SOME ASSEMBLY REQUIRED

Design ←→ Manufacturing Design ←→ Assembly Manufacturing ←→ Assembly

By

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Some Assembly Required
M.Arch. (2015)

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Abstract

Advances in design are transforming the means and methods of production and assembly by impacting how we approach a project from conception. Pushing the industry to rethink how we perceive design and explore working digitally.

Contemporary architectural thinking is heavily influenced by the digital workspace and the overall expression. Through modularization, this thesis has approached design from a small scale perspective to consider the design potentials in details, structure, and processes of construction by incorporating manufacturing and assembly into design from conception to gain a closer relationship between architecture and construction. This is done through the intimate knowledge of assembly and its production, which will then inform modular design, and relate to its method in modular construction. Designing with manufacturing and assembly in mind, means every process will demand a design environment that cannot remain in abstract or neutral states.

This strategy has enabled systems of design, manufacturing and assembly to become a new integrated hybrid for creative design which allows the architect to maintain focus over the digital to physical transition and embrace design intent. The stress on design development and the application of small scale detailed design decisions from conception are necessary in order to achieve accuracy and precision during the digital to physical transition that will assist in the constructability of the design.

This will be shown through devising solutions in modular design and construction to an existing buildings, project parameters. In this regard, there are a number of benefits that can be applied to current and future issues of construction and design which has opened a new window for fresh context where architects may re-engage with the broader culture to benefit society.

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1. Introduction

Advances in design production through the use of digital tools is helping to redefine architecture in both the virtual and physical world. 'The verb design implies certain associative leaps and intuitive calculations that are made based on seeing, thinking and doing. The noun design indicates the outcome of a process that can be analytically rationalized into series of discrete procedures' (Schön, 1988). The current software allows architects to design and conceive construction projects in greater detail of analysis and simulation: however, existing building methods do not allow the full capabilities of the latest design software or techniques to be achieved. Ryan Smith states that 'construction techniques have not changed over the last 80 year and it is believed that construction is one of the slowest of all industries of such scale in implementing sound technological innovation. Past experiences of construction have shown that linear processes and segregated information are the norm, and because of this, the industry lags behind in the available technology' (Smith, 2010). This thesis will explore the relationships between design, manufacturing, and assembly (Figure 1.1), integrating the and new opportunities in architecture within the concepts of prefabrication and modularization.

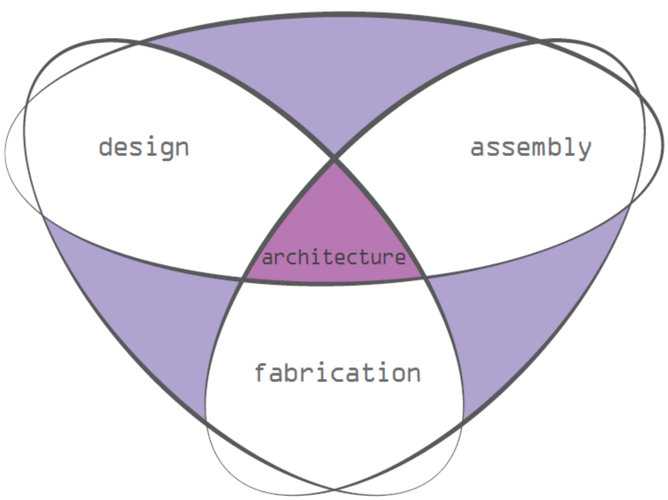


Figure 1.1 - Venn diagram

There is no one direct solution to control the architectural design into the manufacturing, assembly, and construction phases, but there should be a guide to follow so that this transition can be easily adapted and adopted for the specific project's needs. Therefore, this thesis will evaluate design, manufacturing, and assembly processes to gain a stronger relationship between architecture and construction. Conventional onsite construction projects go over schedule and over budget because issues are discovered during the critical phases of production and construction, these issues are addressed with makeshift solutions made by the manufacturer or haphazardly in the field by a contractor, not at their will. These issues include accuracy of assembly and their sequence, and can cause labour intensive, time consuming procedures. The idea is to establish a design process that addresses the needs of trades and project parameters from project conception. The knowledge and research implemented through this process will allow creativity and innovation to occur.

‘The shift of focus began viewing the design of objects to regarding them as production processes, from the raw material to the final assembly’ (Papanikolaou, 2008). This idea was brought about by Taiichi Ohno (Ohno, 1988), and later adapted by James Womack and Daniel Jones (Womack and Jones, 1996). They describe the value of all the processes and resources necessary for the final outcome, from design to construction. It begins with design concepts and the procurement of resources, and then transforming those resources into building components, and continues to the final build (Figure 1.2). This should not be considered as a linear structure; instead it is a network with a complex reiterative process which is conceptually portrayed in the Venn diagram.

This thesis will take one approach towards generating design and processes through greater integration between design, manufacturing, and assembly, to lead to more efficient design. In this thesis project, there is no interest in investigating the process of designing architecture for the sake of the process itself. This aspiration requires control and the ability to consistently have the determination to translate idea into form, intention into substance, through the fusion of purpose with place, craft and ethical design, which will support new trajectories into the discourse of architecture to elevate us all (Moe, 2012).

To harness this ability will help build the practice of architecture and create wide-ranging technological innovation. The possibility to gain control, reduce errors, push design and embrace responsibility is available within the design of prefabrication/modularization. Prefabrication is described as a process of manufacturing and possibly assembling components offsite in a factory and modularization is referred to as manufacturing and assembling a complete factory-finished product that enables the greatest percentage of the project to be completed in the factory, which is then shipped and placed onsite, leaving minimal work for onsite construction (Figure 1.2). Therefore in this thesis, prefabrication is a subset within modularization and digital fabrication is a subset within prefabrication. Recent advances of digital technology in the area of design and production have set in motion a remarkable effect not only in the practice of architecture, but on the entire building industry (Kolarevic, 2008).

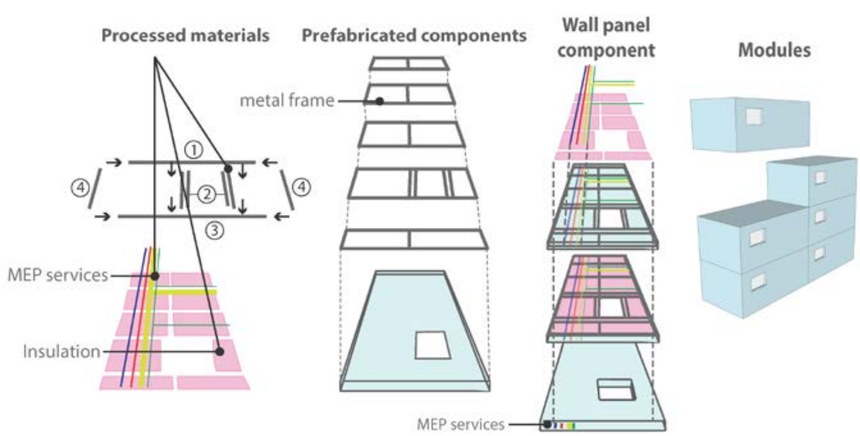


Figure 1.2 – Processed materials to Prefab components to Wall panel to Module

A shift in ideologies is required for any substantial progress within the construction and design industry. The construction and manufacturing industry is a creative resource to engage with. One significant change for the design team will be to work alongside the manufacturer, for their insight and expertise, and to gain an understanding of the machines limitations and benefits for the fabrication to become better informed during the design development phase. This shift would create a design process that is specific to machine dynamics to better inform the design decisions. 'The architect will have to evolve and the architecture of the future will be a hybrid of technologies influenced by science as much as art, and form as much as material, persuading us to rethink and reshape what we think of as the norm within industry standards' (Sheil, and Glynn, 2011). The forces of emerging technology are persuading the Architecture, Engineering and Construction (AEC) Industry to adapt to this shift in ideologies.

This thesis addresses the change in the design process for efficient and informed design. The area of research revolves around the tools and techniques available today. The inspiration from the research transitioned to an investigation in prefabrication and modularization current practices, market trends and opportunities, as well as the challenges within the field. The investigation was supported by research into recent modular and prefabricated case studies that include the Atlantic Yards B2 in Brooklyn NY, by SHoP Architects, SOMA Studios 38 Harriet St. in San Francisco CA, by Lowney Architecture, the T30 Hotel in Xiangyin China, by Broad Group, the Ballingdon Bridge in Ballingdon UK, by Michael Stacey Architects, and the Leadenhall building in London UK, by Rogers Stirk Harbour + Partners. Each precedent was chosen for a particular accomplishment and innovative technique to aid the thesis into a design. The literature related to the selected precedents covers critical commentary on design in prefabrication and modularization, construction workflows, manufacturing the bespoke, digital fabrication, along with building and assembly systems were reviewed.

The ability of digital drawings to drive fabrication machines, that can also guide and assist the process of assembly will create strategic design decisions and provide the opportunity to coordinate digital information of complex workflows, will hold enormous potential for AEC industry.

These digital technologies are repurposing the organizational hierarchy of communication and design from autonomous processes to collective workflows. 'The typical role of the designer as author and sole creator are changing with semi-autonomous, algorithmically driven design workflows embedded in a collective digital infrastructure. This is forcing the discipline of architecture to reorganize, to define the opportunities and the risks involved in these changes' (Marble, 2012). 'One focus of this change is the role design might play and the opportunity for architects to establish new streams that will shift the foundation for the next generation of architects' (Marble, 2012).

2. Problem Statement

Figure 2.1 - Digital representation and physical building are disconnected

Despite attempts to fight against industrialization, by the early 20th century, architects began to embrace its new technologies, as evidenced by the manifestos of the Italian futurists who wanted to abandon the past and embrace the future for a new aesthetic language based on industry, war, and the machine (Ostashevsky, 2010). The pedagogy of the Bauhaus, Metabolism architecture, and the International Congresses of Modern Architecture (CIAM) embraced the industrial revolution. CIAM's Le Corbusier is famous for stating, 'The house is a machine for living (Kroll, 2010).' This statement is not simply translated into the design of a human scaled assembly line; rather the design begins to take on innovative qualities and advances found in other fields of industry, in the name of efficiency (Kroll, 2010). These organizations had ideas about architectural megastructures and had a major part of the radical architecture movement, modernists like Superstudio and Archigram offered a hypothetical vision of a future machine age. During the time of the machine age, Nicholas Negroponte, who founded MIT's Architecture Machine Group in 1967, comprised of a lab and think tank which studied new approaches to human-computer interaction. Human–computer interaction (HCI) involves the study, planning, design and uses of the interfaces between people and computers. Negroponte is a digital idealist who believes that computers would make life better for everyone (Hirst, & Harrison, 2007).

Kieran and Timberlake say 'the failure to overlook the transfer of technologies and processes has led to generations of architects to diminish their responsibilities and focus' (Kieran and Timberlake, 2006). This problem is a key ingredient that initiated the work presented in this paper.

