system. In both case studies, BIM was used as part of the design process: in the Project on 8 Spruce Street, the BIM Model was used to refine the panels' geometries so they could be manufactured at a lower cost,[63] and in the Porter House, the BIM Model allowed SHoP Architects to write a special algorithm which distributed the panels on the building facades. [64]

Figure 4-1: On the left. Part of the 8 Spruce Project mass-customized envelope system (without rain screen).

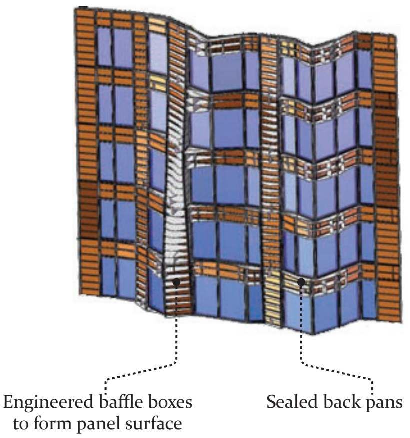
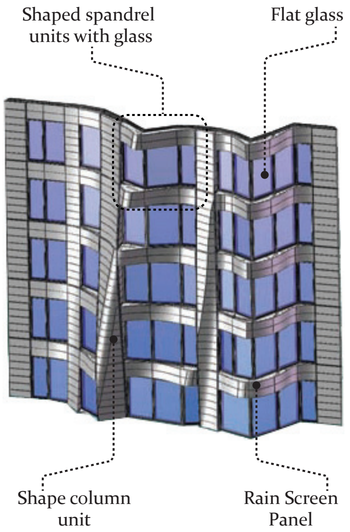


Figure 4-2: On the right. Part of the 8 Spruce Project mass-customized envelope system (with rain screen).



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[63] Emily Carr, interview by Shaul Goldklang, April 4, 2012.

[64] Gregg Pasquarelli, "Versioning" 2013. Harvard University, Harvard Graduate School of Design, http://www.youtube.com/watch?v=CGF63pr4h64&feature=youtube_gdata_player.

In a typical commercial real estate development, the subcontractor--meaning the manufacturer and the installer -- of the curtain wall is responsible for the production of the curtain wall's shop drawings which show exactly how all the elements of the curtain wall are going to look and how they are going to come together. Shop drawings are used for quality assurance and for fabrication of curtain walls elements. The manufacture of envelope systems assembled from thousands of panels that were different from each other would have been almost impossible to accomplish without the aid of BIM.

In both of the projects, BIM was used to identify design mistakes in advance; dealing with them during the construction phase would have been difficult and expensive. The direct connection between the BIM software and the Computer Numerical Control (CNC) machines, which were used to fabricate the panels, saved time and eliminated paper waste. In both projects, BIM was used to minimize the manufacturing costs and to optimize the use of the material. Therefore, the implementation of mass-customized elements in residential buildings is dependent on the promotion of the use of BIM not only by architects but also by other parties who are involved in the creation of the building, such as consulting engineers and fabricators.

However, one problem posed by the use BIM has is that on-site workers are still not used to functioning without paper drawings. This problem can be overcome by using tablet applications which can enable on-site workers to retrieve any drawing of the building in any format that they wish, whether in the form a 3D BIM model or a 2D drawing.

In her 2012 master's thesis at MIT -- *User Innovation in Digital Design and Construction*-- Carolina Soto describes the expansion rate of the use of BIM software in the AEC industry:

> Surveys conducted across the Architecture, Engineering and Construction (AEC) industry in the US indicate that architects, contractors, engineers and owners using BIM have grown from a 28% in 2007, to a 49% in 2009. Similar surveys conducted in United Kingdom, France, and Germany indicate that, by 2010, 36% of the participants had adopted BIM. [65]

Although the use of BIM is becoming more and more common, it is still not the main method used to produce building drawings in the AEC industry.

4.2
DESIGN FOR MANUFACTURING

4.2.1
MATERIAL SELECTION

In both building projects analyzed in the case studies, the architects conducted an extensive study early on in the design process as to what type of alloy would be suitable for the project by connecting directly to material suppliers. By reaching out directly to stock suppliers, the architects were able not only to learn firsthand about the materials' properties, but were also able to avoid brokerage fees and negotiate for wholesale prices, thus saving money on material costs.

The architects took into consideration what metal type would better serve their design intentions, and at the same time would also accommodate the manufacturing technical capabilities. The dimensions of the metal sheets were dictated by the size of the manufacturers' laser cutters and CNC bending machines. The panels' alloy type was determined by the required strength and corrosion resistance properties of the panels and the ability to bend the metal sheet which dedicates the production pace of the panels. This "hands-on" approach for selecting the panel materials contributed to the feasibility of the project despite its complexity. This story shows

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[65] Carolina M. Soto-Ogueta, "User Innovation in Digital Design and Construction : Dialectical Relations Between Standard BIM Tools and Specific User Requirements." Thesis, Massachusetts Institute of Technology, 2012.Page: 15. http://dspace.mit.edu/handle/1721.1/72975.

that by proactively addressing the technical constraints of their projects, architects can find ways to cut material costs and shorten production time.

4.2.2
COLLABORATING WITH THE FACADE SUB-CONTRACTORS

Each facade sub-contractor – meaning the manufacturer and sometimes the installer of the envelope system—has his or her own technical requirements in terms of fabrication methods. In order for architects to understand the fabrication capabilities of their envelope system manufacturer, they need to collaborate with them from the very early stages of the design process. In both case studies, this collaboration made the design financially efficient and ameliorated problems during the manufacturing and installation of the facades panels. During the writing of this thesis, I interviewed a number of fabricators, consultant engineers and on-site construction managers. All of them complained that many architects lack knowledge regarding fabrication and assembly constraints. If architects wish to realize their complex designs, they first need to educate themselves about technical issues by working together with fabricators from the initial stages of their design, taking into consideration material properties, machinery technical capabilities, and budget limits.

4.2.3
THE DELIVERY METHOD OF MASS-CUSTOMIZED ENVELOPE SYSTEM IN COMMERCIAL REAL ESTATE.

The process of executing a typical real estate development project begins with the formation of the project's conceptual design and is followed by the retrieval of entitlements and permits from the local planning authorities. By the time the project developer obtains these entitlements and permits, the architect must have completed complete at least 70% of the project drawings so that bid packages can be sent to different contractors and sub-contractors. Usually there are different bid packages for different parts of the building which correlates with the building's construction phasing and requires different sets of construction expertise. In a typical real estate project, there are bid packages for the building's structure, envelope system (including windows), HVAC(Heating, Ventilation and Air Condition), and electrical systems and finishes. Several contractors compete for each package bid, and they are chosen according to their experience, availability (meaning their ability to allocate enough workers to complete the job on schedule) and, most importantly, their estimate of the cost of the job. [66]

When dealing with mass-customized envelope systems, this mainstream project delivery method might conflict with the need of the architect to collaborate with the envelope systems sub-contractor in the early stage of the design process. As mentioned above, in order to successfully execute commercial real estate buildings that employ mass-customized envelope systems, the architect and the envelope systems sub-contractor need to have pre-construction consulting meetings. In those meetings, they discuss the fabrication capabilities and technical requirements of the mass-customized envelope system, and sometimes the sub-contractor prepares mockups to demonstrate his or her manufacturing skills. However, since the bid usually takes place after the preliminary design process, the sub-contractor who provided the pre-construction services can be out-bided by another sub-contractor who will ask for a lower fee, and then the entire preliminary coordination process will have to be abandoned. Another issue that might come up, is that during those pre-construction consulting processes, the sub-contractor may realize that the developer and the architect have no choice but to use his or her service. The sub-contractor can then take advantage of this situation and charge an exaggerated fee for the job. [67]

There are several ways to overcome these problems. First, after several coordination meetings, the facade sub-contractor will

[66] Christopher M. Gordon, *Innovative Project Delivery,* 02.19.2013, MIT.

[67] Christopher M. Gordon, a Senior Lecturer at Harvard Bossiness School and MIT Center of Real Estate, interview by Shaul Goldklang, June 17, 2013.

have gained an understanding of the scope of the work and the technical requirements for manufacturing all the different elements of the envelope system. At that point, the developer might ask the facade sub-contractor for a Guaranteed Maximum Price (GMP) for the mass-customized envelope system. This would mean that the facade sub-contractor would commit to manufacturing the mass-customized envelope at a certain price; the developer could then evaluate whether or not to go forward with the mass-customized envelope system. [68]

Second, if there is enough time, the architect can approach several facade sub-contractors and have a pre-construction meetings with each of them, then send bid packages for only the mass-customized envelope before sending the bid packages for the other parts of the project. In this way, the architect can have the pre-construction services that are crucial for the successful execution of the mass-customized envelope system at a competitive price. [69]

4.2.3.1 INTEGRATED PROJECT DELIVERY

In its *Guide to Integrated Project Delivery,* The American Institute of Architects presented this unflattering study:

> US Bureau of Labor Statistics study shows construction alone, out of all non-farm industries, as decreasing in productivity since 1964, while all other non-farm industries have increased productivity by over 200% during the same period. [70]

While this lack of efficiency is partially rooted in the conservatism that characterizes the AEC industry and its reluctance to adopt new technologies, it is mostly caused by the conventional Design-Bid-Build contract structure. In this structure, each participant in the project signs an individual contract with the

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[68] Ibid,

[69] Ibid,

[70] “The American Institute of Architects - Integrated Project Delivery: A Guide, Contract Documents.” Page 3. Accessed June 21, 2013. http://www.aia.org/contractdocs/AIAS077630.

project developer. This contract defines the framework, schedule and compensation between the service provider and the developer. The problem with this system is that each individual player works separately; if something goes wrong during any phase of the project -- and something usually does--no one wants to take responsibility for resolving the problem because to do so will cost money and thus reduce that person's compensation. As a result, finger pointing between the project participants begins, causing losses to the project developer.

The interest of each participant is to keep his or her profit. Therefore, if something goes wrong during any phase of the project --and usually something always goes wrong--no one wants to take responsibility to resolve the problem because it will cost money and thus reduce someone's compensation. Thus, finger pointing between the project participants begins, causing losses to the project owner. In many cases these mutual accusations end up in an arbitration process that costs even more, not to mention the damage to the project itself, which may result in the project's not being finished. [71]

In order to increase productivity in the AEC industry, in 2007 The American Institute of Architects (AIA) in collaboration with the AIA California Council published T*he Integrated Project Delivery (IPD) Guide*; this was followed in 2008 by a Standard Form of Tri-Party Agreement for Collaborative Project Delivery. [72] The purpose of the IPD method is to create a positive atmosphere of trust and collaboration between all the project team members in order to add value to the project. This problem-solving attitude is achieved by taking advantage on BIM technology and reconfiguring the conventional structure of the contracts in the AEC industry. [73]

In addition to the fact that the use of BIM improves workflow, enables quality assurance and other analyses, saves time

[71] John L. Tocci, *Innovative Project Delivery*, 03.12.2013, MIT.

[72] Goldberg, Howard G., "The Newest of the New-AIA's Integrated Project Delivery Agreements," The American Institute of Architects. Pages:1-2 http://www.aia.org/aiaucmp/groups/aia/documents/pdf/aiab078756.pdf

[73] John L. Tocci, *Innovative Project Delivery*, 03.12.2013, MIT.

and eliminates paper waste, it also encourages all the project's participants to work together as a team. When using 2D files, the project team members -- meaning the architect and the engineering consultants -- send each other updated versions of their portion in the project design. It is then the responsibility of each team member to revise his or her own design documents accordingly. This method opens the door for slipups when not all the team members receive the same file version, or when some members fail to remember to update their design. Using 2D file systems also requires that participants spend time looking for anomalies, while with BIM models team members all share the same file: potential problems are thus far easier to spot.

B But the biggest improvement that the Integrated Project Delivery (IPD) method offers lies in its flexibility, which allows different professionals to enter the project in its early stages and in the contract structure among all the project participants. The first phase in the IPD method -- the conceptual design of the project -- is the same as in the conventional project delivery methods, but with one major difference. If the project has unique features, key engineering consultants or sub-contractors, they are brought into the design team at this early stage. For example, if the project is a bridge, a structural engineer will be part of the initial design team, and if the project employs a mass-customized envelope system, then the facade sub-contractor will join the design team from the initial stages of the project. In the subsequent phases of the project, the architect and the general contractor can come up with the project schedule and cost estimate. [74]

Another advantage of the IPD method is its contract structure, which aligns the incentives of all the project participants with the fast and successful execution of the project. Based on

[74] Ibid,

the owner's expected return on his or her investment and the target cost of the project, the owner can establish the "profit poll". The compensation is based on preliminary agreements between the owner and the team members, which defines the percentage that each of the team members receives from the "profit poll" according to their level of contribution to the project. Such a contract structure creates an incentive for all parties to work together. If something goes wrong, all team members will understand that any delay in the project, will reduce the "profit poll." Therefore, they will collaborate to in order to resolve the problem as soon as possible to and to minimize loses. Moreover, by working together and increasing efficiency, the project team can increase the "profit poll" and their own reward. [75]

Surveys from The American Institute of Architects' Guide to *Integrated Project Delivery* show that the IPD method results in greater efficiencies:

> "The United Kingdom's Office of Government Commerce (UKOGC) estimates that savings of up to 30% in the cost of construction can be achieved where integrated teams promote continuous improvement over a series of construction projects. UKOGC further estimates that single projects employing integrated supply teams can achieve savings of 2-10% in the cost of construction."[76]

There are three main reasons why Integrated Project Delivery (IPD) seems to be a more suitable delivery method for real estate projects that employ mass-customized envelope systems. First, the IPD method promotes the use of BIM, which, as mentioned above, is crucial for the design and fabrication of mass-customized elements. Second, the flexibility of the IPD method enables the sub-contractor of the mass-customized envelope system to resolve technical and

[75] Ibid,

[76] The American Institute of Architects - Integrated Project Delivery: A Guide, Contract Documents." Page 3. Accessed June 21, 2013. http://www.aia.org/contractdocs/AIAS077630.

cost issues from the early design stages of the project. Third, the IPD method encourages a problem-solving approach that can assist in overcoming unexpected problems that might arise, especially when dealing with projects that have complex geometry and require the use of innovative technology, which is still not commonly used in the AEC industry.

4.3
SELECTING THE SUB-CONTRACTOR FOR THE MASS-CUSTOMIZED ENVELOPE SYSTEM

In both projects examined in the case studies, the manufacturers of the facades mass-customized panels were previously acquainted, either professionally or personally. Permasteelisa North America (PNA) had worked with Gehry on several major projects, so they had not only proved their ability to execute mass-customized envelope systems in large scale projects, but also had communicated well with the architects in Gehry's office. Likewise, in the Porter House project, Reto Hug, the present of Maloya Laser Inc. (MLI), already knew Jonathan Malle, the project manager of the Porter House project in SHoP Architects. Maloya Laser Inc. demonstrated the ability to accommodate themselves to the needs of architects after successfully manufacturing the exhibition panels at the American Museum of Natural History in New York, even though most of MLI's work had been for the aircraft industry.

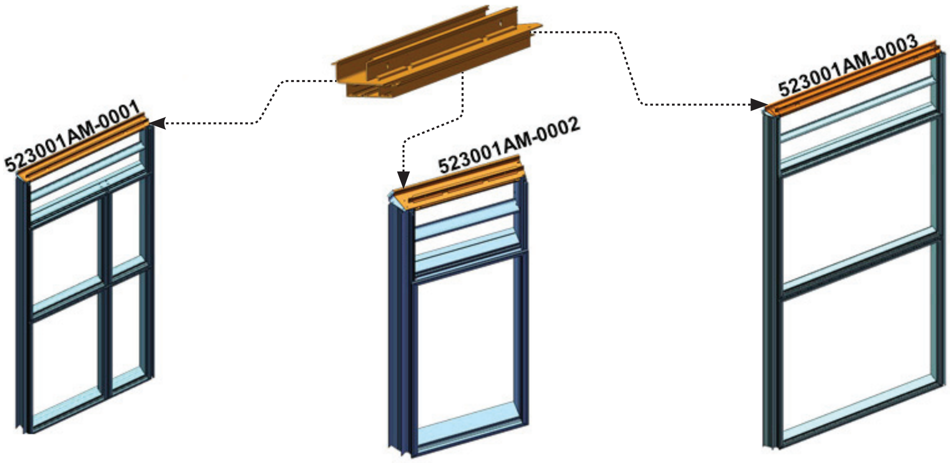
The relationships between players in a large-scaled mass-customization project are clearly important. When obtaining bid offers for the manufacturing of a mass-customized envelope system, the criteria for choosing the right sub-contractor should be more heavily weighted toward previous successful collaboration and proven expertise than toward low pricing. Perhaps the initial expenditure overhead costs will be high, but the owner will have the certainty that the project will be carried out, and that the expertise of the experienced sub-contractor can be relied upon if the project runs into trouble.

4.4
DESIGN FOR ASSEMBLY

In order to ameliorate problems with the installation of the panels, Design for Assembly (DFA) constraints were taken into consideration in the design processes of both projects analyzed in the case studies. Factors such as the size of the crane that carried the panels to the building's upper floors, the dimensions of the trucks that transported the panels to the construction site, the order of the panels' installation, and the technical capabilities of the construction workers and tolerances, were all taken into account in the design of the panels.

The stainless steel sheets in The Project on 8 Spruce Street were imported from Japan and were shaped in Michigan, while the different window frames were manufactured in Biddeford, Maine. All the pieces were shipped to Philadelphia, where they were sub-assembled to panels and were tested for waterproofing, from which they were carried by trucks to the construction site in Manhattan.[77]

Figure 4-3: Part of a window frame part in the 8 Spruce Project which comes in different lengths.



Although most of the panels were different from each other, they were attached to the building's structure in the same manner

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[77] Emily Carr, interview by Shaul Goldklang, April 4, 2012.

as conventional curtain walls. Thousands of aluminum embeds which were implemented in the edges of the concrete slabs enabled adjustment of the panels if there were tolerance inaccuracies in the casting of the concrete slabs. Although the panels were assembled by PNA's New York subsidiary, Tower Installation LLC, a company which had previous experience in installing the curtain wall in IAC headquarters, Frank Gehry's first complete building in New York, PNA engineers designed the panel's assembly process as straightforwardly as possible, so that even a construction worker who had not worked on the IAC building could join the panel's installation team.

In the Porter House project, the zinc panels were attached on a railing system that allowed the panels to shrink and expand under the changing climate conditions. [78] The windowsill panels had a slope of 34 degrees so that pigeon cannot sit on them. [79] As mentioned in page 52 the construction workers did not need special training in order to know how to install the panels, and the order of the panels' assembly took into account tolerance inaccuracies in the panels' installation.

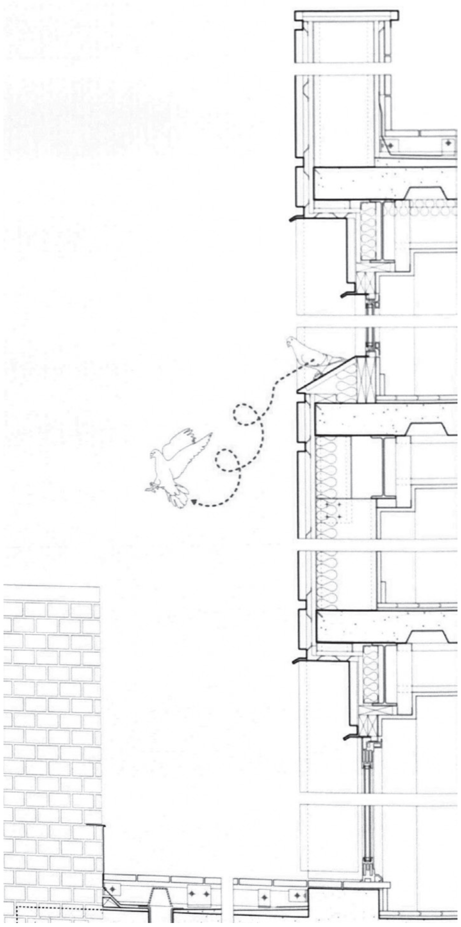

Figure 4-4: Local section of the Porter House showing the special sill panel which was designed to prevent pigeons nesting.

In order to optimize the assembly process of a mass-customized envelope system, all the panels should be assembled

[78] Reto Hug, interview by Shaul Goldklang, April 18, 2012.

[79] Gregg Pasquarelli, "Versioning" 2013. Harvard University, Harvard Graduate School of Design, http://www.youtube.com/watch?v=CGF63pr4h64&feature=youtube_gdata_player.

in the same manner, despite being different from each other. The installation method should be as straightforward as possible, so it that special training is not required. Lastly, the design of the installation system must take into account the tolerance inaccuracies thatz are inherent in the construction industry. In a later chapter, the thesis will outline the key differences between assembly and subassembly processes in the aircraft industry to the AEC industry, and suggest ways in which the construction industry might adapt some of the advances the airline industry has developed.

4.5
SIMPLIFYING THE OTHER SYSTEMS OF THE PROJECT

Clearly, both projects demonstrate the importance of making all systems as easy to install as possible. The structural system of the building and the plumbing and HVAC (Heating, Ventilation and Air Condition) systems should employ the easiest solutions for assembly and construction. As we saw in The Project on 8 Spruce Street, the structural system was a simple “core-and-trigger”; however, the columns at the building perimeter had to accommodate the floor setbacks required by New York zoning regulations. Instead of using diagonal columns whose construction would have been more complex and expensive, the structural engineer came up with the “walking the columns” solution, which simplified the construction and therefore saved money for the project developer.

4.6
THE USE OF RULE BASED DESIGN

As mentioned in chapter two, the purpose of using a mass-customized envelope system in commercial real estate is to introduce a sense of uniqueness and diversity to building facades. By using rule based design, in which an architect defines a set of rules for positioning a limited number of panels in a manner that will make it difficult to detect that the panels repeat themselves, he or she can reduce the number of different elements, thus cutting down on costs, but still keep a sense of variety on the building facade.

An example of how rule based design can cut down on cost and still give a sense of diversity is the brick facade that SHoP Architects designed for the condominium building on 290 Mulberry Street in Manhattan. In this project, zoning regulation required that the building façade be at least 80% brick. SHoP Architects decided to give their own interpretation of the use of brick by designing a system of precast brick panels. They used rule based design to come up with eight different types of precast panels using only a single mold. Thus, SHoP Architects were able to cut down on cost by using only one mold, but at the same time bring uniqueness to the building facade. [80]

Figure 4-5: On the left. The 290 Mulberry Project designed by SHoP Architects.

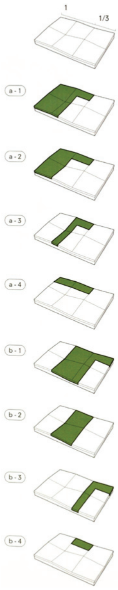

Figure 4-6: In the middle. The eight types of prefabricated brick panels.

Figure 4-7: On the right. The distribution of the panels across the building's facades.

4.7
THE SHORTAGE OF COMPANIES THAT CAN FABRICATE MASS-CUSTOMIZED ENVELOPE SYSTEMS

This chapter of the thesis has addressed the challenges to the realization of mass-customized envelope systems in commercial real estate. The analysis has posited that these challenges are closely related to the cultural and organizational conventions in the mainstream AEC industry, and has suggested ways to overcome them. In the next several paragraphs, the thesis will outline the limitations posed by the fabrication processes themselves, including

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[80] Ibid,

the high manufacturing costs of the elements, and those posed by the fact that only a small number of companies have the technical capability to produce these elements. The remaining section of thesis will attempt to find solutions by looking at the aircraft manufacturing industry.

At the present time, there are only few companies in the AEC industry that have the capabilities to manufacture mass-customized envelope systems for large-scale real estate projects. [iv] This poses two problems for an entrepreneur who wishes to employ uniqueness and diversity in the facades of his or her project. First, the small number of mass-customized envelope systems manufacturers creates a lack of competition in this segment of the market. This situation puts the developer in an inferior position when negotiating an affordable price for manufacturing a mass-customized facade for his or her project.

Second, when there is an unexpected need to cut down on construction costs at an advanced stage of the project, it is very difficult for the developer to bargain with the mass-customized elements fabricator to lower his fee, since it would be almost impossible to replace him with another fabricator. For example, when Bruce Ratner needed to cut construction costs on the 8 Spruce Project, he managed to lower the wages of the unions, but did not succeed in persuading PNA to give up a part of their fee. The lack of fabricators that can manufacture mass-customized elements, especially with complex geometries, leaves developers with very little room to negotiate.

For the same reason, if a manufacturer of the mass-customized elements envelope system should suddenly go out of business during a later phase of the project, it would be almost impossible for a developer to find a replacement -- a situation

[iv] Based on interview with Dennis Shelden Chief Technology Officer in Gehry Technologies, and an associate professor at MIT, here are the names of companies that we managed to came up with that can manufacture mass-customized curtain walls: EXYD form Germany, A-Zanher from the US, Wintech From England, Contract Glaziers from Canada, Sharvain Enclosures from Australia/ New Zealand and Permasteelisa which has global distribution.

that would not occur if all the developer needed to do was to find a new concrete or steel structure sub-contractor. In 2009, SHoP architects were hired by FCRC CEO, Bruce Ratner, to redesign the Barclays Center, a sports arena that is the centerpiece of their mega-development Atlantic Yards project in Brooklyn. SHoP Architects decided to cover the building with 564 mass-customized roosted-steel panels. In December 2011, the panels' manufacturer, ASI Ltd., went bankrupt and the bank closed the factory in Indianapolis, when only third of the panels were produced. However, as part of ASI Ltd's contract with Forest City Ratner (FCRC), ASI Ltd, were required to have a surety, which was with Ohio Farmers Insurance Co. (OFIC). Forest City Ratner (FCRC) and Hunt, the project's general contractor, demanded that OFIC reimburse them for the full sum of the contract with ASI Ltd, which was $32.4 million. Therefore, Ohio Farmers Insurance Co. (OFIC) had no choice but to buy out the bank's position and reopen the plant, because they could not find another manufacturer that had the technical capabilities to finish the job on schedule. [81]

Figure 4-8: The Barckays Center, Brooklyn New York, designed by SHoP Architects, 2012.

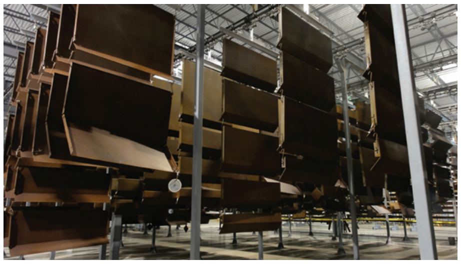

Figure 4-9: On the left. The pre-weathering process of the mass-customized panels.

Figure 4-10: On the right. The installation process of the panels.

[81] "Reshaping of Barclays Center Arena Made Possible By Collaboration, Digital Tools | ENR: Engineering News Record | McGraw-Hill Construction." Accessed June 26, 2013. http://enr.construction.com/buildings/building_types/2012/0716-Reshaping-of-Barclays-Center-Arena-Made-Possible-By-Collaboration-Digital-Tools.asp?page=2.

Clearly, there is a need to bring new players into the construction industry who are familiar with the manufacturing processes of pre-fabricated complex geometries in architectural scale; SHoP Architects did this when they hired Maloya Laser Inc. (MLI) to fabricate the zinc panels of the envelope for the Porter House. In the following chapters, this thesis will argue that aircraft manufacturing companies such as Airbus and Boeing can become game changers in the construction industry. The thesis will also identify the unique characteristics of the aircraft manufacturing industry that make it suitable for penetrating the AEC industry as mass-customized envelope system fabricators. Moreover, the thesis will outline the incentives for the aircraft manufacturing companies to do this.

4.8

THE HIGH COST OF THE FABRICATION OF MASS-CUSTOMIZED ELEMENTS IN ARCHITECTURAL SCALE

It was impossible to obtain the exact costs of the mass-customized envelope systems of the building projects analyzed in both cases studies. Dennis Shelden, Chief Technology Officer in Gehry Technologies, has stated that the cost of the envelope panels of the 8 Spruce Street project was not more expensive than a conventional curtain wall; however, it is necessary to remember that design compromises were made in order to realize the project in a competitive budget (like flattening all the panels which are facing Beekman Street). Even so, it is reasonable to assume that the fabrication cost of mass customized elements in architectural scale will be higher than the manufacturing of mass-produced ones, and therefore developers may be more reluctant to go with building designs that employ such mass-customization. There is a need to find ways to reduce manufacturing costs of mass-customized elements.

In chapter seven the thesis will look into different fabrication processes that are used in the aircraft industry to manufacture the skin of the fuselage and the wings of airplanes. The thesis will also suggest ways to adjust these fabrication processes to the standards of the construction industry, thus lowering manufacturing costs. This thesis does not intend to come up with new fabrication technologies, but rather to suggest ways to adapt existing ones in order to accommodate the needs of the construction industry.

THE REASONS FOR LOOKING INTO THE AIRCRAFT MANUFACTURING INDUSTRY IN ORDER TO FIND WAYS TO ENABLE THE IMPLEMENTATION OF MASS-CUSTOMIZATION IN COMMERCIAL REAL ESTATE

5

The previous chapter categorized the challenges to the widespread use of mass-customization in commercial real estate into three main areas. First, the common methods of mainstream real estate project design and delivery currently in practice in the Architecture, Engineering and Construction (AEC) industry are inadequate to the design process of mass-customized envelope system. Second, there is shortage of companies that are able to fabricate mass-customized envelope systems. This shortage increases the risk level of a real estate project that employs mass-customized elements; moreover, the lack of competition makes the initial costs of mass-customized envelope systems high. The third challenge is the high cost of fabricating mass-customized elements in architectural scale.

This thesis argues that there are three ways to bring the aircraft industry into the AEC industry. First, if aircraft manufacturers can become fabricators of mass-customized envelope systems, the competition in this market share will increase. Second, aircraft manufactures have vast experience in fabricating and assembling mass-customized elements for their airplanes' fuselage and wing skins. Manufacturers in the AEC industry can look into the fabrication processes and tools that are being used in the aircraft industry, outline the similarities and differences in terms of technical requirements between the two industries, and then find ways to adapt the production methods of the aircraft industry to those of the construction industry. Third, professionals in the AEC industry can improve their design for manufacturing and assembly processes by looking at how the same processes are carried out in the aircraft industry; this analysis can help improve efficiency and productivity in the AEC industry. This part of the thesis will also explain why the aircraft manufacturing industry is the most suitable industry for the

AEC industry to look at.

5.1
VAST EXPERIENCE IN MANUFACTURING ELEMENTS IN ARCHITECTURAL SCALE

Scale plays a significant role in the complexity and the cost of manufacturing and assembly processes. The bigger the scale of the product to be produced, the more difficult and expensive it will be to manufacture. The panel size of a standard curtain wall can easily reach 3m X 2m. Therefore, it would be difficult to bring into the construction industry industries like the furniture or the automobile industry, whose their production lines are not designed to accommodate parts on such a large scale. Moreover, it is important to take into account the production pace of each industry: if the production pace is too fast, as it is in the automobile industry where a car is being produced every five minutes, it will be technically difficult to try to adapt this industry to the manufacture of the mass-customized elements of a building, which usually take more time to produce. [82]

Moreover, the complexity of producing large-scale items requires large manufacturing machines. The skin panels of the fuselage and wings of an aircraft reach several meters; aircraft manufacturers are thus already equipped with large-scale water-jets, laser cutters, CNC-bending and tooling machines. Therefore it would be easier for them to transition to fabricating mass-customized envelope systems than it would be for industries such as the automotive or furniture industries, whose their production lines are not designed to process parts on such a scale.

Aircraft manufacturing companies also have expertise in moving large-scale elements, a complex procedure which takes a great deal of time. Aircraft manufacturing companies are equipped with the proper cranes and jigs to move large-scale parts around the factory, and as a result of years of experience, they have learned how

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[82] Daniel E. Whitney, Senior Lecturer in Engineering Systems, Emeritus, MIT, interviewed by Shaul Goldklang, May 3, 2013

to minimize the number of moves necessary for a large-scale panel.

Figure 5-1: A crane transports a part of the Airbus A380 fuselage, in the final assembly line factory in Hamburg, Germany.

Aircraft manufacturers also have highly developed logistical capabilities in shipping large-scale parts from one location to the other. [83] The vast majority of commercial aircraft are not manufactured in one location. Instead, the different parts of the airplane such as the fuselage, wings, cockpit and the empennage are sub-assembled together in different workshops all over the globe, then shipped for final assembly in a single factory. For example, the European consortium Airbus has factories in Europe and Asia; airplane parts are shipped to the Final Assembly Line factories (FAL) in Toulouse or Hamburg. Airbus uses a fleet of five cargo planes named Airbus Beluga (A300-600ST), which can carry wings set and even fuselage parts. [84]

However, the Beluga cannot carry all the parts of the Airbus A380--the biggest commercial plane in the world, which can accommodate 555 passengers; the Beluga can only carry the A380's

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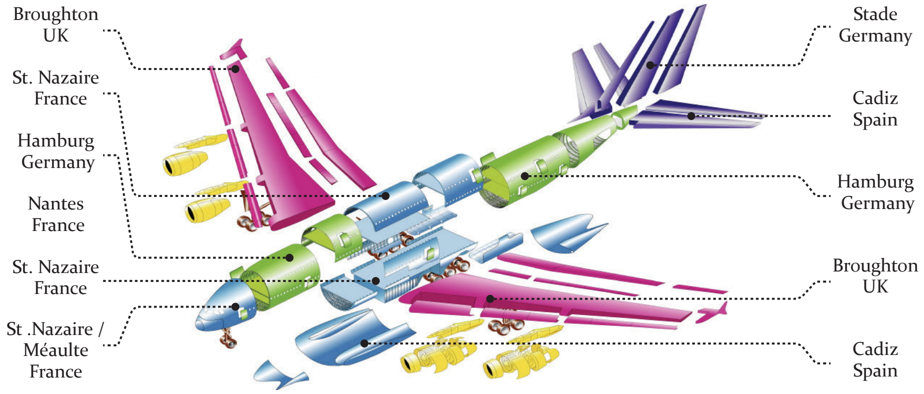
[83] Jacob Goldklang, Chemical laboratory manger and quality assurance supervisor in the Israeli Aerospace Industries, interviewed by Shaul Goldklang, June 1, 2013.