Since the digital era of the 1950's - 1970's, we have seen very little change in terms of construction methods compared to other industries (Kolarevic, 2008). Emerging computer based technologies have been avoiding critical agendas and gaining minor steps beyond the idealist shape making and form. This is partly due to the fact that it is very easy to create a fictional representation with the 3D models available in digital space (Figure 2.1). Philip Bernstein argues that the digital revolutions greatest contribution to the construction portion of the industry is our ability to create faster and fancier representational drawings that can be conveniently organized, reduced, and carried onto the site (Bernstein, 2010) (Figure 2.2). The ones that benefitted the most out of this were clients, not architects (Bernstein, 2010). The computer-aided drawing tools however were embraced by the architectural profession and began to imagine ways this can contribute to a digital society. There was a vast forward movement at the start but compared to other industries 'digital' architecture has not been able to maintain its early potential (Corser, 2010).

Figure 2.2 - Drawings conveniently organized, reduced, and carried onto the site

In recent years, the use of computer-based design tools in contemporary architectural practice has progressed rapidly in transforming form and spaces. However, there has been a lack of focus within the potentials of design practice and knowledge of skills to implement these tools to their greatest potential. Firms are now reorienting their practices and philosophies, dedicating practices centered around collaboration on computer-based design tools and CNC computer capabilities to develop the design practice. This is partly due to the costs of these specialized tools decreasing and becoming more available. Digital fabrication is used as a method of study for architects to test design theories and discover tangible ways of resolving physical elements that were created digitally. The increase of speed and power of new software and hardware is giving designers easy access to a growing toolkit of digital design and manufacturing resources at their disposal. This has opened a new window for fresh context to re-engage with digital design and physical fabrication, which can enable designers to create new processes of design practice and construction to fuel a transformation.

The thesis will compare standard practice of design and construction to prefabrication/modularization's design and construction, in order to adapt them into the project at the beginning to create a more informed design and build process. How can these emerging tools be fully taken advantage of when integrating systems of design, manufacturing techniques and assembly processes, and how they can support new trajectories for us to explore. 'In order to truly accomplish evolutionary innovation we must fully utilize these systems to its full capacity, once this point is reached, we must break that tool and use it in unconventional ways to advance our understanding' (Simondon, 2009). 'We have stepped into a 'post-digital' era, not that digital work is diminishing, but instead a new evolution of the term with the addition of system intelligence. It represents an architecture that is a synthesis between virtual, physical, linked, and other hybrids' (Speaks, 2007).

Intelligent programs are emerging and gaining more significance within design through computation, by cataloging material properties to guide the production of a specific object and transform the material in radical ways. Parametric platforms take the information and use it to computationally map the various components, breaking them down and manipulating each piece into unlimited shapes. Therefore, computation along with the integrated platforms like parametric and Building Information Modeling (BIM), will provide an agency for further quality control, and if programmed into manufacturing machine dynamics, it can lay out processes of fabrication and assembly for a closer relationship of file to factory to site. Such a future has been described in part by Sanford Kwinter: 'the potential of emerging digital tools is boundless, but only if they are used toward a noble goal' (Kwinter, 2008). With the incredible speed and advancement in technology, there is not enough time to fully investigate and utilize the emerging technologies mostly because there is so much technology out there and there are so many different ways of using one technology that it is not clear to anyone which works best or which is the most efficient and productive for their intended use. People tend to find one way to do something with technology and generally stick to that way, slowly educating themselves through general experience and by the time it is familiar, the technology itself is outdated or obsolete, usually within a short period of time (Hensel, 2013). The building industry needs to re-evaluate and update old construction techniques that have limited the industries potential. At the moment, the construction industry is so scattered that most of today's construction methods are not fully utilizing the technology available. With the growing complexity of architectural design and computer-based design tools, technology has become far more advanced than existing construction techniques today. 'Construction is one of the slowest industries of such scale in implementing sound technological innovation' (Smith, 2010), the problem lies in linking the advance level of design and their tools to construction methods. The ambition to persistently translate idea into form, intention into substance, will support new trajectories into the discourse of architecture to make beautiful buildings through the art and science of architecture to elevate us all (Moe, 2012). This thesis wishes to imaginatively engage AEC industries existing modes of design and construction with the application and adaptation of prefab modular design and construction, to speculate about the possibilities of new design and construction methods by integrating design, manufacturing, and assembly from the beginning of the project to gain a closer connection of digital to physical within architecture and construction. Rethinking design and processes in architecture to bring construction techniques into the twenty-first century through informed design decisions to achieve an efficient and possibly future oriented design and build process where the design development is given more stress during the initial phases of the project but produces and builds in a much shorter time in the closing phases of the project (Figure 2.3). Figure 2.3 shows a shift in the order, by putting more emphasis on the design phase, it can potentially reduce most of the other phases in the project, the site development can be decreased because typical modular construction use crawl spaces if need be, and since there are some standard techniques and designs that come with modularization it can potentially reduce the time needed for permits and approvals. The research information will be applied to an existing building to provide a different solution to the project parameters of that existing building using prefab modular design and construction; integrating methods of design, manufacturing and assembly into a project from its conception to run a digital simulation of the critical design and construction phases of the project. The critical details of the project will be constructed digitally to inform and organize the project's design and processes. Twenty-first century design should include detailed strategies for manufacturing and assembly by incorporating these processes from conception into the design, so that the design team is well informed and support an easy transition into the physical world. The industry needs to also incorporate automated machinery and other manufacturing techniques to take control of the repetitive and labor intensive processes.

Due to financial pressures and incentives around efficiencies in economic production, it is next to impossible to disregard this twenty-first century mode of construction of strategic processes, collaborative digital assimilation, and the automation of labour-intensive and repetitive processes that are being followed today.

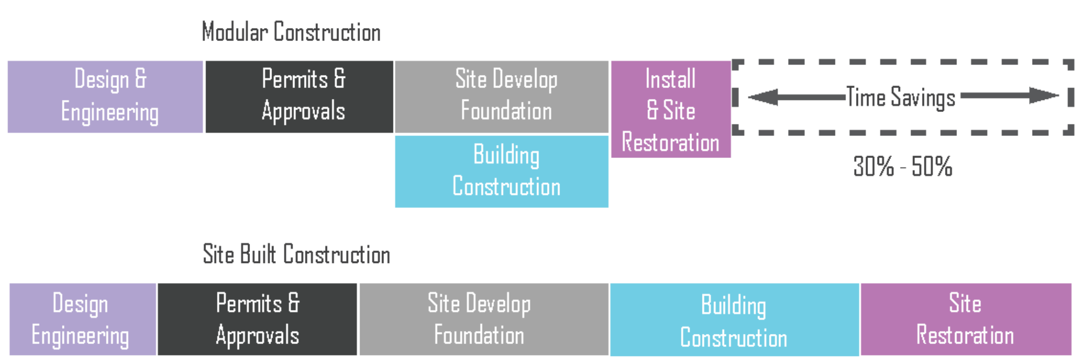


Figure 2.3 – Modular construction should have more stress on the design development phase of the project, and less stress on the construction phase of the project.

3. Setting a Train of Thought - Changing Perceptions

3.1 Design by Searching for a System

An academic project, at the Yale School of Architecture, titled “Assembly” was set out with only one objective, which was to exploit CNC technology. The focus on technology changed their means and methods of design which presented a different way of realizing the project, this in turn, became an experiment within design logic and how they approached the project from conception. As the students began to explore the design potentials, they realized that the central questions to consider was not dealing with the typical large scale design of site and massing; instead, the small scale details within material, fabrication and assembly were the main influence that initiated the dismantling and reconstruction of the design process (Buck, 2013).
Kisho Kurokawa is a renowned architect and one of the founders of the Metabolist Movement, his work was influenced by the attention to detail, the process of work was followed from ‘parts to a whole, and not from the whole to the parts’ (Kurokawa, 1959). The tradition of the craftsmanship did not leave his ideologies, as a result, Kisho continued his passion of fastidious fine details, and implemented them in all of his past and contemporary architecture and art projects. The attention to detail is an integral part of his forms and his signature for indigenous aesthetic of carefully detailed connections and finishes. He stated: ‘This attention to detail is also an important key to understand my own architecture. The belief in the importance of details also suggests the new hierarchy’ (Kurokawa, 1959). Kurokawa believed that Western architecture have been organized with a hierarchy from the infrastructure to the parts and details, while his approach to architecture focused on the autonomy of parts.

The logistics of digital workflows in the architectural design process are shifting the way architects design, the way manufacturers produce, and the way builders build, which in turn, is reorganizing the industry (Marble, 2012). The workflows in this thesis revolve around three themes that were once largely independent of each other, but are recently becoming an integrated system of design, manufacturing, and assembly. Note, it is by no means a linear process, there is constant back and forth development and reiterative processes taking place as the design progresses. The theme that keeps repeating throughout this research is that everything is interrelated; every component has an effect on something else, creating a sphere of influence dictating design decisions.

The first workflow is, Design: current practice is an integrated design process. With the abundance of digital information now available to run simulations that are both descriptive and analytical, the design development can achieve rapid feedback to aid in the design solutions and help the construction processes.

The second theme, manufacturing: is a material and organizational subject on how material properties and digital production influence design decisions. The term “file to factory” gives the architect a direct link to the manufacturing techniques and tools for building components when designing. The architecture firms that are dedicating time for research development will include in house workshops and digital fabrication as a common way to test concepts to aid in the design process. Architects should now incorporate these strategies at the beginning of the project to integrate the design within manufacturing, assembly, and the construction processes.

Through digital fabrication techniques, architects can easily visualize the way components come together with precise accuracy. Working with the manufacturer and understanding material properties, the assembly tolerance, the tool bit, and the machines abilities and limitations will be tested during the early project stages to minimize any unforeseen or uncontrollable phase and minimize labour on site. The detailed design information of materials and machines can allow ‘tolerances and assembly procedures to be numerically controlled and parametrically linked as part of an integrated workflow’ (Marble, 2012). Furthermore, ‘the design logic can implant the building assemblies into the manufacturing process, which will bring the level of design detail back to the role of craft in the design process’ (Agkathidis, Bettum, Hudert, & Kloft, 2010). This ability introduces the third theme of assembly. Knowing how the design will come together can enhance the design and details; the knowledge of the assembly process prior to manufacturing phase and construction phase, will create new geometries and components, to allow for new shapes in design and structure. Prior assembly knowledge will establish strategies to organize and map for delivery schedules, material production, storage, minimizing guess work, increasing safety, reducing congestion, and optimizing the construction schedule so there is limited downtime. Designing for assembly is the next step beyond digital fabrication where the rational of assembling building components is part of the design criteria at the beginning. ‘File-to-factory becomes factory-to-file, creating a shared iterative relationship between design concepts, material properties, methods of production and assembly sequences’ (Marble, 2012). The design information surpasses the representational and goes into highly precise sets of instructions used to drive the manufacturing and assembly processes.

There is a fourth theme that emerges from all of this but it should be regarded as more of a platform, that platform is labeled as designing the industry. This is not part of the themes because this is an organizational subject that manages multiple platforms which includes the first three themes as part of a larger whole. However, without these themes, this platform would not be possible.

The digital tools at our disposal have expanded faster than our ability to process and incorporate them into existing working methods, and will continue to do so because in the time it takes to fully comprehend something, it will become outdated (Hensel, 2013). The way to incorporate new information into design, manufacturing and construction relies on multi-disciplinary, specialized teams to follow, update, and adapt the information as it comes. Currently this is being addressed with the use of Integrated Project Delivery (IPD) and Building Information Modeling (BIM) techniques. Although these techniques are continually growing into new industries, it is taking other professions a longer time to make the transition as people begin to see their benefits. This in itself is also a design issue for organization as some may have biases that support or constrain from collaboration and the capabilities available within the digital platform. 'The question for architects to figure out is their position to either manage the multi-disciplinary teams, or if they can be redefined within a system of design and production. 'What will architects bring to the table? The definition of a new professional identity might be in order' (Marble, 2012).
Either scenario puts pressure on the architect to grasp the opportunities that will become available or define new ones that solidify their role in the context of specialized skills and information. This thesis depicts a hybrid of both, exploring the amalgamation of digital communications among architects, engineers, manufacturers, and builders, in order to alter how we conceive processes, labor, and the tools we use, that are structuring our industry.

> 'Technology is only one aspect of the problem; more connected thinking and barrier removal is required if the industry is to truly leverage the advantages that Design for Manufacturing and Assembly brings.'
>
> - Graham Herries, Functional Director, Laing O'Rourke (Film, 2014).

3.2 AEC Industry view on Modular Design and Construction

The AEC industry was established to create a set of standards between each industry, with the concept that each industry worked as separate entities, putting rules and limitations dedicated to certified specialists for liability purposes. Recently, they have been coordinating and integrating the industry into a cohesive unit to work more efficiently with the use of applications like BIM. Modern trends and complex projects continue to influence the exchange of information and coordination (Staib, Dörrhöfer, and Rosenthal, 2008). BIM, manufacturing methods, and productivity gains, will once again rejuvenate century's old-construction processes. 'Prefabrication and modular construction are processes that have been used by generations of construction professionals. Over the past century, these processes have developed a stigma of cheapness and poor quality. Therefore, why should people conduct forward-thinking market research on what many consider to be undesired, well-established methods used on construction projects?' (Abley, 2004). Through modern technology that persona is void; prefab modular design is being realized as a key component to innovative solutions to future constraints within the construction industry. These constraints include limited work space, access, and labour available on site, small urban infill in dense urban areas, and less time on schedule and impact on site. This re-emergence of prefabrication and modularization effect how project teams collaborate, and in some cases share all the risks (Kratochvil, 2005).

The digital tools available to us today have given the architect the ability to explore different methods of design with the use of online communities' digital platforms and communication to coordinate between disciplines in ways that they were potentially incapable of doing before.

The National Research Council identified "greater use of prefabrication and modularization" as a key breakthrough opportunity that could significantly improve the efficiency and competitiveness (Kratochvil, 2005). Much like BIM, what is most striking about prefabrication and modularization is the ability to encompass all of these trends; it brings all professionals together to improve productivity in construction. With a construction market facing critical shortages for onsite skilled labor, players are trying to be leaner, many believe the time is right now, more than ever, for widespread adoption of off-site prefabrication and modularization solutions on a major scale in the construction industry (Bernstein, 2011).

3.3 Collaborative Integration

The practice of architecture is beginning to recognize the advantages of modular design by adapting the design process into the digital realm. However, now that the digital foundations have been laid, designers are finding that the surface has only been scratched, and that there is a great untapped potential in the tools being developed which will have a great impact on practice, primarily in the design process and communication methods (Kieran, and Timberlake, 2006).

The construction and manufacturing industry is a creative resource to engage with. The practice has used three-dimensional digital models since 1989 to fully describe and understand the design intent. The thesis approach is to directly engage with the means and methods of construction through design, and control the process in detail. Architects are trained to critically think about the means and methods of design. At the moment, these are distinct from the physical means and methods of construction; this has traditionally and contractually been in the hands of the contractor (AIA, 2007). The professional obligation of an architect is to produce a set of documents at a level of detail sufficient to communicate design through a set of design documents (AIA, 1997). These documents may take the conventional form of two-dimensional drawings of plans, sections, elevations, and specifications as referenced in the RAIC, Canadian Handbook of Practice for Architects (Hobbs, 2009). Regardless, these documents do not comprise a set of instructions for construction and assembly of a building, and the drawings should not be exclusive to a visual perception and a set of drawings. The information should be imbedded into a design model that can be prescribed into a series of logical procedures for assembly and construction. The computer model should contain every aspect of the project, from site orientation, material quantity, down to each electrical socket. The model can be broken down into components which will be designated to specific trades to be fabricated and assembled. The project is then built with all the efficiencies and quality found in an assembly line and is built as designed (Beorkrem, 2013). The practice has used three-dimensional digital models since 1989 to fully describe and understand the design intent (Holden, 2012). The thesis approach is to directly engage with the means and methods of construction to control the projects process through design in detail. The success in today's complex construction is largely in part due to a closer link between the processes of design and its construction sequence. 'The constructability of a design is dependent on an effective means of communicating between the two' (AIA, 2007).

Many of today's projects include an architect that is closely involved with the fabrication, assembly, and construction processes. The success of the project requires all parties to conceive of contract that can create a cohesive relationship between each party involved to determine whether or not a design can be built as designed, and how difficult it is to build. The design documents must be clearly detailed for others to clearly interpret and comprehend the means and methods of construction in order to depend on others to be responsible for the building process (Corser, 2010).

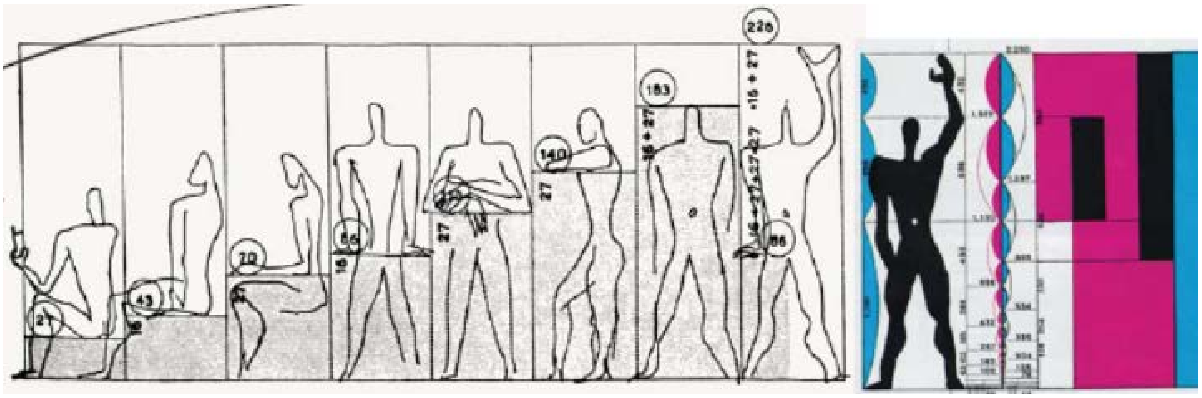


Figure 3.3.1 - Le Corbusier's Modulor Man 1946

Communication is also an act of design and construction, best illustrated by the constructionist model in which the architect Tadao Ando has communicated direct specifications for his unique concrete form making and Le Corbusier's drawings that communicated the Modulor proportions (Figure 3.3.1). Acts of making and re-making are fundamental to the way that architects and contractors relate to a specific design. Now the reliance on the unique craft can be automated from intelligent technology, which will eliminate most of the individual interpretations that are generated on site (Iwamoto, 2009). However, this automation can result in the loss of expert knowledge and can also mean that a cumulative group of experts may not get the opportunity to make recommendations to develop the design and processes further. The thesis views design as a process of collaboration, based on the experience of the participants and fuelled by research.

4. Methodology

I had the privilege of previously working in a precast modular construction company, alongside an engineer, in the office where we oversaw the production of the crew in the attached factory. Building models in the university workshop was a similar process to the one at the company, except the designs went directly from me into the machines at the school's workshop. I was always intrigued with the sense that a drawing could be interpreted by machines to carry out the intended design with precision accuracy and this created my passion for the subject. I quickly noticed any of the flaws of the designs were my own and not lost in translation. With this forewarning in mind, I wanted to know everything about these digital tools and how the machine operated; for instance, the material reaction of the blades on the machine and its tolerance, in order to fully realize the design concept and to utilize my capabilities and test them as far as I could.

Figure 4.1 - Hybrid Globe, Nuit Blanche, 2013

My initial research explored these areas and the tools that dealt with the complexities of design and fabrication. The interest in this thesis began with CAD/CAM design and production, researching new technologies of digital fabrication and their capabilities. Working with a team, one of the projects I was involved in was the Hybrid Globe, for a Nuit Blanche installation in 2013, using CNC technology that was component fabricated (Figure 4.1). Prior to finalizing a thesis project, the research went into exploring different manufacturing techniques used today to determine where the research needed to be focused and establish the type of project to explore further. I began to map out processes of the means and methods of production and the tools that were being used today so that I may find a pattern in design, manufacturing, and assembly. The intent was to show that there was a workflow to be learned and a process to discover (Figure 4.2).

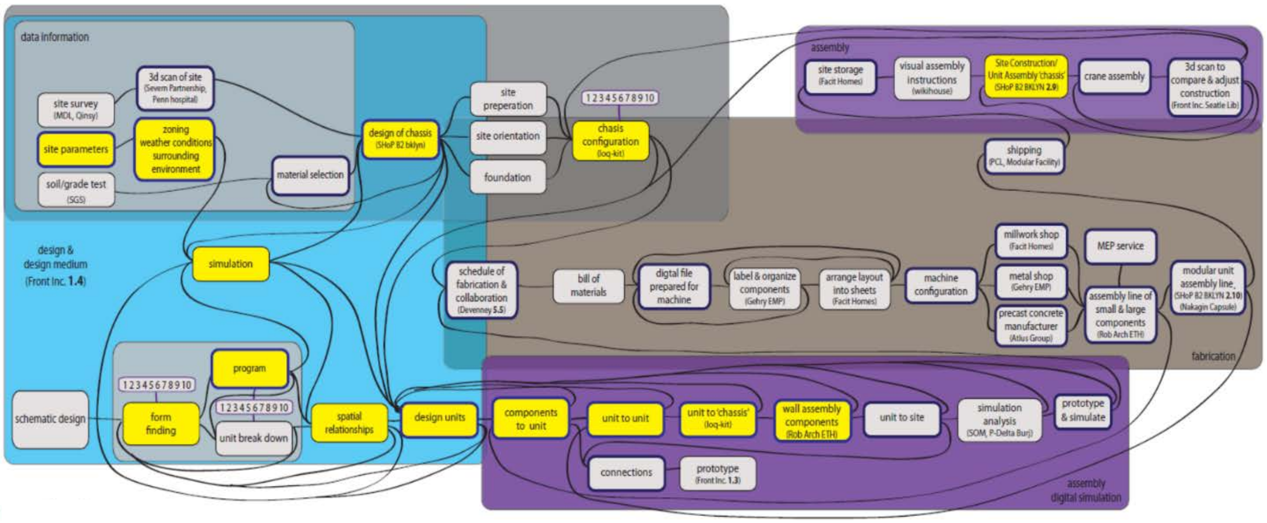


Figure 4.2 - A custom script to map out different prefabricated, modular construction projects which were integrated into one detailed process to track and highlight the relevant aspects of each case study researched

This was not reducing my research in the slightest, in fact it was the opposite, there were so many different ways to design and produce the same thing with infinite scripting scenarios.