[84] "Transport of Major Aircraft Sections | Airbus, a Leading Aircraft Manufacturer." Accessed July 4, 2013. http://www.airbus.com/company/aircraft-manufacture/how-is-an-aircraft-built/transport-of-major-aircraft-sections/.

Figure 5-2: The distribution of the A380 sub-assemblies labor in throughout Airbus factories all across Europe.



empennage. Airbus had to come up with a complex transportation operation to ship the enormous parts of the A380 from different cities in Spain, Germany, France and the UK to the FAL in Toulouse via land and sea. These, are of course, extreme examples, but they demonstrate that aircraft manufactures are experienced with handling to the complexity that comes with the fabrication of large-scale elements. [85]

[85] Jesus Morales, V.P. A350 Industrial Cooperation & Partnership (former V.P. A380 Transportation),The A380 Transportation Project and Logistics, University of Darmstadt , The 13th Colloquium in Aviation, January 18, 2006.

Figure 5-3: On the top. The loading of the A380's empennage to the Airbus Beluga (A300-600ST).

Figure 5-4: On the bottom left. The use of a raft to transfer a part of the A30 fuselage.

Figure 5-5: On the bottom right. Residents of a small town in France cheering as the A380's cockpit passes through their streets.

One might argue that the railroad manufacturing and ship building industries are also experienced with manufacturing elements in architectural scale, and might be industries that could play a role in the production of mass-customized elements for construction. However, while train carriages are in architectural scale, their skin panels are generally repetitive; sections of an airplane fuselage are by definition different because of the required changes of aerodynamic constraints. Moreover, the hulls of ships are made out of steel, and while the construction industry uses steel structurally, it prefers other, more malleable metals for use with envelopes. To use steel in the mass-customized envelopes is to add another level of difficulty to the construction, and as mentioned earlier, the goal is to make construction/assembly of such systems as simple as possible. The yacht manufacturing industry might be more relevant, since a yacht's hull is made out of aluminum, which is common material for exterior panels in the construction industry.

5.2
THE FAMILIARITY OF AIRCRAFT MANUFACTURERS WITH THE USE OF BIM

As mentioned in chapter four, Building Information Modeling (BIM) played a crucial role in the successful execution of mass-customized envelope systems in commercial real estate developments. Chapter three discussed how BIM is used for the design and fabrication processes of the mass-customized envelope systems of both case studies.

The aircraft manufacturing industry has years of experience working with Computer Aided Design (CAD) and BIM software. Aircraft manufacturers began using CAD software in 1968, mainly for automated 2D drawings.[86] The common software for 2D drawings was Professional CADAM® and for 3D BIM modeling CATIA™ ; both softwares were developed by the French company Dassault Systèmes, which is a part of the Dassault Group that manufactures aircrafts for

[86] Daniel Schrage, and Dimitri Mavris, Georgia Inst. of Technology, Atlanta Chapter DOI: 10.2514/6.1993-3994,Publication Date: 09 August 1993 - 11 August 1993. Page: 11.

military and business uses.[87] During the 1990s, Gehry Partners, LLP, established a subsidiary named Gehry Technologies which modified the CATIA™ into a BIM software called Digital Project Systems™ that accommodates the technical needs of the AEC industry. Digital Project Systems ™ was used by Gehry Technologies in numerous projects, including the Project on 8 Spruce Street.[88]

There are many similarities between the way BIM was used in the buildings in the two case studies described in chapter three and the way aircraft manufacturers use BIM. From the initial stages of the conceptual development of the aircraft, engineers from all the relevant disciplines use BIM to locate conflicts between the different systems and to come up with ways to cut down on manufacturing and assembly costs. The BIM model is also used to fabricate the different pieces of the aircraft. Using tool-path software, the BIM model is connected to computer-controlled machines that carve molds, cut out skin panels, and attach them together using robotic laser welding, friction stir welding. or riveting. Robotic arms are also used for the complex weaving of carbon fibers of elements made out of composites. [89]

The components of the BIM model contain parametric data that define the connection between them, in order to enable a faster update of the model. For example, a BIM model of a wing is made from an upper and lower skin panels that are connected by a grid system of ribs and stringers. The dimensions of each component of the model are determined by its structural application. Therefore, any change in the model will cause the rest of the model to automatically update to accommodate the structural requirements.[90] BIM is also used to conduct numerous types of analyses from weight conclusions to aerodynamics tests, which in the past was expensive and time-consuming since it required the building of a special

[87] Ibid,12.

[88] Dennis Shelden, Chief Technology Officer in Gehry Technologies, interviewed by Shaul Goldklang, June 27, 2012.

[89] "Megastructures Airbus A380 - YouTube." Accessed July 13, 2013. http://www.youtube.com/watch?v=sq9hkoWE9L8&feature=youtube_gdata_player.

[90] Robert Phillips, Robert, Sal Caruso, and Steven Serabian. "Automating the Design and Manufacturing Processes of Aerostructure Components." American Institute of Aeronautics and Astronautics, 1995. doi:10.2514/6.1995-3975.

mockup which was then tested in a wind tunnel. [91]

Aircraft engineers use BAM (Building Assembly Model or 4D BIM software, (meaning BIM software that shows progress across time) to create simulations of sub-assembly and final assembly lines processes to ensure that the sequence of assembly does not cause any conflicts and to be sure that technicians will have the proper access to all the places they need to reach for maintenance purposes. During a part of the design process of the A400M, a militarily transport aircraft, Airbus engineers used Dassault Systèmes' DELMIA to run simulations of the A400M final assembly line process. The reason Airbus engineers chose to use DELMIA for assembly simulation is because they can import files from CATIA™ and vice versa. Boeing also limits all their suppliers and sub-contractors to the use of a certain version of specific software in order to ensure a smooth transition of files. [92]

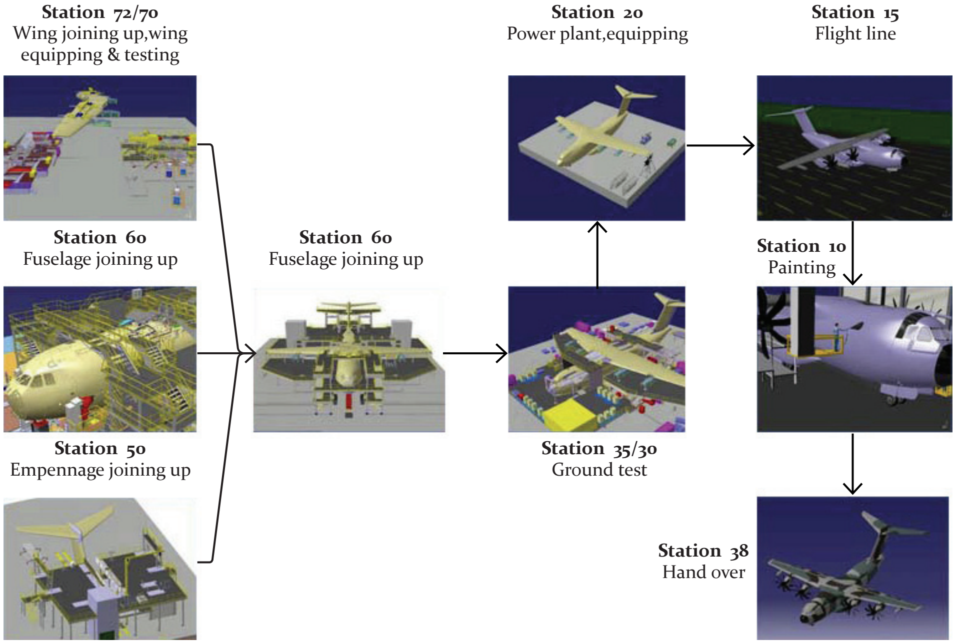


Figure 5-6: A 4D BIM model of the A400M Final Assembly Line (FAL).

While there is a significant difference between creating a virtual simulation for an aircraft assembly process and planning/designing/developing a real estate project, the point is this:

[91] Jacob Goldklang, Chemical laboratory manger and quality assurance supervisor in the Israeli Aerospace Industries, interviewed by Shaul Goldklang, June 1, 2013.

[92] Menéndez, J. L., F. Mas, J. Serván, and J. Ríos. "Virtual Verification of the AIRBUS A400M Final Assembly Line Industrialization." AIP Conference Proceedings 1431, no. 1 (April 25, 2012): 641–648.

aircraft engineers have the technical ability and experience to use Building Information Modeling. Indeed, the aviation industry is even more familiar with the use of BIM than the AEC industry is. It would therefore be reasonable to assume that the use of BIM will not present an obstacle for aircraft manufacturing companies in fabricating mass-customized envelope systems. However, further research needs to be conducted in order to define the needs of the AEC industry from those of the aircraft industry in order to see how 4D BIM software can be utilized most effectively.

5.3
THE GLOBAL PRESENCE OF AIRCRAFT MANUFACTURING COMPANIES

As described in chapter two, intensive urban development is expected to take place in the next twelve years across a number of frontier markets such as China, India and Latin America. The two prominent aircraft manufacturing companies in the world, Airbus and Boeing, have factories, workshops, sub-contractures and suppliers all over the globe, including in China and India. [93;94] This global distribution has several advantages that will enable aircraft manufacturing companies to enter the AEC industry in emerging markets. First, companies like Boeing and Airbus already have established bases of operation around the globe. Secondly, they are familiar with the local cultures: they have already developed connections with the authorities, business communities and even workers unions. Such familiarity mitigates the barriers to entry into frontier marketsSecond, the global spread of Airbus and Boeing of workshops and factories can enable them to build final assembly lines of mass-customized envelope systems in different locations according to the market demands, and save money on shipping.

[93] “Boeing: Presence and Partnerships.” Accessed July 13, 2013. http://www.boeing.com/boeing/aboutus/international/partners.page.

[94] “Worldwide Presence | Airbus, a Leading Aircraft Manufacturer.” Accessed July 13, 2013. http://www.airbus.com/company/worldwide-presence/.

5.4 MOVING BEYOND TECHNOLOGICAL MATURITY

With skyscrapers twisting toward the skies above our major cities and jet airlines continually going in and out of our airports, we tend to think that both the airline and AEC industries are still growing and evolving. However, closer examination shows that both industries have, in fact, matured. Indeed, the aircraft industry is stagnating, and the AEC industry, for all its fancy CNC machines, has not changed much since the 1960s.

There has been no significant technological progress in the commercial aviation industry since the 1980s. In 1975, Boeing started to design the 757 model in order to replace the 707, which had been in service from 1954. However, despite the large investment in research and development, the new 757 did not represent a significant improvement: it carried the same number passengers, went the same speed, and had the same range as its predecessor. It did, however, comply with stricter safety and noise regulations. [95]

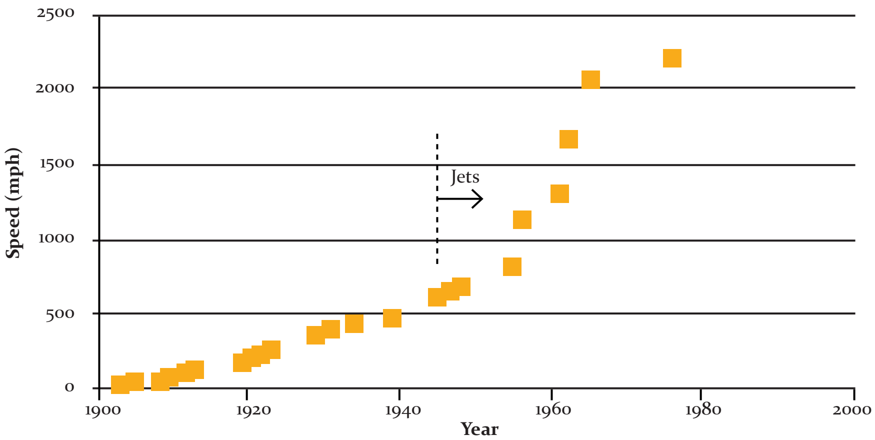


Figure 5-7: The progress of absolute airplane world speed records as another indication for the technological maturity in the aircraft manufacturing industry.

The second sign of the technological maturity of the commercial aviation industry was the economic and environmental failure of the Super-Sonic Transport (SST) planes. There were only two active model types of SST planes, the Concorde (1976-2003) -- which was an Anglo-French collaboration -- and the Soviet (Tupolev) Tu-144 (1968-1975). Boeing was working on its own model,

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[95] J. McMasters, Boeing Co., Seattle, WA; R. Cummings California Polytechnic State University San Luis, California, "Airplane Design as a Social Activity - Emerging Trends in the Aerospace Industry (AIAA)." Chapter DOI: 10.2514/6.2002-516 Publication Date: 14 January 2002 - 17 January 2002: 2-3.

the Boeing 2707, but the plane never became commercially active. While the SST planes carried only a small number of passengers (128), they were able to fly medium and long distances at almost twice the speed of a regular jet plane. However, the manufacturing and maintenance costs of SST planes were extremely high; they consumed an enormous amount of fuel and suffered from a bad reputation as result of accidents. The last flight of the Concorde in 2003 symbolized the technological stagnation of the commercial aviation industry. [96]

Another sign of the technological stagnation in the aviation industry is shrinkage of the number of aircraft manufacturing companies. In 1945, there were 21 commercial and military aircraft manufacturing companies in the US, but by 2005, there were only six.

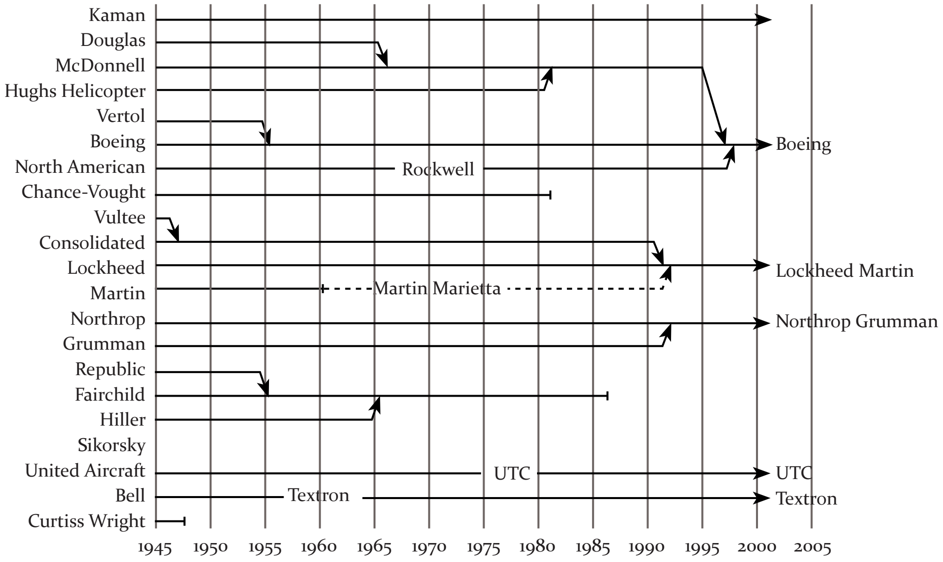

Figure 5-8: Consolidation of US aircraft manufacturers.

The end of the Cold War contributed to the downsizing of military aircraft manufacturers, as did the fierce competition and the inability of engineers to come up with new and better products for the market. In the 1990s, after the Cold War ended, commercial aircraft manufacturers realized that in order to remain profitable

[96] J. McMasters, Boeing Co., Seattle, WA; R. Cummings California Polytechnic State University San Luis, California, "Airplane design - Past, present, and future (AIAA)." Chapter DOI: 10.2514/6.2002-516 Publication Date: 08 January 2001 - 11 January 2001: 7.

in a highly competitive market, they needed to stop trying to build “faster, farther, higher” aircraft and instead aim for ”quicker (to market),better, cheaper” manufacturing processes. [97]

During the same time period, the AEC industry also reached some sort of technological stagnation. CAD and BIM software might be faster and have friendlier interfaces, but their core concepts had not changed much from Ivan Sutherland’s 1963 Sketchpad.[98] Moreover, the notion of buildings that are prefabricated in factories and assembled on site had already been realized several times in history, by Joseph Paxton’s 1854 Crystal Palace and Moshe Safdie’s Habitat in 1967. Finally, much-touted technologies such 3D printing and self-assembly structures are still in their infancy; their application in architectural scale remains in the realm of science fiction.