The initial study had a linear structure when touching on the basic stages, but this quickly developed into a continuous loop of reiterative processes when each stage had an influence on the previous step. This revealed that there is little information provided to the design team on how the tools can be incorporated into a project from the beginning for a direction and set of instructions or a method to choose from when one decision may influence or reflect another.

Figure 4.3 - Full-scale facade mock-up, Seattle Central Library

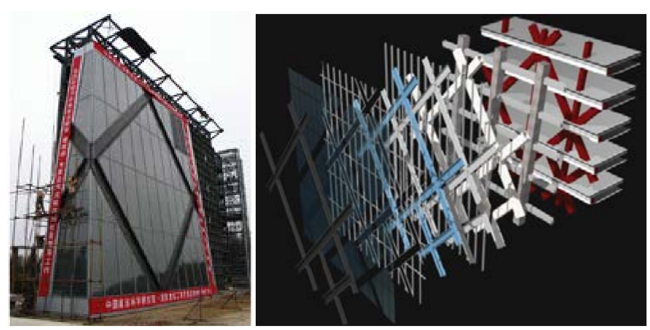


Figure 4.4 - Full-scale facade mock-up CCTV

The prefab projects include production processes that use a purely digital design and production process, detailing every aspect, this creates lean construction with an integrated team that follows the design and the construction from the beginning of the project to the end. Research on designing for assembly and prototype projects such as the Seattle Central Library in the US, and the CCTV in China by Front Inc. to study the complex geometries and test the configurations to withstand extreme environment conditions; each phase of the production and construction process was continually 3D mapped to compare with the

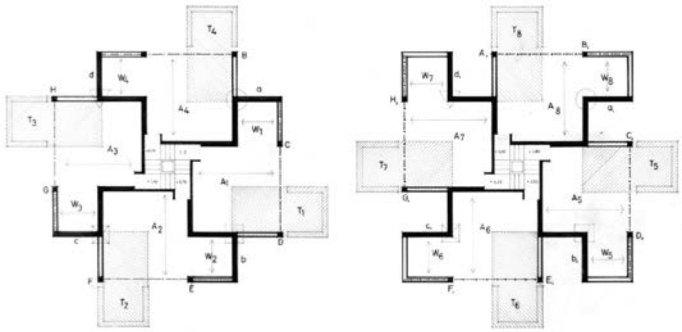


Figure 4.5 - Kafka Castle calculated module layout

3D model to make sure it was exact, if anything was out of place from the digital model by a few millimeters they would rebuild (Figure 4.3 and Figure 4.4). Research on assembly and connections from a group called loq-kit designed universal connections for maximum flexibility in their assembly and layout, the connections can be attach and detach accordingly; this presented the prospect of customization and flexibility for future adaptation. Case study research on module orientations and layouts from the Atlantic Yards B2 bklyn in New York, and Kafka Castle displayed the variations of custom module designs and layouts (Figure 4.5). Research on logistics and planning case studies were conducted to understand the required steps and collaboration needed for projects that were purely digital design and production processes. One in particular was the Sutter Medical Center by Devenney Group Architects which involved design specifications, coordinating teams, detailed schedules and communications with the use of BIM 3D modeling and 3D mapping (Figure 4.6 and Figure 4.7).

Figure 4.6 - Sutter Medical Center photo match of 3D Model to construction progress

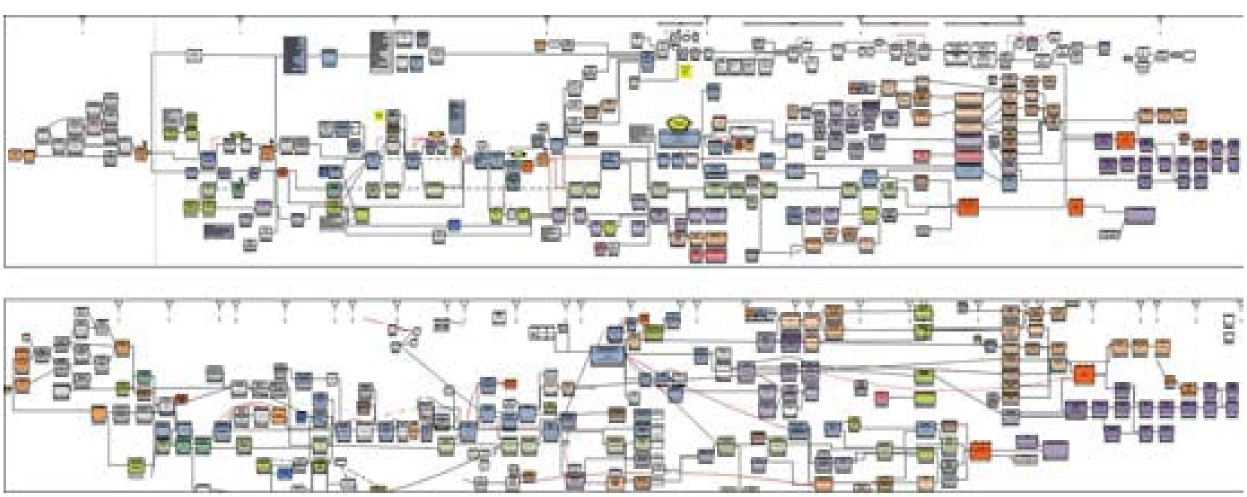


Figure 4.7 - Devenney Group Architects workflow map to coordinate teams

Knowledge gained from the previous research was implemented into the thesis project to include design for the manufacturing of components and sub-components, and design for assembly to requires accurate design detail for exact placement, and have integrated teams to follow a project from beginning to end. After extensive research I noticed a lot of case studies focused on the production and less on the assembly, in a crude way, assembly seemed to be an afterthought for some projects. When I first began using this technology, I noticed the machine had produced the parts but the assembly was left to manually plan and implement. After constructing the artifact, I learned there were more efficient ways to produce these parts that would aid in the assembly and its sequence. I concluded that in addition to the integration of design and manufacturing, the assembly process must also be merged into a holistic process. This integration is the next step that should be considered for a project to be optimized, resulting in greater design intentions and a new method of design. In order to grasp this integration of interrelated processes of design, manufacturing, and assembly, I explored modular construction and how this concept can be applied towards multifamily buildings. Having never dealt with modular construction before, I researched the modular market and discovered that modular construction was breaking ground on mid to high-rise buildings and major opportunities are foreseen in the residential sector of the AEC industry. Therefore, I decided my thesis project will engage with modular multi-family housing. Modular construction encompasses collaborative workflow integration at its core and was the best way to achieve the goals set. With the initial research on modular processes imagined, modular design was next to be considered. Some critical points to consider include an analysis on modular design and it's the limitations; for instance, the size of an enclosed unit that can be shipped. The allowable sizes were found by reviewing the Ministry of Transportation (MTO) website and consultant. This influenced the modules size, however, the actual size did not limit the design, rather it acted as a guide because of a modular technique called volumetric building, where separate modules can be added to create a larger span or space, for example, four modules can be considered as sub-assembly components to create one large unit, therefore, the design can potentially take any form or shape. Knowing the benefits of modular construction helped me chose a site that would benefit from modular processes and features. The allowable sizes for shipping a modular unit may also be affected by the access onto the site, therefore, many variables such as street width, crane, clearances, and lot size needed to be considered beforehand to finalize the ideal size of one module. It is important to try and include as many variable as possible so that the modules are designed for the largest percentage of work to be completed offsite. The structure and connections were influenced by the shape, orientation, and sequence assembly of the modules onsite. To do this, assembly and its sequence needed to be strategically planned in advance for the most efficient workflow to be conducted when the module arrives onsite. The research showed that to achieve a holistic process, each condition had an influence on the previous work and had an effect on the design. Other areas that contributed to this effect include code considerations and integrating other consultant considerations outside of the design team to be implemented throughout the building, as well as small scale design considerations such as module orientation, how they are assembled, MEP services that are distributed in the building and how they connect into the module, the structure of the module and the overall structural design for the building, fire separations, and the connections for assembling the modules onsite (Figure 4.8). This will all contribute to, and have an influence on, larger implications in the design and theories.

This integration between the other teams and the implications small scale details will have within the project has realized an opportunity to integrate the homeowner to participate with a custom design of their multifamily units. Therefore, with all of the knowledge acquired by the architect during the design development phase will be used to help shape and organize a custom living arrangement for the homeowner. One of the goals in this thesis was to imaginatively engage architecture's existing modes of design and construction in provoking and altering construction processes with the application and adaptation of modular construction, to rethinking design in architecture and the building industry. I believe this will be done through the stronger ties with the homeowner in developing their personal needs into a multifamily development compared to traditional methods of a multifamily development where the homeowner only has the choice between the sizes of their unit. This particular ideology has opened up the idea of a potential dialogue that can begin to alter the perception of how we design and build residential towers. The comments are not so much summaries as they are extensions of the arguments with the aim to encourage a continuing dialogue and debate about the role of the architect.

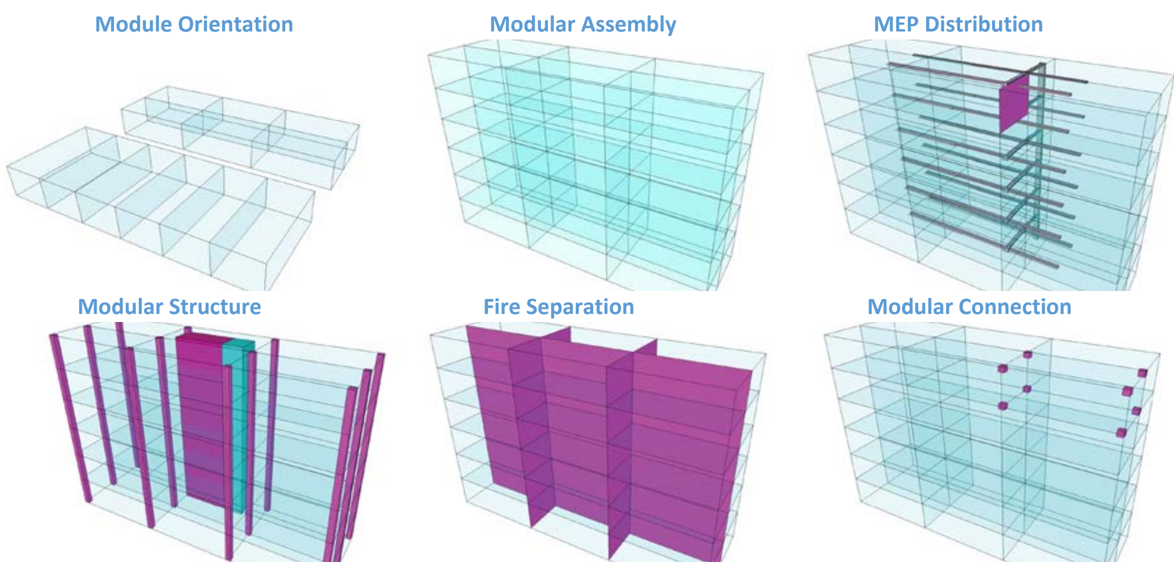


Figure 4.8 – Small scale design considerations that have an influence on larger implications of design and theory