The argument of this thesis is that instead of trying to develop new construction technologies that will require huge investments in time and money, the AEC industry should try to optimize already existing technologies in order to achieve incremental improvements. Since there are some similarities between the aircraft manufacturing industry and the AEC industry in terms of scale, materials, and the use of design and fabrication computational tools, it make sense for the AEC industry to look into the aircraft manufacturing industry in order to find ways to optimize design and execution processes of commercial real estate projects.

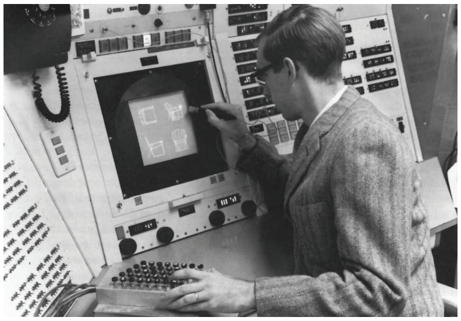

Figure 5-9: On the left. Demonstration of Sketchpad with its division of the screen to four views: top view, front view, side ,and perspective view which is still common today in animation and CAD software.

Figure 5-10: The on-site assembly of the pre-cast units of the Moshe Sadie’s Habitat’67.

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[97] Ibid, 6.

[98] “Ivan Sutherland : Sketchpad Demo (1/2) - YouTube.” Accessed July 13, 2013. https://www.youtube.com/watch?v=USyoT_Ha_bA.

THE DESIGN FOR MANUFACTURING AND ASSEMBLY PROCESSES IN THE AVIATION INDUSTRY

6

6.1 HISTORICAL BACKGROUND

The design process of aircraft has evolved during the years and was influenced by technological developments, geo-political changes (wars), increase in regulatory requirements, and clients' demands. Prior to the First World War, aircraft design and manufacturing was the domain of a small group of aviation enthusiasts surrounded by a few skilled technicians. The design process was based primarily on trial and error – aircraft designers had little theoretical background. The goal was to just be able to fly with some sort of level of control. "Customer needs" was a concept that did not even exist at the time. [99]

The same aircraft design and manufacturing methods were practiced until the mid-1950s, slowly growing a small market of aviation fanatics. The industry was also supported by government organizations like the National Advisory Committee for Aeronautics (NACA) and some key academic institutes, while at the same time it was developing connections with the military. Whether the clients were civilian or military, they were actively involved in the aircraft design and manufacturing processes. The relationships between the design engineers, manufacturing and testing staff were relatively close. Even during the Second World War, when there were vast technological developments and an increase in demand, the design processes did not change much. [100]

The Second World War created an enormous demand for military purpose aircraft, which was accompanied with the increasing complexity of the technical systems that were integrated into aircraft. Aircraft were equipped with radar and other electronic devices as flying aids, and needed to carry weapons systems, including nuclear ones. The introduction of jet and rocket propulsion, increased aircraft speed, altitude and range provenance made it necessary to find more durable materials for the aircraft skin. These developments took place at the same time that demand for

[99] J. McMasters, Boeing Co., Seattle, WA; R. Cummings California Polytechnic State University San Luis, California, "Airplane Design as a Social Activity - Emerging Trends in the Aerospace Industry (AIAA)." Chapter DOI: 10.2514/6.2002-516 Publication Date: 14 January 2002 - 17 January 2002: 4.

[100] Ibid,6.

commercial air travel grew. [101]

As customers became smarter and more demanding and the technical systems became more complex, manufacturing costs grew and regulatory requirements increased, leading to a dramatic change of design and manufacturing and in the organizational structure of staff that took place during the 1960s. It was no longer possible to simply build a 1:1 scale mockup of the aircraft and try it out. Instead, the design was based on a series of calculations and analyses that were conducted by an engineering staff that grew from ten to a hundred people to thousands of people for a single project. The increasing number of tests and analyses required a larger number of engineers with a deeper understanding of specific topics; no longer could an aircraft be built by a small team of "generalists". [102]

Gradually, the manufacturing, design and business sides became separated from each other, and a huge bureaucratic effort was needed to hold "coordination meetings" between all the different departments; this became especially difficult when a client demanded a customized product. In the early years of its use, rather than enhancing communication between the increasingly compartmentalized organizational groupings or reducing the number of tests, the use of the digital computer in the aircraft design process vastly increased the ability of designers to analyze all aspects of the aircraft, thus adding more complications to the design process.[103]

A simple example of poor collaboration culture that can cause a delay in the manufacturing is Boeing's 737 final assembly line in Seattle. The engineering teams that were supposed to provide technical support to the assembly line workers were located in different buildings in Boeing's campus in Seattle. It rains in Seattle, so if one of the factory floor workers had a problem, the engineers

[101] Ibid,4-5.

[102] Ibid,5.

[103] Ibid,

tried to work it out over the phone; no one wanted to continually cross the sprawling campus in the perpetual rain. However, as the demand for the 737 increased during the 1990s, Boeing--like the rest of the aircraft manufacturers --realized that a profound organizational change was needed in order to meet customers' needs and stay profitable in an extremely competitive market. During the 1990s, the 737 production line went through a complete organizational makeover, which led it to become it the most sold airplane in the world; by 2013, Boeing had sold more than 7,000 units of its 737 model. [104]

6.2
FROM "FASTER, FARTHER, HIGHER" TO "QUICKER (TO MARKET), BETTER, CHEAPER" MANUFACTURING PROCESSES - THE CURRENT METHODS OF DESIGN FOR MANUFACTURING AND ASSEMBLY PROCESSES IN THE AVIATION INDUSTRY

With the end of the Cold War and the understanding that aviation technology had reached some sort of maturity level, aircraft manufacturers realized that instead of trying to come up with an innovative aviation technology, they needed to focus their research and development efforts in optimizing design, manufacturing and assembly processes in order to stay profitable in a highly competitive market. The process of changing organizational and cultural structure is a never- ending one, and for the last 20 years aircraft manufacturers have experimented and refined different methods to improve their production lines.

This section of the thesis will outline and provide examples of several procedures which are used by aircraft manufacturers to optimize design, manufacturing and assembly processes: *Concurrent Engineering* (CE), *Lean Manufacturing* and the ability to utilize BIM for *Digital Mock-Up* (DMU) and *Product Data Management* (PDN). There is a strong parallel between the organizational changes which were made by aircraft manufacturing companies to optimize the processes of aircraft production, and many of the recommendations made in chapter four in regard to streamlining the production

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[104] Tom Cummings, The Boeing Company, "Lessons Learned from 737 & 787 Jet Liner Programs (AIAA)." Publication Date: 18 September 2007 - 20 September 2007. Pages: 4-5.

process of mass-customized envelope systems in commercial real estate. These recommendations include the need for proficient use of BIM, the significance of materials selection, cooperation with sub-contractors from the early stages of the project, and as much simplification of the technical systems as possible to compensate for the premium of the mass-customized envelope system .

6.2.1
THE DEVELOPMENT PROCESS OF AN AIRCRAFT

Like any other consumer product, the development process of a commercial airplane begins with the inception of a concept that is based on an analysis of market studies. As mentioned above, the two dominant companies that manufacture airplanes for commercial use are Airbus and Boeing. However, during the 1990s, each company developed its own vision of the future trends in the airline industry. Airbus wanted to capture the rising number of travelers from Asia to Europe and the United States and thus decided to develop different types of airplanes that would accommodate a system of “hub and spokes” airports. A passenger would take a mega-jet plane, the A380, from one major hub to the other, and from the huge airport he or she would need to take another smaller plane to the final destination. Boeing, on the other hand, did not share this level of optimism regarding the increase in the number of passengers from Asia. Therefore it continued to manufacture highly effective, medium and large-scale airliners that carried fewer passengers than the A380, in order to support a point-to-point airport system. Meaning, passengers would fly from an airport near their home to their destination with no stops in the middle. [105]

Whatever might be the approach to the airplane design, even from these early stages, engineers are an integral part in concept design meetings. Engineers are always asked to give their estimates on seating combinations, fuel consumption, and range, in order to

[105] Daniel E.,Whitney, *Mechanical Assemblies Their Design, Manufacture, and Role in Product Development.* New York: Oxford University Press, 2004. Page: 365.

obtain some sort of approximations on the feasibility of each design alternative. Once a basic design has been established, drawings of components, devices and systems are produced alongside an analysis of functionally and testing, up until the production-oriented processing of all relevant data. The entire development process of the airplane is concentrated around the use of BIM. [106]

6.2.2
THE USE OF BIM, 4D BIM, DIGITAL MOCK-UP (DMU) AND PRODUCT DATA MANAGEMENT (PDM) IN THE DEVELOPMENT PROCESS OF AN AIRCRAFT.

As already mentioned in chapter five, BIM and 4D BIM software are used to design, analyze, and integrate between the various systems of the aircraft. The input from all the different systems engineers flows into a single BIM model. For example, the master geometry of the airplane is defined by the feedback of manufacturing engineers and aerodynamics analysis that is conducted using simulation software. 4D BIM software is used to create simulations of sub-assembly and final assembly processes and to ensure that the sequence of assembly does not cause any conflicts between different technical systems. Mechanical systems such the wing flaps are first designed using Digital Mock Up (DMU), in order to optimize the design process and to detect technical problems in advance, so that the first production of the physical mockup will function properly. [107]

The development process of an airplane requires a huge amount of documentation for manufacturing and integration purposes. While Airbus A340 is composed of a set of 150,000 drawings, the drawings number of Airbus A380 has doubled detailing about 70 key systems assembled from several hundred components. Moreover, the BIM model is no longer limited only to designers and technical systems engineers, but also it is also accessible to suppliers, sub-contractors, appraisers and even marketing staff. [108]

In order to manage the flood of information, Airbus

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[106] Roland Haas and Manoj Sinha. “Concurrent Engineering at Airbus – a Case Study.” I*nternational Journal of Manufacturing Technology and Management 6,* no. 3 (January 1, 2004): 243.

[107] Ibid, 244, 247, 248.

[108] Ibid, 247.

developed the Product Data Management (PDM) system, which defines a strict protocol of how to use the BIM model, what the level of accessibility of each of the participants to the BIM model is, how to update it, how to archive old versions of the model, and which file formats are allowed to be imported into the model, a decision which also determines the type software and which versions of that software are permitted. In the A380 program, there were 1,800 work stations with CAD /PDM capabilities; without the PDM's strict protocol the project could easily have become chaotic. [109]

The way the aircraft manufacturing industry uses BIM as a platform for design and integration between all participants in the development of the airplane, resembles the way Frank Gehry and Permasteelisa North America (PNA) used CATIA™ in order to refine the design of the mass-customized stainless-steel panels of the Project on 8 Spruce Street so that they could fit the budget of a commercial real estate project and at the same time carry out Gehry's design intent.

6.2.3
CONCURRENT ENGINEERING

Concurrent Engineering (CE) is a product design method that aims to take into account manufacturing and assembly considerations which are which are usually considered in the later stages of the product development. CE also breaks down the overall product development into appropriate, independent work packages that can be managed in parallel. CE enables developers to cut down on manufacturing and assembly costs and to fast track the product development life cycle. CE optimizes supply chain, clarifies the interfaces between the different skills and roles, and set new methods of collaborative working. While BIM provides the platform for integrating between project participants, CE is the protocol that determines how this collaboration will take place. [110]

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[109] Ibid,245, 246, 248, 249.

[110] Ibid, 242, 247.

6.2.3.1

THE USE OF CONCURRENT ENGINEERING IN DEVELOPMENT PROCESS OF AN AIRPLANE

As mentioned above, the complexity of the technical systems in airplanes along with the enormous number of tests which are required by regulations, led to the massive increase of the engineering staff and to the difficulty of coordinating between all of them. Concurrent Engineering (CE) sets the protocol for which technical disciplines engineers need to conduct coordination meetings and in what stage of the airplane development process these meetings should occur. The purpose of these meetings is to ameliorate in advance potential problems of manufacturing and assembly, in order to avoid them the later stages of the project, when it would be extremely expensive to fix them. Moreover, through these meetings, engineers who have an extensive knowledge only on a particular subject, can learn about the needs of the other systems in the plane, and thus take into account other considerations including financial constraints.

In 1990, Rockwell and Messerschmitt-Bölkow-Blohm (MBB) developed the X-31A, an experimental fighter jet, whose purpose was to test maneuvering capabilities and integrated design methods for manufacturing and assembly, in order to increase production efficiency and reduce costs. The project staff consisted of a design team from Rockwell, and an engineering and manufacturing team from MMB. As part of the project protocol, the two teams were required to have weekly design integration meetings. In one of the first meetings, the manufacturing representative pointed out that with the current design of the airplane, the fuselage would require a mold which was longer than 30 inches for the purpose of hot forming the titanium skin. A mold of that size would drastically increase the manufacturing costs. Using BIM, the design team was able to instantly update the shape of the airplane fuselage, so that the hot forming mold would not be longer than 30 inches and would still maintain the aerodynamic properties of the airplane: nothing would be compromised. [111]

Such use of Concurrent Engineering in the aircraft manufacturing industry resembles some of the design strategies that SHoP Architects employed in developing the mass-customized envelope system in the Porter House. From the early stages of the project, SHoP Architects collaborated with the manufacturer of the envelope system panels, Maloya Laser Inc. (MLI). Shop designed the envelope system panels to accommodate the size limitations of MLI laser cutter machine, thus avoiding unnecessary changes before the panels' production phase. Concurrent Engineering is also consistent with Integrated Project Delivery (IPD), which encourages the integration of key sub-contractors s and engineering consulates from the early stages of the project.

6.2.3.2 COLLABORATING WITH STUCK SUPPLIERS

Concurrent Engineering (CE) underscores the importance of optimizing supply chain processes. It is crucial that engineers collaborate with stock suppliers in order to develop an exact match between the properties of materials and their application.

Weight efficiency is one of the key challenges that airplane engineers have to tackle. The aircraft weight is a crucial factor in determining the number of passengers that the plane can carry and the amount of fuel required. In simple words, the weight of the plane defines a major part of the expenses and the income level of each airplane.

The aircraft skin is made from two types of material, metal alloys and different types of composites. In the past, Airbus had a passive approach with regard to the types of metal it received from its suppliers, as long as it met customers' demands as well as airworthiness standards. In 2002, as part of the A380 design process;

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[111] Sidney A Powers, Rockwell International Corp., El Segundo, CA , "The Integrated Design and Manufacturing Approach to the X-31A (AIAA)." Publication Date: 23 September 1991 - 25 September 1991: 1,9.

it became apparent that as a result of its unprecedented size, it was necessary reduce the airplane's weight. Therefore, Airbus initiated an internal competition between different engineering teams in order to come up with innovative solutions to optimize materials efficiency in order to reduce the skin weight of the A380. [112]

Each engineering team was assigned with a different group of material types: Aluminum Lithium (Al-Li), AlMgSc alloys and Fiber Metal Laminates (FML). All the teams worked together with Airbus' primary metals suppliers (Alcan, Alcoa and Corus) in order to optimize the mix of the alloys and to fit each material to a proper application. By proactively collaborating with their metals suppliers, Airbus managed to reduce the weight of the A380 wings by 20%, and the process was also implemented in producing the company's other models. [113]

Like Airbus, SHoP Architects realized that they needed to have a profound understanding regarding the properties of the material they would chose to work with in order to streamline the production process of the mass-customized envelope system for the Porter House. By working together from the early stages with the project envelope system sub-contractor, Maloya Laser Inc. (MLI), they learned that MLI's CNC bending machine performed faster when bending zinc sheets. Therefore they personally contacted the world biggest zinc suppliers at the time, VM Zinc, in order to receive a wholesale price and avoid paying the brokerage fee.

6.2.4
LEAN MANUFACTURING

Another method that aircraft manufacturers use to optimize airplane production is Lean Manufacturing. Lean Manufacturing is a production management method which aims to reduce waste and to increase efficiency in order to create value for the customer: the definition of what is *value* and what is *waste* is determined by what

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[112] Worldwide Presence | Airbus, a Leading Aircraft Manufacturer." Accessed July 13, 2013. http://www.airbus.com/company/worldwide-presence/.

[113] Marco Pacchione, Jens Telgkamp, Metal Design Principles, Airbus, "Challenges of the Metallic Fuselage "ICAS 2006, The 25th International Congress of The Aeronautical Sciences: 2-5, 7.

the customer is willing to pay for. Lean Manufacturing focuses on optimizing the efficiency of information and materials flow in order to reduce spending on inventory and production life cycle. [114]

The origin of the Lean Manufacturing method comes from a production system developed by Toyota (also known as TPS- Toyota Production System). The uniqueness of TPS is that on the one hand, it is a strict and clear system of instructions, and on the other, it enables flexibility and creativity in order to promote continuous improvement of the production process (known as *Kazien*). Lean Manufacturing was adopted by other automotive manufacturing companies, along with industries that produce consumer goods, metal processing firms and the aerospace industry. Although Toyota was quite open about its production method, it took a while for other manufacturers to comprehend that the TPS was not about the use of cutting edge manufacturing technologies, but rather the organizational culture of manufacturing and assembly processes. [115]

6.2.4.1
THE FOUR RULES OF TOYOTA PRODUCTION SYSTEM

The Toyota Production System can be encapsulated into four basic rules. As trivial as they may seem to an outsider, the rules relate to every aspect of the manufacturing and assembly process: the goal is to streamline and optimize every single action in the production process.