5. A Case for Modular Design and Construction

Modular houses are constructed off site, transported to a site, and assembled into a finished home. All of the materials from framing, roofing, plumbing, cabinetry, interior finish, and electrical, are identical to what you would find in a conventional "stick-built" home. The modular factory system combines engineering know-how and factory-production methods to design and build more efficiently and with greater quality control that results in a better product, and at a quicker rate when the work is done simultaneously instead of linearly. Even stick-built houses today use a growing number of mass-produced, factory-built components that range from windows to complete wall assemblies, because the factory environment helps to organize the construction process. Virtually all of the best products in the world, from computers and appliances to automobiles and planes, are manufactured in factories, yet building onsite is still the preferred method in construction (Kieran, 2003), even though clients would reject new appliances and automobiles that were built in someone's backyard with no one watching over the assembly. Building modular compels the client and the developer to complete most, if not all, of the planning steps before beginning construction because the manufacturer cannot begin production without detailed designs. It is much easier to skip some of these steps when building onsite, since some tradesmen can potentially build things as they go when confronted with design flaws, this happens because detailing requires a large investment of time. Therefore, the planning discipline imposed by modular design and construction allowed me to understand the interrelated processes and stresses on preplanning within the design development phase to establish the assembly processes and efficiency within the design and construction of the project. The holistic aspirations of integrating teams and the discourse of architecture in modular design is defined by the close relationship and management of the overall project; better control over the design and its intended design outcome will lead to a quick turnaround.

Until the very end of the last century, exact repetition was the only way to achieve economies of scale (Moe, 2012). This was dominated by the modular industry because they can utilize this type of economy effortlessly compared to onsite construction. As a result, exact repetition lead to perceiving modular design and construction as a commodity. However, this barrier has been lifted by advances in digital techniques, as well as the techniques for building and assembling modules. Modules can come together in a number of ways to create an incredible variety of spatial forms including large span spaces and open-sided modules that can be combined to expand the design possibilities for modular construction. Almost any building can now be divided into modules, certain project types like multifamily, schools, hospitals and offices will receive the greatest economic benefit and will have significant advantages using this type of construction. Today economies of scale can be achieved through mass customization. The term mass customization describes the ability of certain products with pre-designed features to be customized. Digital design, computer numeric control (CNC) fabrication technologies, and various systems approaches allow mass customization to replace exact repetition as a means of achieving economies of scale. With the thesis workflow implemented architects can use this workflow to create custom designs and achieve an industrialized economy of scale.

A thesis objective is to have adherence for the client's aspirations by being more user oriented within the design process of a multifamily design, therefore, customization within modular design create an architecture that will elevate us all. Giving the client one principle company of design and build, utilizing machines instead of hands to achieve consistent results, This eliminates uncertainty and enables clients to be more involved/engaged with the project. Modular design and construction have more control over design specifications earlier in the process, meaning less arbitrary issues and alterations discovered late into the project. This has been deemed influential to architects as a way to position themselves within the radical and dynamic shifts in the industry today.

> 'Architecture can be a machine to live in, one that can embrace technology'
> - Anna Stewart, Laing O'Rourke's chief executive and project director of the prefabricated and modular Leadenhall building, UK (Films, 2014).

5.1 Brief History of Modular Engagement in Architectural Design

Figure 5.1.1 - Image of the Crystal Palace

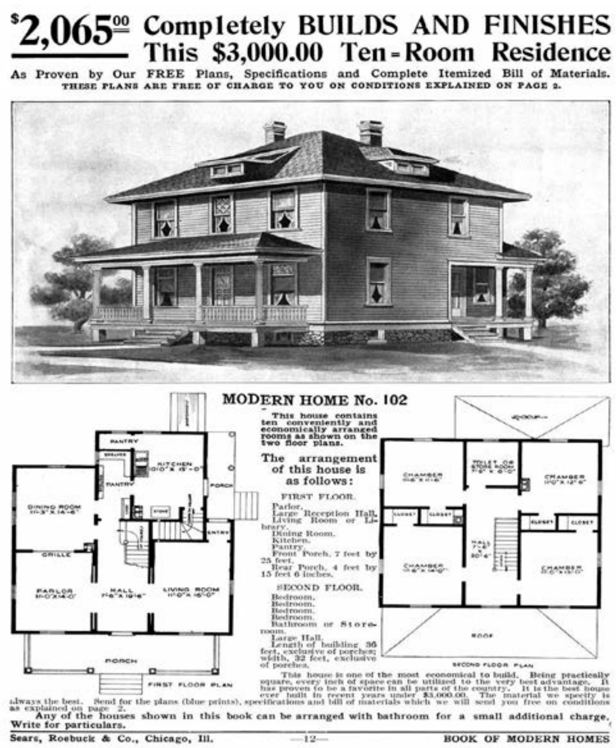


Figure 5.1.2 -Sears's catalogue home

An integral piece of history in prefabrication involves the Crystal Palace for Britain's Great Exhibition in 1851. The construction period took a few months to assemble and disassemble for relocation (Hutchings, 1996), (Figure 5.7.1). Prefabrications most famous development was 1908-1940, by Sears Roebuck Company who delivered mail-order homes that were assembled like barn houses. Prefab construction did exceptionally well due to the increased demand during World War II for its temporary and rapid economic fix using mass produced homes (Hutchings, 1996), (Figure 5.7.2). Evolution in prefabrication has shown significant advances in developing processes in construction and materials for more refined buildings. A notable milestone for modular building techniques was built in America, with a 500 room deluxe Hilton Palacio del Rio in San Antonio in 1968. The core of the building and all the guest rooms of the hotel were constructed as modular units with all six sides, which included all of the fixtures and furnishings. It took 46 days to place all of the rooms by crane and 202 working days in total from design to completion. The building is still in use and is a testament to the quality (Hutchings, 1996). The use of modular design has fluctuated based on economic pressures, but the technological advancement has increased what modular design can achieve. Attention for its efficiency, reduced waste and environmental accomplishments are major drivers for modular design, while providing a solution to the shortages of onsite skilled workers.

5.2 Market Drivers

The labor intensive techniques used in the practice of construction have seen very little change over the years. The construction industry has been criticized for low productivity relative to other US industries in the last forty years, as many seek efficiency with respect to time, cost and quality (Rahman, 2013). 'Adopting modular construction will be more defined as these areas are comprehensively acknowledged by key industry influencers, and market drivers are integrated with long term project development objectives' (Rahman, 2013). As companies become educated on modular design and their construction, the more they are willing to use it in projects. Market drivers are pursuing this through lean construction and performance architecture due to depleting resources, environmental concerns, and economic pressures (Bernstein, 2011). The demand for "green" construction and the growing appeal of integrating other industries through BIM technologies have many looking towards modular construction techniques, creating new generations of modular buildings being developed and installed. The National Research Council's 2009 report and the National Institute of Standards and Technology's (NIST) 2010 report have both recommended increased use of prefabrication, modularization, and preassembly as 'an opportunity for breakthrough achievement' (Bernstein, 2011). Modular construction has the ability to bridge all of these market drivers together because of the rapid developments in manufacturing and digital fabrication which are ultimately tied to the prefabrication of components within a factory setting, and modular transportation issues are continuously being addressed to make it possible for greater amounts of modular designs where the majority of the work can be fully fitted and finished offsite. Intentions of a fully finished modular unit creates an emphasis on preassembly offsite and assembly once it arrives to site for this method to be possible. These market drivers and technological developments make modular design a critical field for further research.

5.3 Building Sectors

The 2012 McGraw-Hill Construction labeled architects will have the greatest opportunity for modularization in multifamily units, K-12 schools, and hotels, because these typologies are cited to have the largest levels of activity. The value of this activity starts at $60 billion over the next two years (Bernstein, 2011). The potentials of modularization and its importance in this thesis moving forward will explore how architecture can gain leading roles in the development of multifamily modular housing.

5.4 Multifamily Development

A condominium developer is usually looking for the quickest return on investment, therefore phases are standardized to speed up the projects schedule. The design of the units become carbon copies of its predecessors and the layout will typically depend on the maximum number units that can fit on one floor. The homeowners have no contribution into the design and have little choice in options of living arrangements, other than choosing 1 – 4 bedrooms. The homeowner is expected to adjust their lifestyles to fit according to the unit, this I believe should be opposite. With the idea of team integration and coordination from the onset of the project has made me realize an opportunity for greater involvement with the potential homeowners, that way, the homeowner will be able to design a home unique to the individual with their lifestyle in mind, and have a greater choice in the number of beds and spaces within the unit as they can potentially create a spaces that range in width and number of floors. The more involved the user becomes the greater appreciation they have for the home. The ease and service of its delivery process are designed together to better reveal issues and support customer purposes.

The stress during the design development stages to work with homeowners could potentially create investment incentives with the added benefit of modular techniques that guarantee design intent and schedule. Having the construction phase accelerated due to modular techniques offsite can still achieve a fast return on investment.

5.5 Opportunity

The most notable opportunities in modular construction include reducing schedules and labour onsite, as well as the process of integrating and coordinating teams from the begging to the end of a project (Bernstein, 2011). Modular construction can offer guaranteed quality and control of a design on a fast schedule when compared to a traditional scheduled build of the same design. A fast schedule will also have a reduced impact on the surrounding area or active sites with existing businesses. For example, some modular suppliers have been known to deliver a wide range of facilities on schedules that seem impossible such as the SOMA Studios in section 5.8.2 and the T30 tower in section 5.8.3.

In modular construction, more focus is emphasized on the design phase to coordinate complex projects and for taking the time to strategically plan and arrange the factory floor to increase productivity. Most modular projects show the time spent on the design development phase is insignificant compared to the amount of time saved in the factory and onsite (Smith, 2010); strategic production techniques allow for less disruption and less downtime between workflows while construction time onsite is reduced from repetitive and lean processes by eliminating procedures through integrated approaches in the project with the use of better direction and communication (Moe, 2012). Lean processes in modular design and construction follow a production management-based approach where the process is structured throughout the design to maximize value and to reduce waste of anything in excess because the efforts are aimed at improving total project performance. These techniques will form the integration of design, manufacturing, and assembly, which open new opportunities to design and build. If there is no time saved on the schedule of a modular build (Figure 5.5.1), the stress on the design development will have the added benefit of assuring the details and quality are exceptional, and assurance on the schedule when the project calls for tight deadlines. It challenges the belief that there must always be trade-offs between time, cost, and quality (Hensel, 2013).