“Rule 1: All work shall be highly specified as to content, sequence, and outcome.” [116] For example, a worker who is responsible for installing the car seat to its chassis will always clamp the bolts in the same order. The torque and time frame for turning each bolt is specified. However, Toyota workers do not memorize instructions; instead they learn by doing, and their supervisors are not problem solvers, but teachers. For instance, a trainee is asked to install the seat and then the teacher poses him or her series of questions such as

[114] Steven Spear and H. Kent Bowen, “Decoding the DNA of the Toyota Production System,” Harvard Business Review, September – October, 1999 : 97-98. http://www.busn.uco.edu/gwillis/ISOM%204043/Decoding%20DNA%20of%20TPS.pdf

[115] Ibid,

[116] Ibid, 98.

the following: How do you do this work? How do know you are doing the work correctly? How do you know the outcome is free of defects? What do you do if you have a problem? This learning process gradually gives each worker a deeper understanding of his or her role. Moreover, this teaching method encourages each worker no become a problem solver and suggest ideas on how to improve production processes. [117]

"Rule 2: Any improvement must be made in accordance with the scientific method, under the guidance of a teacher at the lowest possible level in the organization."[118] As mentioned above, although TPS is a detailed and strict instructions system, it also enables the promotion of constant improvement. Since frontline workers are the ones who are most familiar with production and supply processes, they are expected to detect problems and suggest improvements, while their supervisors need to facilitate the framework for testing their workers' suggestions. The review process of a suggested improvement resembles a scientific experiment: a production worker raises a hypothesis for improvement and together with his or her supervisor the two determine how the experiment will be executed, how long it will last, and what will be a result that will lead to a change in the production line. [119]

"Rule 3: every customer-supplier connection must be direct, and there must be an unambiguous yes-or-no way to send requests and receive responses." [120] One of the issues that the TPS aims to resolve is unnecessary expenses on excess inventory. Instead, supply is pulled "just-in-time" -- meaning only what is needed, when it is needed, and in the amount needed. Toyota developed the *Kanban* System, which uses a laminated card that clearly specifies the part's identification number, the number of parts in each container and the location of the part supplier and the worker (customer) who installs

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[117] Ibid, 98-99.

[118] Ibid, 98.

[119] Steven J. Spear, "Learning to Lead at Toyota", Harvard Business Review, May 2004.

[120] Steven Spear and H. Kent Bowen, "Decoding the DNA of the Toyota Production System," Harvard Business Review, September – October, 1999: 98. http://www.busn.uco.edu/gwillis/ISOM%204043/Decoding%20DNA%20of%20TPS.pdf

the part. [121]

Now let's go back to our seat installer. When a shift starts, a cart with a container of a specific number of bolts that need to be installed awaits the seat installer in a specific location near his or her working station. When the quantity of bolts in the container reaches a certain number, the seat installer place a *Knaban* card on the cart signaling to a specific "delivery boy" that there a need for a refill. Using the *Kanban* card, the "delivery boy" can easily find the location of the required bolts in the storage room and bring them swiftly to the seat installer's working station.   If the bolts in the storage room are almost depleted, the "delivery boy" places a different *Kanban* card in a noticeable location -- usually near the storage manager's office -- to indicate that there is a need to renew the bolts stock in the storage room. In a way, the *Kanban* system is the epiphany of Lean Manufacturing; it is straightforward, it avoids duplications, prevents redundant actions and cuts down on supply expenses.

"Rule 4: The pathway to every product must be simple and direct." [122] The purpose of this rule is to minimize the time periods between one action and another. For example, the location of the trolley tools in the working station is designed to reduce the time that a production line worker needs to reach out to the tool box. Even the position in which the tools are arranged inside the toolbox is set to accommodate the worker's order of operations.

6.2.4.2
THE TOYOTA PRODUCTION SYSTEM IN THE AIRCRAFT MANUFACTURING INDUSTRY- THE STORY OF BOEING 737

The 737 is the world's most common commercial airplane. Boeing began to manufacture the 737 in the late 1960s. However, as the demand for the 737 increased dramatically during the 1990s, Boeing came to realize that the changes in the market demands required essential adjustments in the 737's final assembly line, design processes, relationships with sub-contractors and even with clients'

[121] "737 Final Assembly Line - YouTube." Accessed July 14, 2013. http://www.youtube.com/watch?v=Ihtl-SZLU90.

[122] Steven Spear and H. Kent Bowen, "Decoding the DNA of the Toyota Production System," Harvard Business Review, September – October, 1999: 98. http://www.busn.uco.edu/gwillis/ISOM%204043/Decoding%20DNA%20of%20TPS.pdf

expectations. [123]

The rise in demand for 737 model created a density problem on the final assembly line floor, which was a result both of the increasing number or fuselages assembled simultaneously, and the lack of storage area. Team leaders accumulated unnecessary inventory "just in case" they were needed, in order to avoid delays on account of missing parts. Huge delays were created by the use of a heavy crane to move fuselage parts from one working station to the other. Because of safety regulations, an entire production team had to wait while the crane moved slowly around the floor. At its peak, the crane moved 8,000 times a month. [124]

Little integration was done before clients' customized orders reached the final assembly line floor, forcing workers to perform physical integration down to the bracket level, which was labor intensive and prone to errors and rework. Moreover, the engineers who were supposed to provide technical support were located in a distant building, creating more holdups in resolving the problems. [125]

In order to be able to meet the increase in demand for the 737 airplanes, and also to reduce production costs, Boeing decided to completely change the 737's final assembly line so that it would run according to the guidelines of Lean Manufacturing. Instead of using a crane to move fuselage parts around the factory floor, engineers had the 737 move slowly in a straight line between nine assembly stations. This method also helped the floor manager follow the progress of the assembly procedure and quickly track delays. The use of the cranes was limited to three movements per one airplane.[126] The *Kanban* cards method replaced the former wasteful storage system.[127]

Moreover, sub-assembly processes were pushed back to sub-contractors, in order to reduce the complexity in the final assembly line. Clients were able to customize their airplanes only from a

[123] Daniel E. Whitney, Senior Lecturer in Engineering Systems, Emeritus, MIT, interviewed by Shaul Goldklang, May 3, 2013.

[124] Tom Cummings, The Boeing Company, "Lessons Learned from 737 & 787 Jet Liner Programs (AIAA)." Publication Date: 18 September 2007 - 20 September 2007: 3-5.

[125] Ibid,

[126] Tom Cummings, The Boeing Company, "Lessons Learned from 737 & 787 Jet Liner Programs (AIAA)." Publication Date: 18 September 2007 - 20 September 2007: 5-6.

[127] "737 Final Assembly Line - YouTube." Accessed July 14, 2013. http://www.youtube.com/watch?v=Ihtl-SZLU90.

certain family of variations, so as to avoid individual solutions which were prone to mistakes, reworking and delays. Finally, the technical support engineering team was moved to a space overlooking the final assembly line floor: this move enabled them to improve communication and avoid delays in finding technical solutions when necessary. [128]

Figure 6-1: Boeing 737's Final Assembly Line (FAL), before the company switched Lean Manufacturing methods.

Figure 6-2: Boeing 737's Final Assembly Line (FAL), after the company switched Lean Manufacturing methods.
One can notice the marks on the factory floor indicating the tools' trolleys and the parts' carts designated location.

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[128] Tom Cummings, The Boeing Company, "Lessons Learned from 737 & 787 Jet Liner Programs (AIAA)." Publication Date: 18 September 2007 - 20 September 2007: 5-6.

It seems logical that if the aircraft manufacturing industry was able to adopt Lean Manufacturing in order to optimize the production and assembly processes of airplanes, it should be able to make a similar transition to manufacturing the mass-customized envelopes for real estate development. The industry has the experience and know-how needed, and the parallels between the design and assembly of the 737 and A380 airplanes and the construction of the mass-customized envelopes used in the projects analyzed in the case studies are strong. It is true that Lean Manufacturing was developed in the sterile environment of a factory, while buildings are being constructed outside on a construction site. Thus if the AEC industry decides to make more use of Lean Manufacturing, the majority of building components will need to be sub-assembled in a factory and then transported for final assembly at the construction site. This adaptation, however, would fit in with the goal that the parts of the envelope should be as easy to assemble as possible: Concurrent Engineering, Building Information Modeling, and Lean Manufacturing can be used to develop the envelope sections whose "bugs" have been worked out and which are ready to be easily installed.

ADAPTING FABRICATION METHODS OF AN AIRPLANE SKIN TO THE STANDARDS OF THE CONSTRUCTION INDUSTRY TO ENABLE THE WIDESPREAD USE OF MASS-CUSTOMIZED ENVELOPE SYSTEMS IN COMMERCIAL REAL ESTATE

7

Until this point, the thesis has outlined the similarities between the design for manufacturing and assembly procedures in the aircraft manufacturing industry and the processes of the design and execution of the real estate projects described in the two case studies in chapter three. The purpose of this comparison was to demonstrate that there are flaws in the dominant project delivery methods in the AEC industry that prevent the widespread adoption of mass-customized envelope systems in commercial real estate. By looking into design and assembly processes in the aircraft manufacturing industry, the AEC industry can learn how to streamline its project delivery methods, thus enabling the realization of real estate projects that employ mass-customized envelope systems and also cut down on production costs. But more importantly, this comparison shows that aircraft manufacturers have the technical expertise and organizational skills to make the transition into fabricating mass-customized envelope systems for commercial real estate developments.

As mentioned at the end of chapter four, one of the crucial obstacles for the widespread use of mass-customized envelope systems in commercial real estate is the high fabrication cost of these systems. This section of the thesis will look into different fabrication methods of an airplane fuselage and wing skin, and will suggest ways in which these fabrication methods can be adapted to the standards of construction industry, thus cutting down on manufacturing costs.

7.1

THE KEY DIFFERENCES IN FABRICATION STANDARDS BETWEEN THE AIRCRAFT MANUFACTURING TO THE CONSTRUCTION INDUSTRY

The safety and aeronautical regulatory requirements regarding the tolerances level, material properties, and quality assurance tests of airplane fuselage and wings skin, are radically different from those which are required of envelope systems. This regulatory gap between the two industries gives the opportunity to find ways to adapt the manufacturing technologies of fuselage and wing skins to the standards of the construction industry, thus reducing production costs of mass customized envelope systems for commercial real estate developments.

7.1.2

THE MATERIALS USED TO PRODUCE FUSELAGE AND WING SKINS, AND THEIR SUITABILITY FOR THE PRODUCTION OF MASS-CUSTOMIZED ENVELOPE SYSTEMS IN BUILDINGS

The skin of the airplane fuselage and wings needs to cope with completely different types of loads than does a building envelope system. As the plane takes off and while it is cruising in higher altitudes, airflows put a tremendous pressure on the fuselage skin, while at the same time an air condensation system in the passengers' cabin pushes the skin outwards. This system of loads changes constantly as a result of the maneuvers of the airplane, the changing climate conditions, and the altitude during the flight. Airflows beneath and above the wings also cause a fluttering effect: in the Boeing 747, the wing tip can move up and down half a meter. [129] Fuselage and wing skin panels must therefore be made from materials that are strong enough to withstand the mighty air currents but lightweight enough to optimize fuel usage and enable the maximum number of passengers' seats. The main material groups of which fuselage and wing skin panels are made from are different types of composites, titanium, and aluminum alloys from the 6000s and 7000s groups. [130]

Composites are materials which are made out at least two different types of materials: fibers-- carbon or glass -- and some type of resin. The fibers are placed in a mold, and their pattern is determined by the directions of forces that the part will need to cope with. Then the fibers are soaked with the resin and put in a vacuum bag inside an autoclave. In an extremely delicate procedure, the resin is heated inside the autoclave, while air is sucked out of it to eliminate air bubbles that might weaken the finished part. After

[129] Jacob Goldklang, Chemical laboratory manger and quality assurance supervisor in the Israeli Aerospace Industries, interviewed by Shaul Goldklang, June 1, 2013.

[130] Arie Ben-Dov, Manager of Metallurgic Engineering in the Israeli Aerospace Industries, interviewed by Shaul Goldklang, May 26, 2013.

the part cools down, it is taken outside of the mold for inspections and installation. Another group type of composites is called FML (Fiber Metal Laminates): this type is a hybrid built from altering layers of aluminum foils and fibers/adhesive layers also bonded using autoclave. [131]

The aircraft manufacturing industry began to explore the use of composites as a result of the desperate need to reduce the weight of aircraft, a concern that is not relevant to the construction industry. Moreover, in addition to the high production costs of composites, the International Code Council (ICC) requires a series of tests that are extremely time-consuming and expensive in order to allow the application of composites in the construction industry. For all these reasons, the use of composites in the construction industry is almost non-existent.

Therefore, this thesis will focus only on manufacturing processes of the metallic parts of the fuselage and wing skin. This part of thesis will suggest ways to accommodate these manufacturing processes to the standards of the construction industry. Later, the thesis will explain why titanium and aluminum alloys from the 6000s and 7000s groups are inadequate metals for the manufacturing of mass-customized envelope systems, and will propose alterative alloys which are more suitable for the needs of the construction industry.

7.1.3

DIFFERENCES IN TOLERANCES REQUIREMENTS BETWEEN THE AIRCRAFT MANUFACTURING INDUSTRY TO THE CONSTRUCTION INDUSTRY

In order not to reduce the aerodynamic properties of the airplane, the required tolerances between the panels of the fuselage are no more than one tenth of a millimeter, so that air will not flow into the plane. Although the systems in the plane are protected from wetness, the skin of the fuselage and wings is supposed to serve as a waterproof system. [132] This is completely different from a building's envelope systems, in which the waterproofing system is separated

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[131] Tom Cummings, The Boeing Company, "Lessons Learned from 737 & 787 Jet Liner Programs (AIAA)." Publication Date: 18 September 2007 - 20 September 2007. Pages: 5.

[129] Jacob Goldklang, Chemical laboratory manger and quality assurance supervisor in the Israeli Aerospace Industries, interviewed by Shaul Goldklang, June 1, 2013.

from the curtain wall panels, which are only used as a rain screen. Moreover, since the use of materials such as concrete, wood, bricks and mortar is prevalent in the construction industry, it is impossible to reach tolerances that are more precise than a quarter of an inch. Even precise factory-manufactured systems are designed to adapt to the inevitable inaccuracies of building in a construction site using organic materials that change constantly. Since building construction does not require the same level of accuracy as aircraft production, it allows for the manufacturing of parts that do not employ such strict tolerances, thus reducing manufacturing costs.

7.1.4
THE LACK OF NEED FOR QUALITY ASSURANCE TESTS FOR FUSELAGE AND WING METALLIC PANELS IN THE MANUFACTURING PROCESS OF BUILDING ENVELOPE SYSTEMS

As mentioned above, the airplane fuselage and wing skin need to cope with extreme conditions which expose them to a higher rate of fatigue and damage tolerance.[133] The average life cycle of an airplane fuselage is 15 years[134] and in order to prevent it from being shorter, it is necessary to conduct periodic maintenance and quality assurance tests. Quality assurance tests are also an integral part of the manufacturing processes of the fuselage and wing skin, and they begin with the stock supplier. As part of the production line of the raw material from which the airplane skin is to be made, the metal sheets go through an ultrasound scan so that micro-cracks can be detected.[v] The intensive airflows that hit the airplane skin can cause several micro-cracks to converge into a bigger crack that can reduce the aerodynamic and waterproofing capabilities of the airplane skin, but most importantly can become a safety hazard. The initial ultrasound scan which is done by the stock supplier is very expensive because it filters out a lot of raw material from becoming suitable for manufacturing aeronautical parts.[135]

As the raw material arrives at the manufacturing plant, it goes through chemical and mechanical properties analyses. Small

[V] Micro-cracks are measured in micro-millimeters.

[134] Daniel E. Whitney, Senior Lecturer in Engineering Systems, Emeritus, MIT, interviewed by Shaul Goldklang, May 3, 2013.