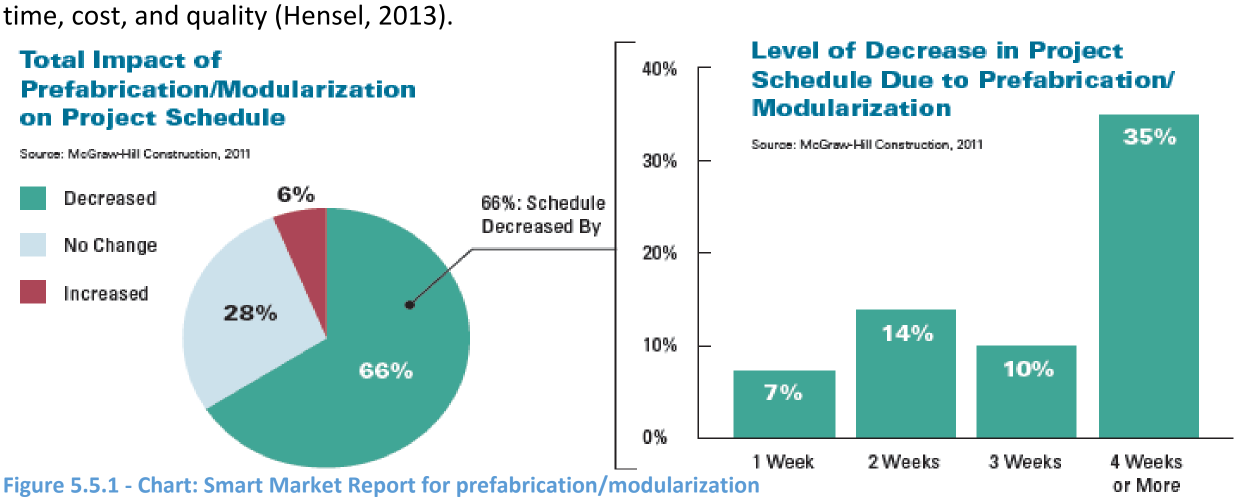


Figure 5.5.1 - Chart: Smart Market Report for prefabrication/modularization

5.5.1 Factors Driving Future Use

The Smart Market Report (SMR) is a construction market research company from McGraw Hill Construction Financial that inform and provide comprehensive and credible forecasts and trends. They state that because of the economic downturn, most of the architecture firms that are non-users of modular construction, are influenced by the opportunity to save money and concerned about their bottom line in order to stay competitive (Bernstein, 2011). The other top factors influencing their decisions to use modular construction are time, owner demand, competitiveness, and quality. The fact that owner demand is high enough to make an impact indicates that the public is becoming more educated and aware of the opportunities for future use. Therefore, tight budgets and time, while trying to maintain quality are critical for architecture firms to consider more use of modular techniques.

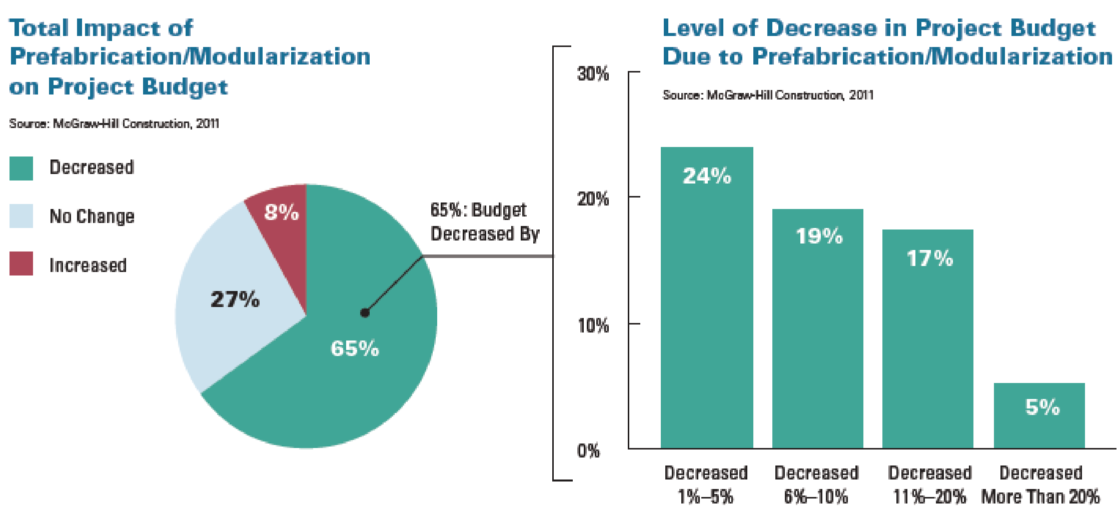


Figure 5.5.1.1 Chart - Smart Market Report on prefabrication/modularization Budget

5.6 Precedent Case Studies of Modular Construction

The purpose of the precedent case studies was to demonstrate how prefabrication and modularization impact architecture in order to be equipped with the right knowledge so that architects can discover more creative and innovative ways to design, manufacture, and assemble. The workflows in design and construction processes of modularization will be researched and used for references to the thesis project to gain a better assessment in areas that may have been difficult to determine or find otherwise. The case studies include; Atlantic Yards B2 in Brooklyn, NY, by SHoP Architects, because it has similar principles and processes in predesign and manufacturing that I want to implement into the thesis project. The second is SOMA Studios, which was chosen for its small urban living design and assembly build process onsite. The third precedent is the T30 Hotel in Xiangyin, China, which was researched for its unique manufacturing viewpoint and the how the projects workflow conducted the speed, accuracy, and assembly of its prefabricated components. The fourth precedent is a bridge design in Ballingdon, United Kingdom, by Michael Stacey, to evaluate a comparison between how a project is procured with and without prefabrication and modularization techniques.

The four case study precedents are adapted in influential ways to configure the thesis project and determine some undefined areas of the project. An overview of the general data upon which these case study projects are developed are provided to outline how these systems influence the design and construction process. The thesis project will incorporate this research to help outline some unknowns of multifamily modular housing such as schedules of managing and coordinating processes, roles and responsibilities, and detail work like structure and connections of the modules, wherein I can make an educated guess.

The first precedent case study involved looking into the ShoP Architects practise, as well as, one of their current projects. The core values of ShoP establishing and exploring new methods of practice in architecture. Their goals are to leverage design, finance, and technology to produce innovative architectural forms while to streamlining the design and construction process (Holden, 2012). Their approach is to eliminate any communication gaps between design and construction. The firm is strongly geared towards research and development to investigate the current trends and technology within the industry. They will then use that knowledge to consult with contractors and fabricators and begin to comprehend the way they work, in order to create better synergy to use as a tool during the design phase of the project so there is no language barrier (Holden, 2012). This is done to seamlessly integrate the means and methods that will be used during construction and incorporate them into the design development phase of the project. It also helps the fabricator to understand the design components of the model and the way it can be produced in order to translate the concept into a physical build. However, this collaboration in reality is not always possible, therefore, SHoP will assume what the means and methods of production are from the manufacturer if they cannot be provided/accessed during the design phase (Holden, 2012). They look into the entire project and consider the site, the cultural and economic environment, a client’s physical needs and budget constraints, as well as construction techniques, branding, markets, and post-occupancy issues.

5.6.1 Precedent One

Project name: Atlantic Yards B2 2012 – 2015

Architecture firm: ShoP Architects	**Number of floors:** 32
Construction company: Skanska USA Building	**Number of unit types:** 363
Manufacturer: Xsite Modular & Forest City Ratner	**Unit size(s):** Avg. 90-sm (940-sf)
Location: Brooklyn, NY	**Lot size:** 370-sm (4000-sf)

The scheme of the project was born from a need to find a more economical way to deliver 6,430 units of affordable and market-rate rental housing, comprising 560,000-sm (six million-sf) into 14 buildings, in a 22-acre village (M, 2012) (Figure 5.6.1.1). The B2 team consist of developer Forest City Ratner, and the contractors is Skanska, with sub-contracting work to ShoP Architects for the design and Arup are doing the engineering for the B2. The B2 team expanded to include Xsite Modular, who focus on high-rise modular buildings. Xsite and Forest City Ratner Company (FCRC) are partners in a 9,300-sm (100,000-sf) factory a few miles from the Atlantic Yards site. From the first cut of metal to placing the module onsite, will take about 20 days. "And we'll get faster," says Susan Jenkins, vice president of Skanska. BIM uses both model and clash-check, for thousands of small elements that have to fit into tight spaces. The B2-modular team developed a process that also rely on Virtual Design and Construction (VDC) tools as part of the design process (Figure 5.6.1.3). The B2 digital model is designed with production-level drawings for detailed instructions to help clarify the scope of work for each of the subcontractors in the factory and onsite, says Jonathan L. Mallie, a principal of ShoP. (M, 2012).

Figure 5.6.1.1 - SHoP render of B2 Brooklyn

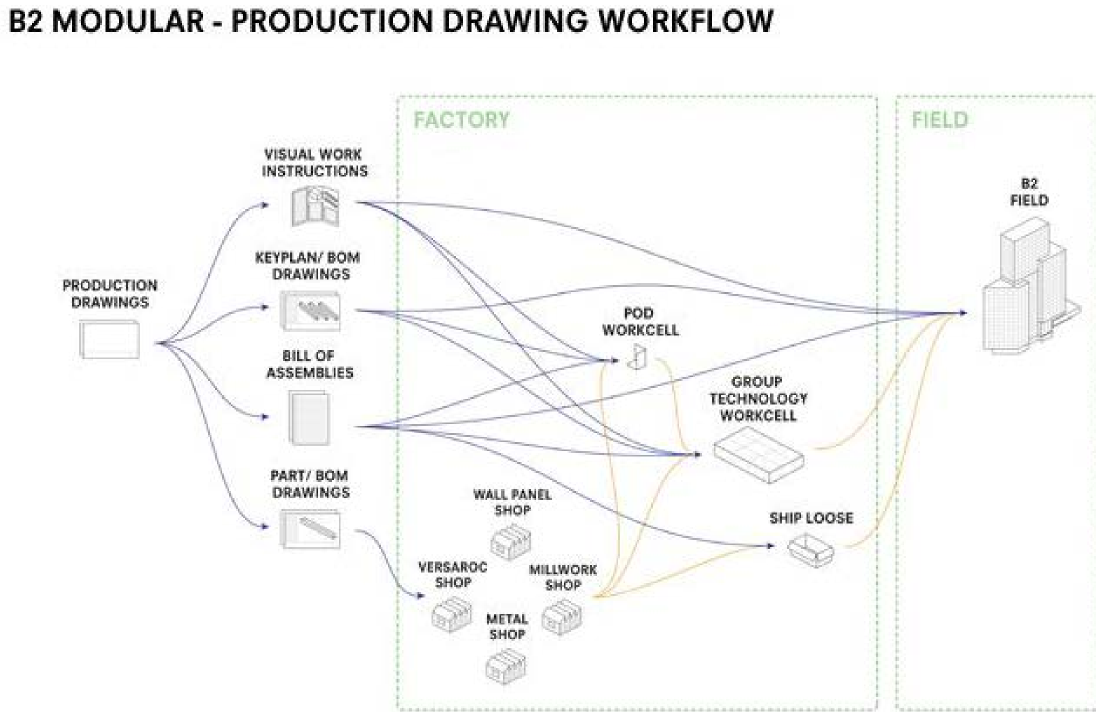


Figure 5.6.1.2 – The supply chain management of production models and drawings to the factory floor

Pro	Con
• Reduced costs by 25% compared to conventional construction, with a goal of $161/sf • Reduced labour, faster, greener, and less disruptive to the neighborhood because 60% of the project will be completed offsite (Dailey, 2014) • Digitally detailed production and assembly instructions • Preconstruction coordination • Innovative and pioneering project • Strong team integration, coordination, and strategic planning	• Permits acquiring the property • Backlash from the public displacing previous tenants • Criticism within the cities employment sector and labor agreements, from the reduced labour incentive of the project. However, an agreement was made with union workers which Forbes states the deal was as innovative as the construction technology itself (Bagli, 2014). • Scheduled to save 4-6 months off an 18 month schedule, completed by December 2014, but is now pushed back to late 2015 due to lawsuits.

ShoP provided a digital model for integration across the teams, as well as a supply chain for the management of production in the factory. Subassemblies are built and inserted into a module. Modules are then built and assembled into apartment units. Apartment units are then assembled into subfloor groups, and subfloor groups are assembled into the building (Figure 5.8.1.3). The BIM/VDC is a cloud platform to facilitate the collaborative design development information to ensure a seamless transition from digital to physical.

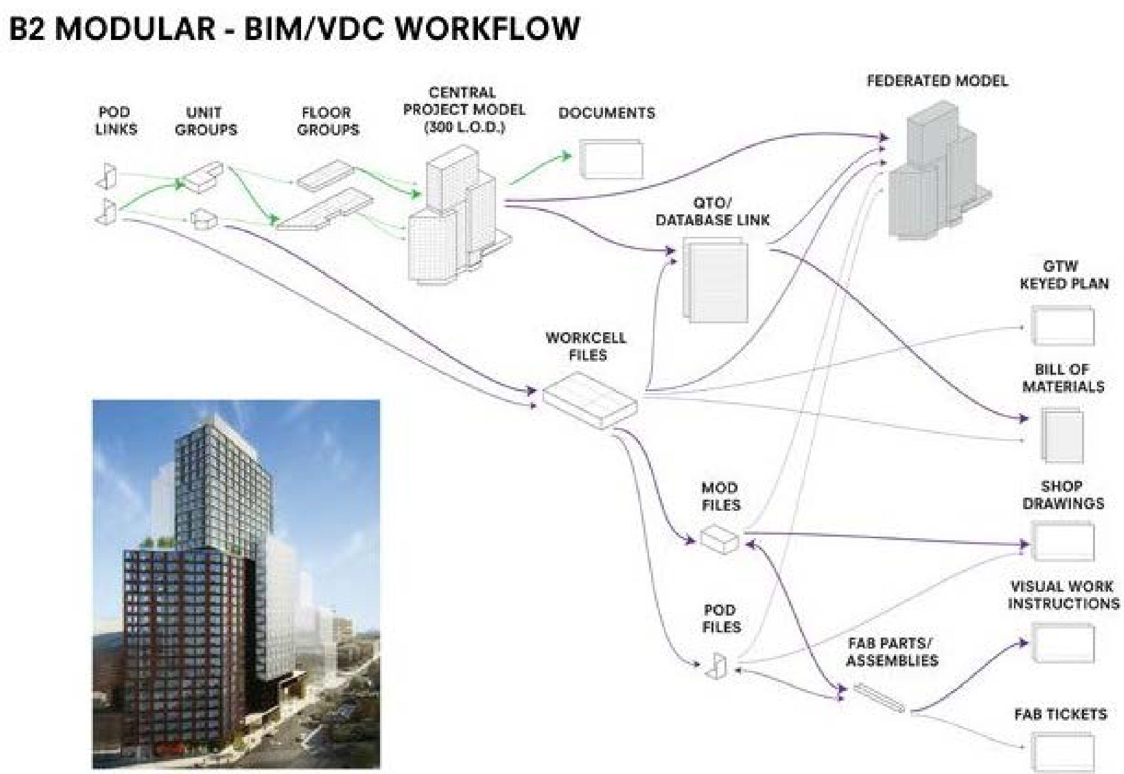


Figure 5.6.1.3 - The B2 BIM-VDC workflow diagram is designed to meet the needs of preconstruction coordination

Step 1: The fabrication process consists of a warehouse divided into designated areas of work (Figure 5.6.1.2). The materials and equipment are sorted and delivered to their appropriate locations by a logistics team for each trade to work simultaneously with others (Figure 5.6.1.4.4).

Step 2: Each module has all of its materials and components (steel beams, sheets of metal, screws, etc.) prepared and ready for trades in the factory. Along with instruction diagrams, which, according to Forbes "looks an awful lot like IKEA furniture assembly instructions" (Dailey, 2014).

Step 3: The steel beams and sheets of metal are assembled into walls and outfitted with all of the electrical and piping (Figure 5.6.1.4.1) (Figure 5.6.1.4.2) (Figure 5.6.1.4.3) (Figure 5.6.1.4.4) (Figure 5.6.1.4.5).

Figure 5.6.1.4.1 - Wall frames in the factory

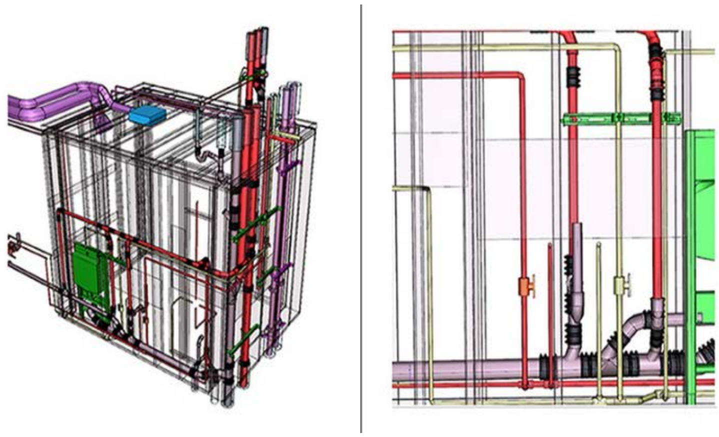


Figure 5.6.1.4.2 - Detailed bathroom piping illustration

Figure 5.6.1.4.3 - Specialists using dedicated equipment

Figure 5.6.1.4.4 - Warehouse divided into clear areas

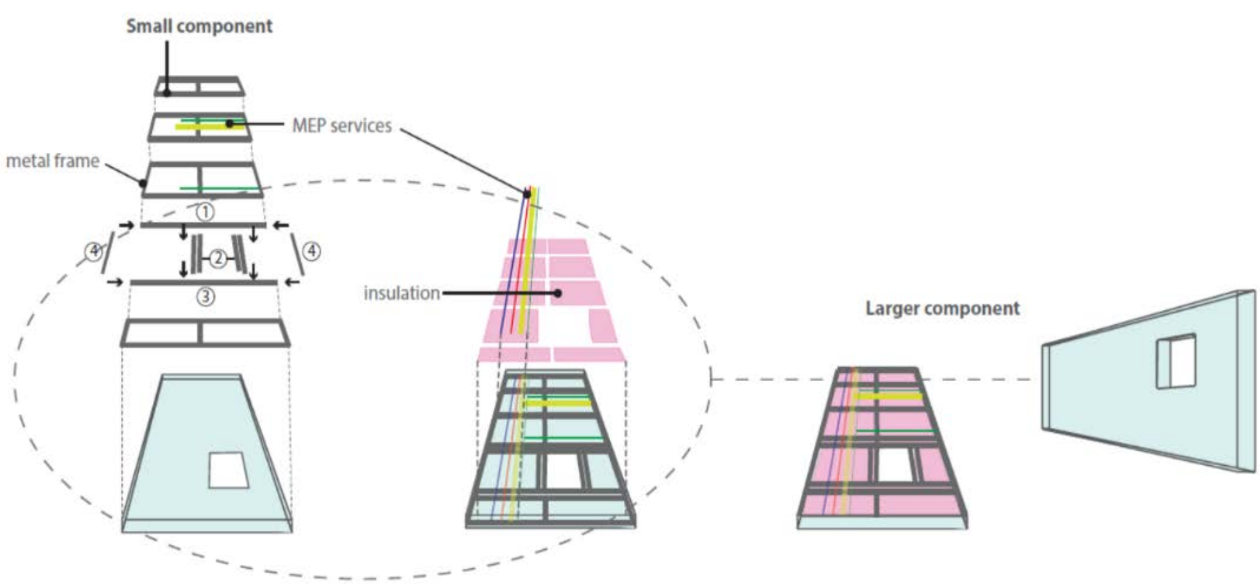


Figure 5.6.1.4.5 - Conceptual diagram of walls outfitted

Step 4: The bathroom pods are outfitted with toilets and bathtubs. The walls are also assembled into the modules (Figure 5.6.1.5). The goal is to complete as much of each module in the factory as possible.

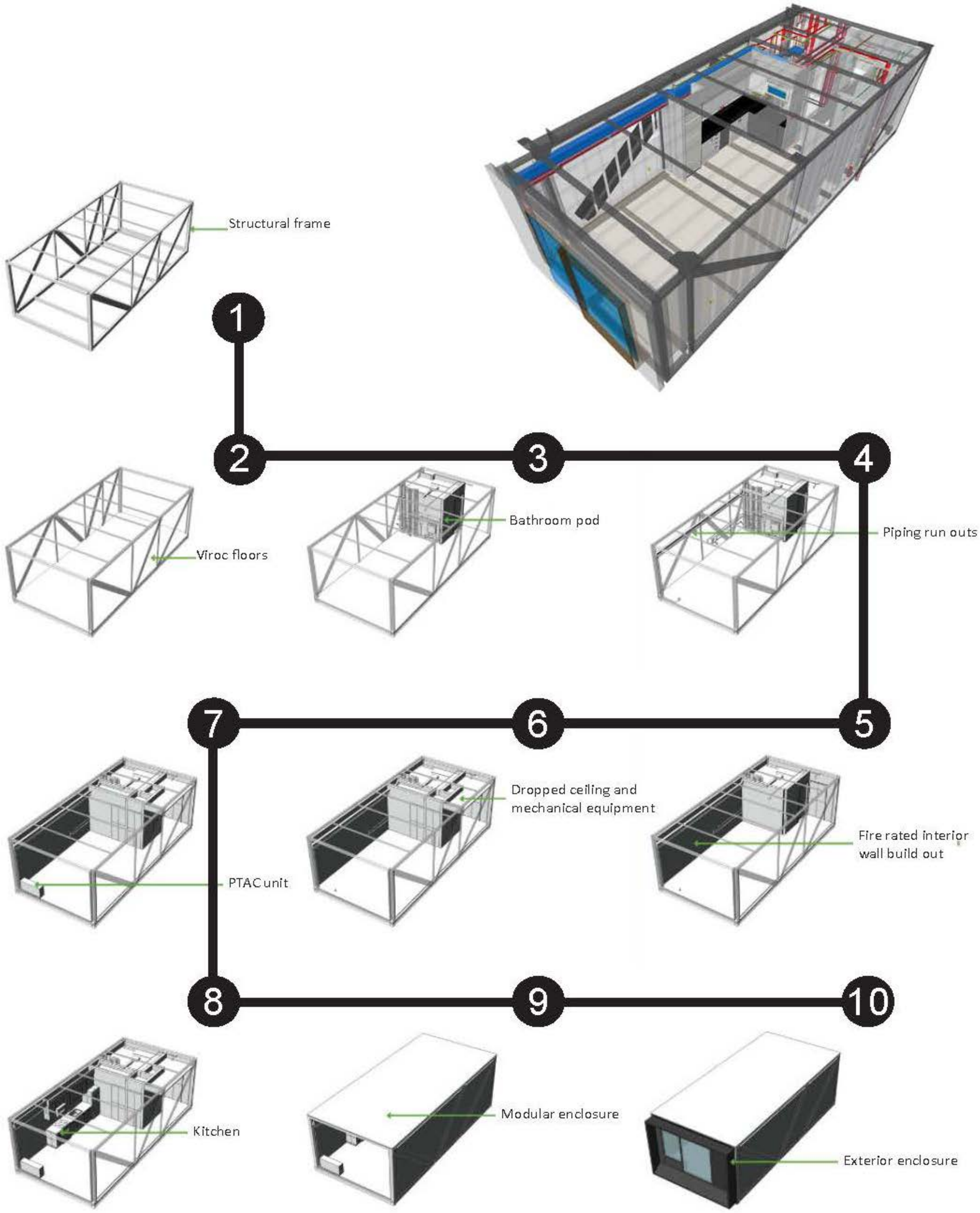


Figure 5.6.1.5 – Unit module configuration

Step 5: Assembled modules are shipped to the site, once it has arrived onsite, the modules are lifted by crane in sequential order into its designated place to create an apartment unit, this process is then repeated, once all units are in place, once all subfloors are set, it will create the subfloor group which will ultimately become the finalized building form (Figure 5.6.1.6).