[135] Jacob Goldklang, Chemical laboratory manger and quality assurance supervisor in the Israeli Aerospace Industries, interviewed by Shaul Goldklang, June 1, 2013.

samples in the size of 4/4/4 cm are cut out from different locations of the metal sheets, for the purpose of a chemical analysis that verifies that the supplier delivered the correct alloy. For mechanical tests, small pieces in the shape of a dog-bone are cut from different parts of aluminum sheet, and taken for the analysis of the material tensile properties using an Instrong device. [136]

Once the skin panel is ready, it goes through None Damaging Tests (NDT). First, it goes through another ultrasound scan to find micro-cracks. Second, the panel goes through a Fluorescent Penetrant Inspection (FPI), the surface of the panel is cleaned from oil or dirt, and a Fluorescent Penetrated Liquid (FPL) is then applied to the surface to the panel. There is a need to wait until the liquid soaks into the panel. The waiting time varies on the type of material and the geometry of the part. Once the waiting time is over, the panel is inspected in a dark room using a UV light. While the purpose of the ultrasound scan is to find micro-cracks that are parallel to the panel surface, the FPI is also used to dedicate micro-cracks that are perpendicular to the panel's surface. [137]

The concern that the aircraft manufacturing industry has with micro cracks is irrelevant to construction industry in general and more specifically to the chemical and mechanical properties which are required from the metallic panels of buildings envelope systems. The whole process of quality testing described above is completely unnecessary in the building industry, and therefore the costs of manufacturing a building's mass-customized envelope systems can be reduced by eliminating these time and money-consuming tests.

[136] Ibid,

[137] Ibid,

7.2
HOW TO ADAPT THE MANUFACTURING METHODS OF METALLIC FUSELAGE AND WING PARTS FOR THE PURPOSES OF FABRICATING MASS-CUSTOMIZED ENVELOPE SYSTEMS IN COMMERCIAL REAL ESTATE

This part of thesis will look into the fabrication technologies that are currently used to manufacture metallic parts of fuselage and wings, and suggest ways of harnessing them for the purpose of manufacturing mass –customized envelope systems in commercial real estate. This thesis will distinguish between fabrication technologies of mass-customized flat and single-curved panels and the manufacturing methods of mass-customized panels with double curvature geometry, which require the use of a mold as part of their production process, an aspect of the construction which also drives up the manufacturing cost significantly.

7.2.1
FABRICATION TECHNOLOGIES OF MASS-CUSTOMIZED ENVELOPE SYSTEMS MADE FROM FLAT OR SINGLE-CURVED PANELS

The most efficient manufacturing technologies used to fabricate metallic panels for mass-customized envelope system are water-jets and laser cutters. Both technologies operate on the same principle. A CAD file is uploaded to tool-path software that is used to determine the intensity and the speed movement of the laser beam/ water-jet, which cuts the panel pieces out from the metal sheets according to the lines in the CAD file. These machines can produce a large number of panels that are completely different from each other, at the cost of fabricating identical panels.

While laser cutters usually cut out the pieces faster than water jets, they also depreciate more quickly and require more maintenance. The decline in the quality of the laser beam causes micro-cracks and overheating (also known as Heat Affected Zones, HAZ) in the cutting areas, which damage the required aeronautical properties of the metal sheet. [138] The depreciation in the quality of one of its laser-cutter machines was the main reason which drove Maloya Laser Inc. (MLI) -- the fabricator of the Porter House mass-customized zinc panels envelope system -- to make the transition from being mainly a sub-contractor for air craft

[138] Ibid,

manufacturing companies, to becoming a fabricator of metallic panels for architectural applications. [139] Like Maloya, other aircraft manufacturing companies can employ depreciated laser-cutter machines to set up a designated production line for metallic panels of buildings' envelope systems.

The hourly rate of laser cutters and water jet machines is determined, among other things, by the purchase price of the machine and its expected number of production hours. 140 Utilizing deprecated laser-cutters for the purpose of fabricating mass-customized metallic panels of buildings envelope systems will extend the duration of the production capabilities beyond the initial expectations. Making the transition to the fabrication of metallic envelope panel systems may thus prove more profitable for an aircraft manufacturer over the long run.

Before setting up a production line of metallic panels of buildings envelope systems, aircraft manufacturing companies need to study the needs of the construction industry, in order to avoid unnecessary expenses on expensive equipment. Laser-cutter machines can process metal sheets up to the size of 16 X 2.5 meters, [141] and the bed of water-jets can reach the size of 6 X 20 meters.[142] However, taking into account transportation and assembly capabilities, dimensions of 2.5 X 4 meters should be sufficient to accommodate most designs of mass-customized panels of envelope systems. Although, the manufactured panels will be in "architectural scale," it does not necessarily follow that the biggest and most expensive machines will be required to fabricate them.

[139] Reto Hug, interview by Shaul Goldklang, April 18, 2012.

[141] "Laser Cutting Machines TruLaser 8000 - TRUMPF Machine Tools." Accessed July 21, 2013. http://www.trumpf-machines.com/en/products/2d-laser-cutting/laser-cutting machines/trulaser-series-8000.html.

[142] "Water Jet Sweden AB." Accessed July 21, 2013. http://www.waterjet.se/en/index.asp.

Figure 7-1: TRUMPF's TruLaser 8000 Laser-cutter machine that can process metal sheets up to the size of 16 X 2.5 meters.

Figure 7-2: Water Jet Sweden AB's water-jets machine with abed size of 6 X 20 meters.

The fuselage and wing skin panels are attached to a system of stringers, either by rivets or by robotic stir friction welding and laser welding so as to reduce the weight of the airplane. [143] The same principle was used to sub-assemble the stainless steel panels at the 8 Spruce Street Project. Since the required thickness of building envelope systems panels is only few millimeters, the stainless steel sheets were flexible enough to employ a single curved geometry, they were fixed to a support system of rails, which was also fabricated using laser-cutter or water-jets machines. Working together with Permasteelisa North America (PNA), Gehry's office was able to reduce the complexity of the envelope system panels so that they employed only single curved geometry; this design enabled craftsmen to rivet the stainless steel panels to a support like a sheet of paper. [144] It was cheaper and faster to rivet the panels instead of welding them, they were able to use rivets because there were no weight constraints, as in an airplane.

[143] Tom Cummings, The Boeing Company, "Lessons Learned from 737 & 787 Jet Liner Programs (AIAA)." Publication Date: 18 September 2007 - 20 September 2007: 4,6-8.

[144] Frank Gehry's Beekman Tower, 2011. http://www.youtube.com/watch?v=vaNoivBeG5I&feature=youtube_gdata_player.

Figures 7-3 & 7-4 depict the support system behind the single curved stainless steel panels in The 8 Spruce Project.

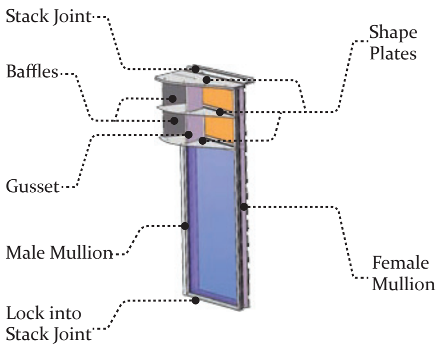

Figure 7-3: On the left. Glass and Shaped Spandrel Unit (without rain screen).

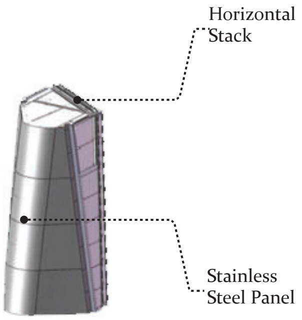

Figure 7-4: On the Right. Shaped Column Unit (with rain screen).

7.2.1.1
ROLL BENDING

Another common technique in the metal processing industry used to fabricate single curved metallic panels is Roll Bending. A lubricated aluminum sheet is pushed between three steel rolls whose locations can be changed. The curvature of the aluminum sheet is determined according to the changing location of the three rolls and the relations between them while the aluminum sheet goes through them. There are also some experiments to develop roll-bending techniques for the purpose of fabricating double curved metallic sheets. [145] However, it is very difficult to control the panel's final geometry as a result of a "spring back "effect, meaning that the aluminum sheet still has some elastic properties and therefore tends to return to its original shape. [146]

Figure 7-5: Roll bending machine.

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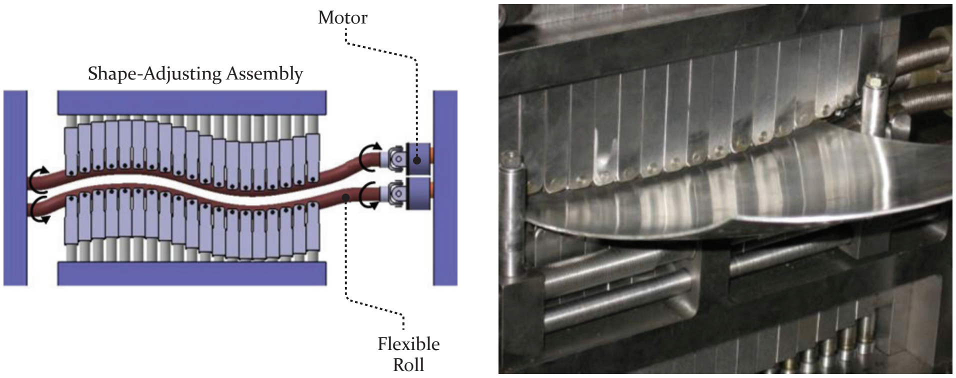
[145] Zhong-Yi, Cai, Ming-Zhe Li, and Ying-Wu Lan. "Three-dimensional Sheet Metal Continuous Forming Process Based on Flexible Roll Bending: Principle and Experiments." Journal of Materials Processing Technology 212, no. 1 (January 2012): 120–127. doi:10.1016/j.jmatprotec.2011.08.014.

[146] David E. Hardt , Professor at the Mechanical Engineering Department at MIT, interviewed by Shaul Goldklang May 23, 2013.



Figures 7- 6 & 7-7: Experiments in developing roll-bending techniques for the purpose of fabricating double curved metallic sheets.

7.2.2
FABRICATION TECHNOLOGIES OF MASS-CUSTOMIZED METALLIC PANELS WHICH EMPLOY DOUBLE CURVED GEOMETRY

This section of the thesis will outline the fabrication technologies of fuselage and wing metallic skins, which are relevant to the production of mass-customized building envelope systems made from double-curved panels. The thesis will also make several suggestions for optimizing these fabrication technologies in order to reduce the manufacturing costs of these complex envelope systems.

Using current fabrication technologies, a mold is necessary to shape an aluminum sheet –at an average size of 2 x 3 meters--to a panel which employs double-curved geometry. Since building envelope systems can be made of hundreds, if not thousands, of panels, the mold must be made of a durable material that will not deform during the manufacturing process. In the majority of cases the mold is machined by a CNC milling machine from a block of cast iron. A good solid mold is a crucial factor to ensure that all the panels will be of the same quality, and that there will be no costly defects. [147] However, the mold is a huge expense that can reach over a million dollars, [148] and this is without taking in to account the cost of the stock, even before manufacturing a single panel. Therefore the thesis will not focus on fabrication methods that require the use of the dual format of male-female molds, but rather look into manufacturing techniques that need only one mold, such as *Superplastic Forming* and *Stretch Forming*. Moreover, since this thesis focuses in mass-customized envelope systems, this part of

[147] Jacob Goldklang, Chemical laboratory manger and quality assurance supervisor in the Israeli Aerospace Industries, interviewed by Shaul Goldklang, June 1, 2013.

[148] Phil Taylor, Senior Sales Engineer at Superform®, interviewed by Shaul Goldklang, June 10, 2013.

the thesis will also explore the two types of molds that enable the fabrication of a variety of panel without the need to create a mold for each different panel. These two types of molds are *Reconfigurable Solid Die* (RSD) and *Pin Die* also known as *Discrete Die*.

7.2.2.1 SUPERPLASTIC FORMING

Superplastic forming is a technique that uses heat and air pressure to form metallic sheets. There are several different superplastic techniques, but the one that is relevant to a large-scale metallic sheet with double-curved geometry is Cavity Forming. First, the metal sheet is covered with graphite to prevent the sheet's adhesion to the tool during the forming process. The sheet is then placed inside an oven where it is bounded along all its sides; the mold is located in the upper part of the oven. Next the oven is heated to 716-932 F° in order to give the metallic sheet plastic properties which enable air pressure to push the now-moldable-sheet to receive the geometry of the mold. After the molded panel is cooled off, it is taken out of the oven, and the excess material in the sheets edges is cut off using robotic laser cutter. [149]

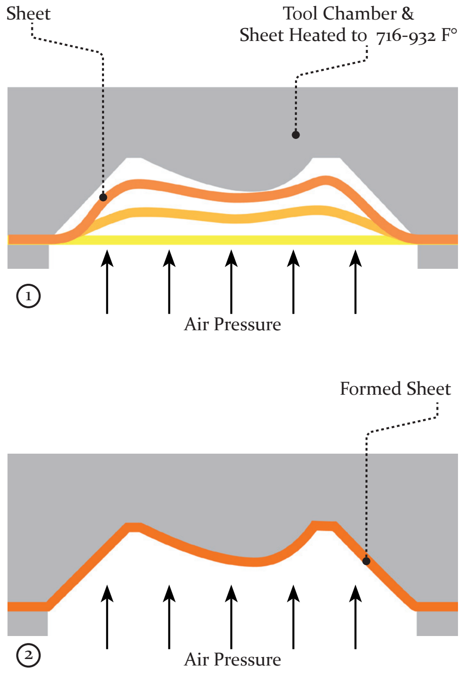


Figure 7-8: On the left. A Diagrammatic description of Superplastic Forming process, using Cavity Forming method.

Figure 7-9: On the Right. Aluminum panel which was shaped using Cavity Forming method for the purpose of a commuter train skin.

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[149] Ibid,

As mentioned above, in order to cope with the intense airflows during flight, the metallic segments of the fuselage and wing skin are made from titanium and aluminum alloys of the 6000s and 7000s groups. However, the same properties that give these metals their strength also cause them to be very time-consuming in their molding processes. Shaping a metal sheet in the scale 2 X 3 meters sheets made from titanium or aluminum alloys from the 6000s and 7000s groups by using superplastic forming technique es can take several hours if not an entire day, depending on the complexity of the desired geometry and the thickness of the sheet. [150] As it consumes more time, the manufacturing process becomes more expensive. Moreover, this production rate -- one part every several hours--is not suitable for the construction industry.

In order to find ways to optimize the superplastic forming fabrication process so that it can be applicable in the manufacturing of mass-customized envelope system, I contacted Superform®, the company that developed the superplastic forming fabrication process back in 1974 in England; the company has factories in England and California. Superform® is a sub-contractor that provides superplastic forming fabrication services for aircraft, trains and high-end car manufacturing companies. Superform® also has some experience fabricating mass-produced envelope systems, working with the tech-savvy-architect, Nicholas Grimshaw. [151]

Superform® uses only two types of aluminum alloys for architectural applications. The first alloy is the 5083, which was originally developed for the naval industry and thus has high corrosion resistance properties, which also make it suitable to be used for buildings envelope systems. The second alloy is 2004, which has reduced corrosion resistance properties and therefore is used for interior applications. The main advantage of these two

[150] Jacob Goldklang, Chemical laboratory manger and quality assurance supervisor in the Israeli Aerospace Industries, interviewed by Shaul Goldklang, June 1, 2013.

[151] Phil Taylor, Senior Sales Engineer at Superform®, interviewed by Shaul Goldklang, June 10, 2013.

alloys is that their superplastic forming process takes only between 15-20 minutes. This production pace is suitable for the needs of the construction industry, but more importantly it reduces significantly the fabrication cost for buildings envelope systems, compared to the production of aeronautical panels. The cost of the 5083 and 2004 alloys -- at the time of writing this thesis -- is $3-5 per pound, depending on the amount and the supplier, which is no different from the price range of the 6000s or the 7000s alloys. Commercial titanium, on the other hand, will cost four times more, and aeronautical titanium can reach eight times more than the cost of the 5083 and 2004 alloys. [152]

7.2.2.2
STRETCH FORMING

Using the stretch forming method, the panel is shaped by stretching the aluminum sheet on top of a mold; the mold also needs to be of a durable material, usually cast iron. First, the aluminum sheet is fastened into two clamps in both side of the mold; then, using a computer- controlled piston, the mold is raised until it stretches the aluminum sheet. Sometimes a rubber blanket half an inch thick is put on top of the aluminum sheet in order to distribute the tensile forces more evenly across the sheet. A worker softly hits the aluminum sheet at strategic points to make sure that there is no gap between the aluminum sheet and the mold. The entire process takes no more than 4 minutes. While the thickness of the aluminum sheet can change the duration of the stretch forming process, the aluminum alloy type has no impact on the process. However, it will take a little more time to shape a titanium sheet, since it is a very stiff metal. Once the panel is ready, the unnecessary material in the sheet edges is taken off using robotic laser cutter. [153]

Since there is no heating involved in stretch forming, it is significantly cheaper than superplastic forming. At the time of the

[152] Ibid,

[153] Jacob Goldklang, Chemical laboratory manger and quality assurance supervisor in the Israeli Aerospace Industries, interviewed by Shaul Goldklang, June 1, 2013.

writing of this thesis, the Israeli Aerospace Industries charges only $75 per hour of work for stretch forming services (not including the cost of the mold and the stock). However, the stretch forming method is limited in the complexity of the geometries it can handle. If the mold employs concave and convex features, a craftsman might need to use a soft mallet to press the aluminum sheet to the mold, which can be extremely labor-intensive and time-consuming. [154]

[154] Phil Taylor, Senior Sales Engineer at Superform®, interviewed by Shaul Goldklang, June 10, 2013.

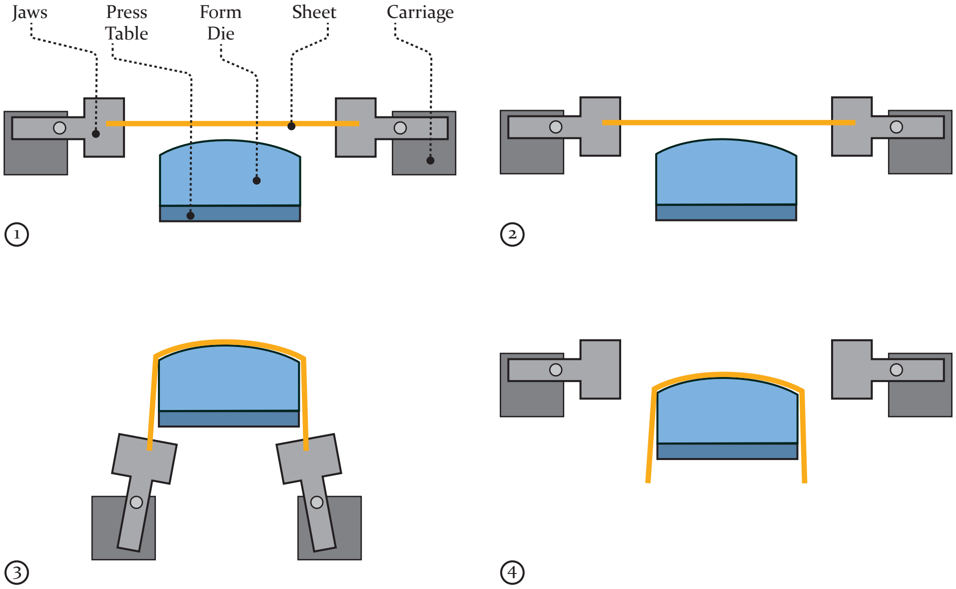

Figure 7-10: Diagrammatic description of Stretch Forming process:

1. Loading
2. Pre-stretching
3. Wrapping
4. Release

7.2.2.3 RECONFIGURABLE SOLID DIE (RSD)

One may assume that in order to manufacture a mass-customized envelope system that is assembled from double-curved metallic panels, it would be necessary to fabricate a huge number of molds that would be different form one another. This, of course, would increase the production costs to such an extent that the project, or at least its mass-customized envelope system, would not be financially feasible. However, as mentioned in chapter four, by employing rule-based design, the architect can reduce the number of different dies that are needed to create a facade which can employ a sense of uniqueness and diversity, at the same time reducing the production costs.

Instead of machining a single die in the maximum size capabilities of the superplastic forming oven or the stretch-forming machine, the architect can design a system of smaller molds. This system of molds can be reconfigured/ assembled in numerous ways, creating a different die with each configuration. According to Phil Taylor, a Senior Sales Engineer at Superform®, the cost of fabricating a Reconfigurable Solid Die (RSD) should not be more than manufacturing one large mold. At the time of the writing of this thesis, Superform®, can fabricate the RSD for an average price of $150,000,[155] while The Israeli Aerospace Industries can do the same mold for $20,000. [156] An RSD might be even cheaper to produce, since it can be machined from smaller blocks of materials that would be easier to handle than the large block of cast iron from which the single solid die is machined. Reconfigurable Solid Die (RSD) should be also suitable for stretch forming as long as the geometrical complexity limitations are taken into account during the design stage. [157]

7.2.2.4
PIN DIE (DISCRETE DIE)

Another technique that enables having a variety of molds without the need to fabricate a large number of molds for the purpose of mass-customized-double-curved-panel-system is the *Pin Die* -- also known as the *Discrete Die*. The Discrete Die is made from matrix of pins that are arranged tightly next to each other; their height can be adjusted manually or by computer control. The tip of each pin is usually shaped as a smooth hemisphere. The short distance between the pins and the mechanical properties of the aluminum sheet prevent the formation of small dimples on the metal sheet surface. [158]

The main advantage of the Discrete Die is that it can be used in several projects, as opposed to the use of a single mold or even the RSD, which is intended to be used in only one project.

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[155] Ibid,

[156] Jacob Goldklang, Chemical laboratory manger and quality assurance supervisor in the Israeli Aerospace Industries, interviewed by Shaul Goldklang, June 1, 2013.

[157] Ibid,

[158] David E. Hardt , Professor at the Mechanical Engineering Department at MIT, interviewed by Shaul Goldklang May 23, 2013.

The long product cycle of the Discrete Die can compensate for its high manufacturing cost. However, since the pins support each other, they can only be shaped to geometries that enable a smooth transition between the pins' heights. A sharp change in the pins' heights might lead to the break of one or even several pins. [159]

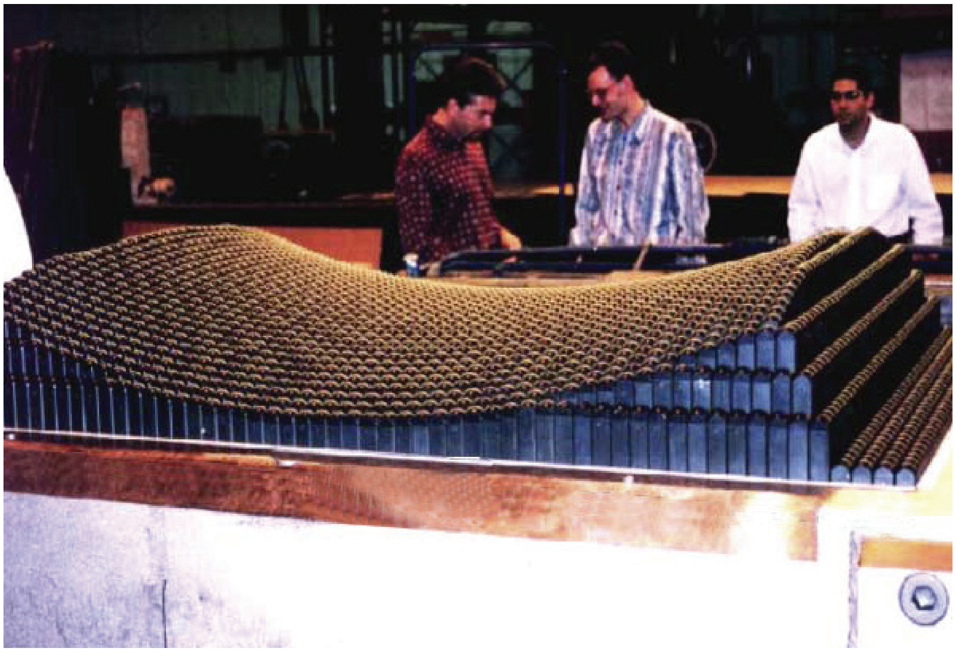

Figure 7-11: A Discrete Die in the length of 6 feet.

During an interview that I conducted with Professor David E. Hardt form the Mechanical Engineering Department at MIT -- who was one of the first researchers in the world to experiment with the implementation of Discrete Die in industrial manufacturing -- he said that he had a number of successful experiences in applying the stretch forming technique with a large scale Discrete Die. However, he was not so confident that the Discrete Die would work well using superplastic forming. His main concern was that the oven heat might soften the metal sheet to the level of which it might employ the dimples pattern of the pin die. Professor Hardt also qualified this statement, however, saying that he is not deeply familiar with types of alloys that are used in superplastic forming, and he cannot completely rule out the possibility that there is some type of alloy

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[152] Ibid,

that might be suitable for the implementation of Discrete Die in superplastic forming.[160]

Figure 7-12: Stretch forming process using a Discrete Die.

As mentioned at the end of chapter five, this thesis avoided focusing on fabrication technologies which are still in their embryonic stage, and has instead suggested ways to optimize manufacturing technologies which are already in use, mainly in the aircraft manufacturing industry. However, there are many other technologies that have the potential to significantly reduce the predicted costs of mass-customizes envelope systems made out of metal sheets. One example of such a technology is the 6 axes robotic arm for bending thin metallic sheets. The movement freedom degree of these robotic arms, with the ability to install different tools at the end of their arms, and the combination of two, three, even four robots that would bend together a single metal sheet can lead to unimaginable geometries; more importantly, they will obviate the need for molds, thus reducing significantly production cost and waste.

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[160] Ibid,

THE INCENTIVES FOR THE AIRCRAFT MANUFACTURING INDUSTRY TO ENTER THE FIELD OF PRODUCING MASS-CUSTOMIZED ENVELOPS SYSTEMS FOR REAL ESTATE DEVELOPMENT

8

Up until now the thesis demonstrated the superiority of the aircraft manufacturing industry over the Architecture, Engineering and Construction (AEC) industry in terms of utilizing Building Information Modeling, employing logistical skills, developing an organizational culture and fabricating capabilities for the production of large scale mass-customized metallic panels. This section of the thesis will outline the financial incentives for the aircraft manufacturing companies to enter into the business of manufacturing buildings' mass-customized envelope systems.

8.1
DIVERSIFYING RISKS

All industries take on risk: the type of risk that aircraft manufacturing companies are exposed to is completely different than those faced by the real estate industry However, when an aircraft manufacturing company decides to enter the field of manufacturing of building envelope systems it will, in fact, diversify its exposure to risks: to wit, if the demand for jumbo jets declines, the company can still count on steady income from its envelope systems production line.

8.1.1
THE MAIN RISKS WHICH OF THE AIRCRAFT INDUSTRY

In addition to the economic recessions that cause the decline in demand for commercial flights (generally more than any other service), three main factors have caused a decline in demand for commercial airplanes during the course of history. The first is an increase in oil prices like the one that took place during the 1970s as a result the formation of OPEC, which led to the coordination between the main Petroleum producing countries regarding the export volumes of and prices of oil [161]. The second comes from terrorists' attacks like the tragedy of 9/11 in 2001, [162] which initially caused people to refrain from flying and later added burdensome security checks on passengers. Third are the unexpected technical accidents

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[161] J. McMasters, Boeing Co., Seattle, WA; R. Cummings California Polytechnic State University San Luis, California, "Airplane Design as a Social Activity - Emerging Trends in the Aerospace Industry (AIAA)." Chapter DOI: 10.2514/6.2002-516 Publication Date: 14 January 2002 - 17 January 2002: 1.

[162] Ibid,

which harm the reputation of airplanes manufactures and carriers, such as the one that took place at the beginning of 2013, when the Federal Aviation Administration (FAA) grounded all of Boeing's 787 Dreamliner jets as result of their self-combusting batteries.[163] Grounding an entire producing line of jumbo-jets is a rare event, one that has happened only twice in history of commercial aviation.[164]

8.1.2
THE CHRONOLOGY OF REAL ESTATE CYCLES

Real estate supply and demand cycles have unique characteristics that distinguish real estate from other commodities. Research shows that except for the last five years, there has been a perfect historic correlation between economic recessions and housing production. [165] As demand for space increases, rent and prices of real estate also rise, which incentivizes developers to build housing and office space. However, because the process of retrieving entitlements, permitting and construction can take several years, there is lag between the moment the developer realizes that there is a demand in the market for a certain real estate product and the moment he or she can actually deliver the building. During this time period, the market demand can completely change. Moreover, buildings are being constructed in larger "chunks" than the market demands. Therefore, eventually there is always an excess supply of space, which leads to a decrease of rents and real estate prices until the cycle begins again. [166]

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[162] "Press Release – FAA Statement." Accessed July 21, 2013. http://www.faa.gov/news/press_releases/news_story.cfm?newsId=14233.

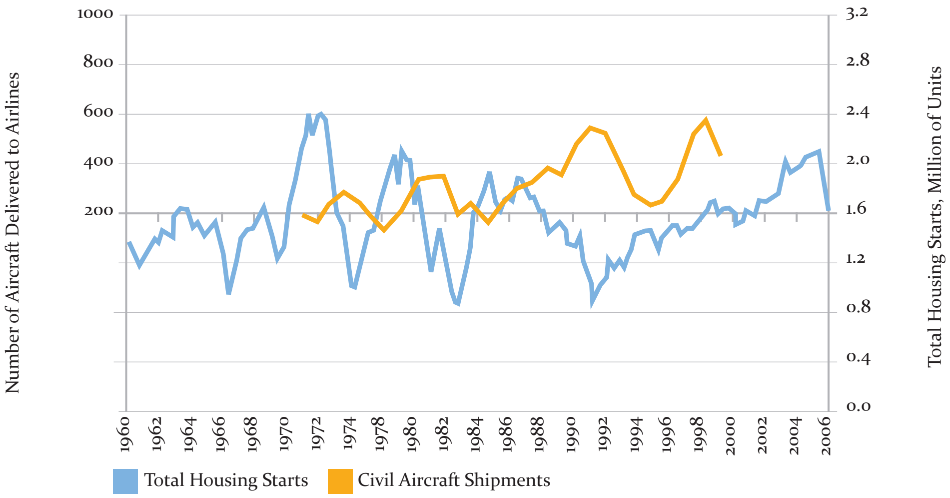
[163] Megafactories | Boeing 747 - National Geographic, 2013. http://www.youtube.com/watch?v=8CCFjMRQTYI&feature=youtube_gdata_player.

[165] William Wheaton, *Real Estate Economics*, 26.08.2012, MIT.

[166] Ibid,

8.1.3
THE LACK OF CORRELATION BETWEEN HOUSING PRODUCTION AND CIVIL AIRCRAFT SHIPMENT

Looking at Figure 8-1, one can clearly see that there is no distinct historical correlation between housing production and the shipment of civil aircraft. Therefore, by going into manufacturing building envelope systems, an aircraft manufacturing company could help maintain a steady cash flow: when the demand for civil aircraft is down, production of building envelope systems could compensate for the loss in income.



Figures 8-1: Comparison between total housing starts and civil aircraft shipments.

Data from Aerospace Industry Association of America & Torto Wheaton Research

8.1.4
THE GLOBAL NATURE OF THE AIRCRAFT MANUFACTURING INDUSTRY VERSUS THE LOCALITY OF THE REAL ESTATE INDUSTRY

One of the key differences between the aviation industry and real estate is that while the decline in demand for airplanes is usually global, real estate recessions are usually local. While there is a downturn in the demand for space in the US and Europe, the real estate markets of Latin America, Asia and the Middle East can be flourishing. Except for “black swans” like the Credit Crisis of 2008, real estate markets are usually even diversified at the municipal level. For example, while rents and price per square foot in New York City are reaching historic heights, Detroit is filing for bankruptcy.

As mentioned in chapter five, the two dominant aircraft manufacturing companies – Airbus and Boeing--have sub-contractors and subsidiaries spread all over the globe. Moreover, these two companies have very advanced logistical expertise in transporting large-scale elements around the world. These two factors mean that aircraft manufacturing companies that decide to enter the production of mass-customized envelopes for commercial real estate already have the flexibility to shift the focus of production from one factory to the other according to the demands of the market; it also means they have the ability to ship envelope systems parts to a variety of locations when demands in these locations rise.

8.2
AIRCRAFT MANUFACTURING COMPANIES HAVE ALREADY OVERCOME THE BARRIERS TO ENTRY IN EMERGING MARKETS

As outlined in chapter two, most future urban development will take place in frontier markets such as China, India and Latin America. A foreign company that wishes to succeed in these markets not only needs to have a deep understanding of the supply and demand trends in the market it wants to penetrate, but also be familiar with the local authorities, the regulatory requirements, the local culture and business community. This process of getting to know a new regional market can sometimes take years.

Aircraft manufacturing companies such as Boeing and Airbus have already gone through this process. For years, Boeing and Airbus have had sub-assembly lines in China and India and other frontier markets; they are already familiar with the local authorities and have strong networks inside the local business community. All of this would clearly ease the transition into becoming a supplier of envelope systems in the construction industry in the markets where urban development is expected to be the strongest.

8.3
AIRCRAFT MANUFACTURERS ALREADY HAVE THE EXPERIENCE AND THE TECHNICAL CAPABILITIES TO PRODUCE MASS-CUSTOMIZED ENVELOPE SYSTEMS FOR COMMERCIAL REAL ESTATE

As described in detail in chapters six and seven, aircraft manufacturing companies have the entire skill set to manufacture mass-customized envelope systems, and therefore would have to make a relatively small investment in order to begin production.

8.3.1
HIGH PROFICIENCY WITH BIM USE

Building Information Modeling (BIM) -- which plays a key role in process of producing mass-customized envelope systems for commercial real estate projects -- is widely used by aircraft manufacturers, and used in a more sophisticated manner than in the AEC industry. BIM and 4D BIM software are used not only to design and fabricate the airplane fuselage and wing parts, but also to analyze their assembly process. Moreover, Digital Project (DP), the dominant BIM software which is used in the AEC industry for detailing buildings that employ complex geometry, is actually a leaner version of CATIA™ , the main BIM software that is used in the aircraft manufacturing industry. Therefore, aircraft manufacturing companies will not have to spend money on buying new working stations or on special training for their design engineers and manufacturing technicians. Aircraft manufacturers can also take advantage of their already existing transportation infrastructure to ship the envelope systems' panels from the factory to the construction site.

8.3.2
AIRCRAFT MANUFACTURERS ALREADY HAVE THE TECHNICAL EQUIPMENT AND PERSONNEL TO MANUFACTURE BUILDINGS' MASS-CUSTOMIZED ENVELOPE SYSTEMS

Probably the most important factor favoring a move by the aircraft industry into mass-customized envelope production is that fact that aircraft manufacturers already have the required machinery to fabricate the envelope systems. They have the extradition machines, autoclaves, painting stations , 6 axes robotic arms, CNC machines, laser cutters, 3 axes water-jets, stretch forming machines, superplastic forming ovens and other necessary equipment. They can thus avoid the initial massive expense that is needed to set up a production line. Moreover, since aircraft manufacturing companies are using Toyota Production System to continually self-improve, they can learn how to streamline the production processes, so that while certain machines are not being used for producing aircraft parts they can be utilized to manufacture mass-customized envelope systems.

As already mentioned in chapter seven, aircraft manufacturers can use depreciated laser cutters that no longer meet the required standards for fabricating aeronautical parts, for the purpose of manufacturing buildings' mass-customized envelope systems. Further research needs to be done in order to find more fabrication machines and production equipment that is no longer adequate for manufacturing aeronautical parts, but would still be suitable for the standards of fabricating elements for mass-customized envelope systems. Furthermore, since aircraft manufacturing companies would use the same equipment in the production of both airplane parts and mass-customized envelope systems, they would not need to spend time and money training employees to use them, and there would be no need to recruit new manpower -- at least at early stages of the transition.

8.4

THE STEPS THAT AIRCRAFT MANUFACTURING COMPANIES NEED TO TAKE IN ORDER TO SMOOTH THEIR TRANSITION TO THE AEC INDUSTRY

Although aircraft manufacturing companies already have the technical equipment and the skilled workforce to manufacture mass-customized envelope systems, they need to realize that there are crucial differences between the organizational cultures of their industry and that of the AEC industry. While an aircraft is designed and manufactured under the umbrella of one entity, buildings are usually designed by a design team of architects and engineering consultants. This team is usually separated from the construction team and from the sub-contactors who fabricate the building's parts. If aircraft manufacturers want to smooth their transition to producing mass-customized envelope systems for commercial real estate, they need to set up a team of architects and engineers who would serve as liaisons between architects and developers and the different manufacturing departments in the company. The role of this team would be on the one hand to provide information to architects and developers regarding the technical capabilities, schedule and cost estimates, and on the other to understand the design intents of the architect and the budget constraints of the developer. This idea of setting a team that will connect architects and developers to the envelope systems fabricators derives from the conclusions of the two case studies in chapter three. In both case studies architects accommodated the design of the project facades to the technical and budget limitations in order to see their vision realized.

Another key difference between the processes of aircraft production and erecting a building is that while airplanes are being assembled in the same sterile environment of a factory, a building is constructed on a specific constriction site. Every construction site can be thought of as a production line floor in a factory. Since every construction site and every building are different, it would be extremely complicated to fully exploit Lean Manufacturing methods to optimize fabrication processes, cut down on costs and shorten the construction of a building.

If the AEC industry wishes to become more efficient by utilizing Lean Manufacturing methods, the process of erecting a building needs to shift as much as possible from the construction site to the factory floor. Aircraft manufacturers can apply their experience in installing plumbing, electrical and air condition systems in the fuselages of aircraft to producing modular units for the construction of buildings. In the modular construction method, the building is comprised of six sided boxes which are fabricated in a factory and transported to be assembled on the construction site. All the systems and finishes are already installed in each pre-fabricated unit before it reaches the site construction. While the finishes inside the passengers' cabin are limited by safety regulations and therefore are not like the interior finishes of a home or an office, one must keep in mind that aircraft manufacturers have experience installing prestigious finishes in first class and private jets. [167]

In addition to the experience of aircraft manufacturers in sub-assembling airplane parts which contain much more complex systems than those of a building, aircraft manufacturing companies can use their familiarity in implementing Lean Manufacturing principles for the purpose of streamlining the production of modular units, thus cutting down manufacturing costs and shortening the production cycle of a real estate project. Shortening the duration of the building construction period has great importance. Developers decide to launch a real estate development venture based on their analysis of the market in a certain point in time. Since it take years to finish a project, by the time the building is finished the market demands can completely change and the developer may realize a lower price than what he or she expected. The more portions of the building that can be fabricated in a factory, the more the AEC industry will be able to take advantage of Lean Manufacturing methods to shorten the time of the construction, thus lowering the risk for the developer. Using a modular construction method can also reduce the environmental hazard, since most of the construction work is done in the controlled environment of the factory instead of on the construction site.

The option of going into the manufacturing of modular construction units opens the door for aircraft manufacturers to provide Design-Build services. The same team of architects and engineers that was suggested earlier as a liaison between aircraft manufacturers and developers might also provide design services. Since this team would be working under the same roof as the

[167] Jacob Goldklang, Chemical laboratory manger and quality assurance supervisor in the Israeli Aerospace Industries, interviewed by Shaul Goldklang, June 1, 2013.

modular unit fabricators, the design and production processes could become even more efficient. Moreover, the technical expertise and skilled workforce of the aircraft manufacturing companies would allow them to produce modular units with more diversification, in keeping with the spirit of mass-customization.

8.5
IS THE MARKET OF PRODUCING MASS-CUSTOMIZED ENVELOPE SYSTEMS LARGE ENOUGH FOR AIRCRAFT MANUFACTURERS?

Even if aircraft manufacturers would be able to minimize their initial investment in setting a production line for mass-customized envelope systems, there is still the question of whether the market of producing such envelope systems is big enough to shake the needle of such huge conglomerates as Boeing and Airbus. This part of the thesis will provide a “back of an envelope” estimation of the potential market size of mass-customized envelope systems. This estimate can be used in making a judgment as to whether a move into the production of mass-customized envelopes for commercial real estate is in the financial interests of Boeing and Airbus.

8.5.1
BASIC ASSUMPTIONS

Our first assumption is that mass-customized envelope systems would be fabricated and assembled in the same way as a unitized curtain wall. We can thus make a ballpark estimation of the cost of mass-customized envelope systems by looking at the cost per square foot of a curtain wall. According to a report from May 2011 by Davis Langdon at AECOM company, one of the world’s biggest construction consultancy firms, the cost of a curtain wall which is made from glass and solid metallic panels ranges between $93 and $107 per 1 square foot. [168] We will take the more conservative assumption and choose a cost of $93 per 1 square foot, canceling the extra complexity of the fabricating mass-customized elements with the increased price of the raw materials.

The second implication that derives from the

[168] Davis Langdon, An AECOM Company , Curtain Walling - Still Going Strong, May 2011: 11. http://www.davislangdon.com/upload/StaticFiles/EME%20Publications/Specialist%20Costs/SpecialistCosts_Curtainwalling_May11.pdf

assumption that mass-customized envelope systems are basically sophisticated curtain walls is that the implementation of mass-customized envelope systems will be probably be more common in office buildings than in housing. As mentioned in chapter two, according to a McKinsey report regarding the future urban development in China, between 20,000 to 50,000 office buildings, of at least 30 floors each, are expected to be constructed by 2025 in Central Business Districts (CBD) all across China. [169] For This thesis assumes that a typical floor perimeter is 780 feet [140 feet X 250 feet] with an area of 35,000 square feet per floor , and that the typical floor-ceiling height is 12 feet. [170] Therefore, the average envelope area of a typical 30 story office building would be 280,800 square feet.

The thesis investigates three scenarios: a conservative scenario in which only 20,000 office buildings will be built during the next 12 years in CBDs all across China; a moderate scenario where 35,000 office buildings will be constructed; and an optimistic scenario in which 50,000 office building will be erected by 2025. As mentioned above, this thesis will make the conservative assumptions that all these office building would be no taller than 30 floors and the cost of a curtain wall would be $93 per 1 square foot. These assumptions lead to the following calculation for three scenarios:

The number of expected office building to be constructed in China X The cost of a curtain wall per one square foot X Typical envelope area of an 30 floors office building = **How much will be spent on China's office buildings curtain walls until 2025**

[169] "Preparing for China's Urban Billion | McKinsey & Company," March 2009. Accessed June 8, 2013 :6. http://www.mckinsey.com/insights/urbanization/preparing_for_urban_billion_in_china.

[170] Peter Roth, *Real Estate Products*, 28.09.2012, MIT.

	The number of expected office building to be constructed in China	The cost of a curtain wall per one square foot	Typical envelope area of an 30 floors office building	**How much will be spent on China's office buildings curtain walls until 2025**
Conservative Scenario	20,000 Buildings	$93	280,000 square feet	**$522.3 billion**
Moderate Scenario	35,000 Buildings	$93	280,000 square feet	**$914 billion**
Optimistic Scenario	50,000 Buildings	$93	280,000 square feet	**$1.306 trillion**

For the sake of the simplicity of this exercise, this thesis will assume that there will be no extreme ebbs and flows in China's economy and that it will stay steady in the next 12 years, which means that number of new office buildings that will be built each year will be the same. Thus, even according to the conservative scenario, *$46.025 billion* per year is expected to be spent on office building curtain walls, a sum which represents approximately 50% of the revenues of Boeing (S81.7 billion)[172] and Airbus ($74.5 billion) in 2012.[173]

One might argue that no one manufacturing company would take over the entire market of curtain walls for office buildings in China, and that the figure is thus exaggerated. However, there is also a vast potential in the markets of India and Latin America: even if three or four such companies were to enter this market, profits would still be enormous. Moreover, this estimate does not take into consideration the multifamily residential buildings, which, with population estimates soaring, will be necessary by 2025. The point is this: there is a market there, and it is large enough for the aircraft manufacturing industry to consider.

[172] The Boeing Company, The Boeing Company 2012 Annual Report :8. https://materials.proxyvote.com/Approved/097023/20130301/CMBO_157699/The_Boeing_Company_AR_3-11-13b/The_Boeing_Company_AR_3-11-13b.pdf

[173] "EADS 2012 Full Year Results." Accessed June 30, 2013. http://www.eads.com/eads/int/en/news/media.6f21f5fb-944b-4fa8-a204-691e0b03d5a3.-

CONTRIBUTIONS AND FURTHER RESEARCH

9

9.1
THE IMPORTANCE OF MASS-CUSTOMIZATION IN COMMERCIAL REAL ESTATE

The thesis began with the observation that until now, the "Digital Movement" in architecture has not succeeded in becoming widely adopted by mainstream real estate. Yet by taking advantage of computational technologies, architects can avoid the boring repetitiveness which was introduced by the Modern Movement in architecture and instead use mass-customized elements to give a unique and diverse designs to the different parts of a building.

As mentioned in chapter two, research has shown that good design adds value to buildings. This thesis made the argument that a building with beautiful facades not only increases its own value, but also raises the value of the buildings around it, which can in turn mitigate objections in zoning board meetings and smoothe the process of retrieving entitlements from planning authorities. Although there is a rational basis for this argument, further statistical analysis is required to provide evidence for this argument.

9.2
LESSONS GAINED FROM THE CASE STUDIES

It is obvious that the main challenges of implementing mass-customization in commercial real estate projects come from the relatively high cost of the fabrication and assembly of mass-customized elements in architectural scale and the shortage of companies that can fabricate them. However, the main contribution of the thesis is the insight that cultural conventions and project delivery methods in the Architecture, Engineering and Construction (AEC) industry also contribute to the problem. Many of today's architects have become so concerned with the discourse around computational technology that they have lost their connection to a project's construction side; these roles have been taken over by sub-contractors and construction engineers, leaving the architect with little more than the role of design consultant. If architects wish to reclaim their role as "Master-Builders" they have to understand the needs of the other parties that are involved in the process of commercial real estate development. Instead of relying on sub-contractors and consulting engineers to resolve the technical issues of the project design, architects need to adopt a proactive approach and educate themselves about these issues by working together with fabricators from the initial stages of their design, taking into consideration material properties, machinery technical capabilities, and budget limits.

On the other hand, it is obvious that part of the enormous financial success of real estate projects examined in the two case studies -- The Project at 8 Spruce Street and the Porter House --came as the result of their unique design. Developers need to acknowledge that a good architectural design adds value to a building, and while they have the right to benefit financially from their investment, they also carry the responsibly to make our urban environment beautiful.

9.3

OTHER INDUSTRIES SUITABLE FOR ENTRY INTO THE PRODUCTION OF MASS-CUSTOMIZED ENVELOPE SYSTEMS

The aircraft manufacturing industry has vast experience in manufacturing mass-customized metallic elements in architectural scale; it also has proficiency in the use of Building Information Modeling (BIM) and has advanced logistical expertise in transporting large-scale elements around the world. The thesis thus chose to look into the design and assembly processes of this industry in order to identify which of these processes might be adapted by the AEC industry so as to streamline its project delivery methods, enabling the more widespread application of mass-customized envelope systems in commercial real estate. Moreover, the thesis argued that the current limited competition between mass-customized envelope fabricators would be increased by the penetration of aircraft manufacturers into the relatively small field of existing fabricators.

As already mentioned in chapter five, another industry that has the potential to move into the field of producing mass-customized envelope systems for commercial real estate is the yacht manufacturing industry. Yacht manufacturing companies usually produce a limited number, or in many cases, only a single yacht from a certain model. Yacht manufacturers also have vast experience is fabricating double-curved metallic panels. Yacht manufacturing companies are significantly smaller in size than aircraft manufacturing companies, so they might be more suitable for small-scale real estate projects such as retrofits of small buildings or floor additions. However, there is a need for a more comprehensive research regarding yacht design and manufacturing processes in order to identify how these might be used in the AEC industry.

9.4
THE IMPORTANCE OF INCREMENTAL IMPROVEMENTS

This thesis did not presume to introduce a new technology that will enable the manufacturing of mass-customized elements in architectural scale at a competitive price. Instead, the thesis outlined incremental efficiencies, either in design and organizational processes or fabrication technologies, in order to streamline the production of mass-customized envelope systems. The theme of the importance of incremental improvements runs through the entire thesis. It begins with description of the design process of the stainless steel panels on the Project on 8 Spruce, where Gehry's office collaborated with Permasteelisa North America (PNA) in adapting the geometry of the panels so as to cut down their manufacturing cost. During the 1990s, aircraft manufacturers came to realize that the aviation technology had matured and in order stay profitable in an extremely competitive industry, it needed to optimize the design and production process. Aircraft manufacturers used Concurrent

Engineering, incorporated Lean Manufacturing and made more precise material selection in order to streamline the production process of aircraft and reduce costs. Accumulated together, these optimizations made a significant difference in the quality and the cost of an aircraft.

This thesis adopted the approach of looking for small improvements in order to create additional value. Therefore, the thesis exploited the gap between the required standards of the construction industry and the aircraft manufacturing industry, and outlined several fabrication technologies that could be adapted to the standards of the Architecture, Engineering and Construction industry; it also suggested that such adaptation could reduce fabrication costs. One of the key principles of Lean Manufacturing is the search for a continuous improvement of the production processes (known as *Kazien*). There is still a great deal of room for extensive research regarding potential fabrication technologies that are in use the aircraft manufacturing industry to suit the to the standards of mass- customized envelope systems. For example, useful research could be conducted to find which alloy types and dimensions would be suitable for use in superplastic forming with a Discrete Die in the shaping of metal sheets. Such information could prove valuable to engineers in the development of techniques for production of mass-customized envelope systems.

9.5
THE SCOPE OF THE MARKET OF MASS-CUSTOMIZED ENVELOPE SYSTEMS

The thesis concluded by outlining the incentives for the aircraft industry to transition part of its operation into the fabrication of mass-customized envelopes for commercial real estate, presenting a ”back of the envelope” estimation regarding the potential market for such systems. However, more rigorous due-diligence is required in order to obtain more accurate predictions for the demand of mass-customized envelope systems in different markets around the globe and in different real estate sectors such as multi-family housing and office buildings. There is also the need to conduct a thorough study regarding the size and capabilities of the dominant curtain-wall manufacturers in order to be familiar with the competition.

Today, mass-customized envelope systems are considered almost avant-garde. In order for them to become a widespread phenomenon in commercial real estate, we must do more than merely reduce manufacturing costs. There is a need for cultural acceptance of mass-customization in architecture. Just as modern architecture's Le Corbusier's Unité d'Habitation introduced the modern residential block, and Mies van der Rohe's Seagram Building presented the modern office building, the " Digital Movement " in architecture needs its own iconic buildings that will set the bar higher for mainstream real estate. It will take a visionary architect and a courageous developer with the right market timing to be able to execute this type of building.

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