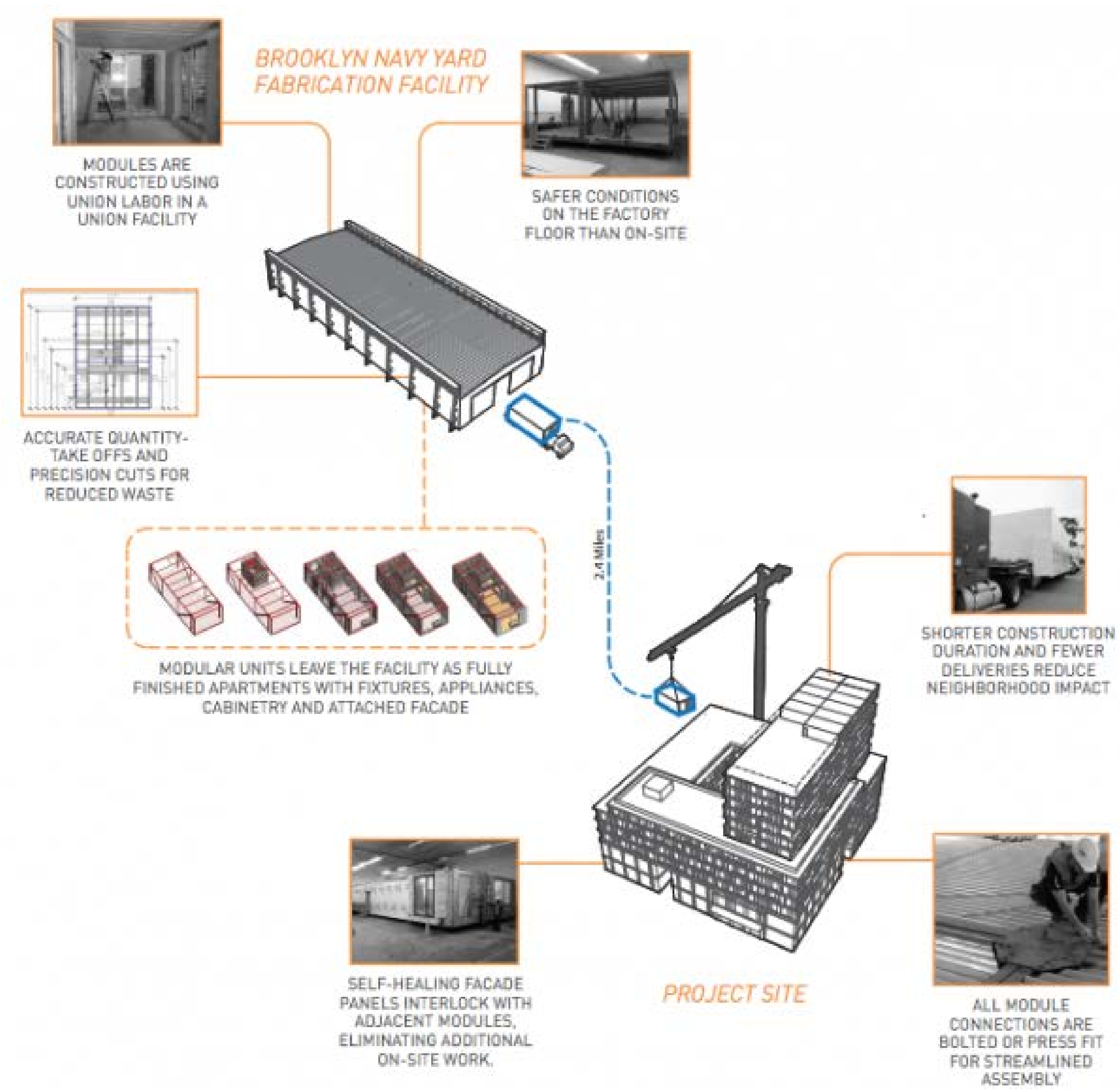


Figure 5.6.1.6 – General flow of modules trucked from factory and crane lifted onsite having the majority of the work complete

Step 6: Each module has a kit of precut connectors and equipment for workers to save time onsite. The press-fit pipes are installed as each level goes up (Dailey, 2014) (Figure 5.6.1.7).

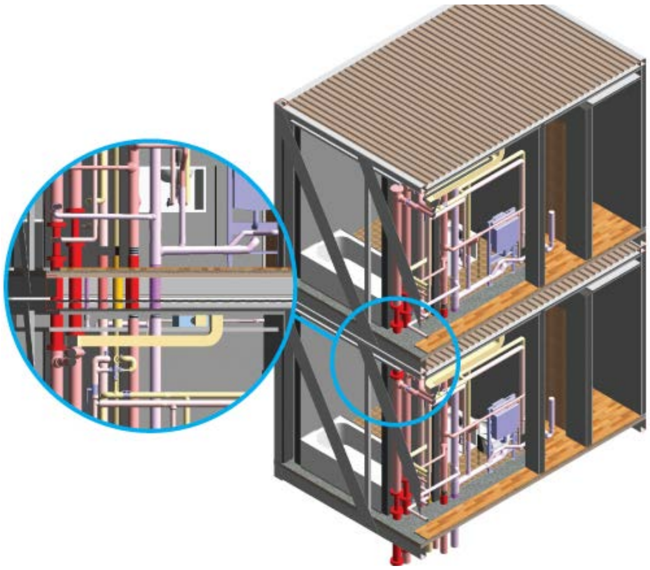


Figure 5.6.1.7 - A kit of precut pipes to install for onsite assembly

The 322-ft tall tower contains 930 steel modules (Figure 5.6.1.8), out of the 930 modules, only 17 are the same. The structure of the building was examined to adopt into the thesis project. The modules themselves consist of structurally efficient tubes that can withhold their structural integrity during shipping, eliminating the need for any temporary bracing (Figure 5.6.1.9). Since the project is pioneering in ways such as the structure, I believe the structure on B2 is overly designed because the modules themselves are structurally sufficient to make up the structural brace frame but they were designed with an added exterior brace frame and truss for the module to be docked inside. This creates a larger wall assembly, more materials, and less interior space.

A modular design will inevitable involve a proficient structure, because of the redundancy in the structure that requires a floor and ceiling for each module (Figure 5.6.1.7). The thesis integration of design, manufacturing, and assembly, make it necessary to understand the structural properties and detail connections needed for production and assembly purposes, this knowledge can provide an opportunity for a leaner and more efficient structural design and construction processes. Instead of perceiving this as issues or constraints, the integration strategy considers them as design benefits. Therefore, the precedent research is needed to understand and adapt the issues gathered by the case studies and turn them into design benefits to suit the thesis project.

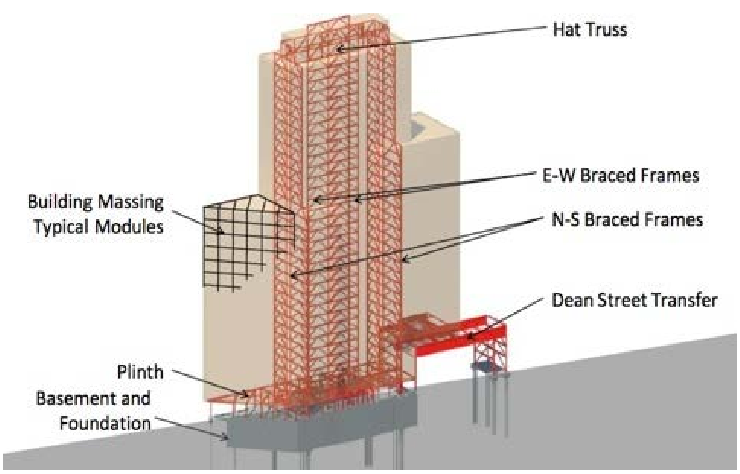


Figure 5.6.1.8 - Structural scheme

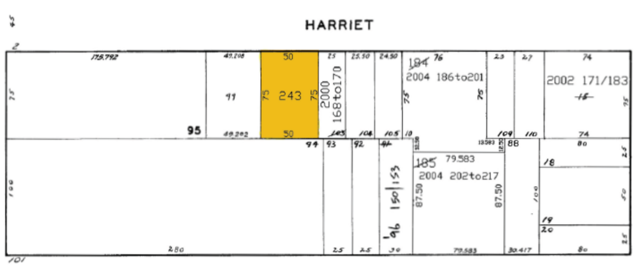

Figure 5.6.1.9 - Module structure

5.6.2 Precedent Two

Project name: SOMA Studios, 38 Harriet St. 2012 – 2015

Architecture firm: Lowney Architecture	**Number of floors:** 4
Construction company: Pankow	**Number of unit types:** 23
Manufacturer: ZETA	**Unit size(s):** Avg. 30-sm (300-sf)
Location: San Francisco, CA	**Lot size:** 350-sm (3,750-sf)

Figure 5.6.2.1 - 38 Harriet St. render



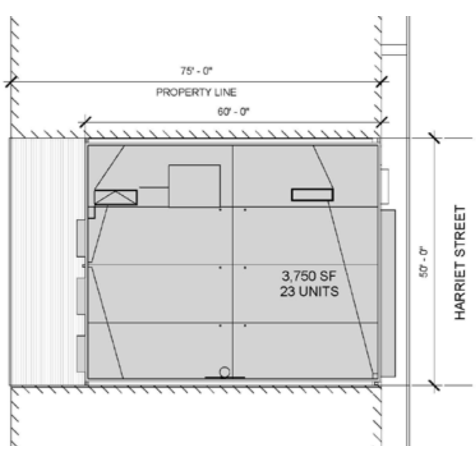
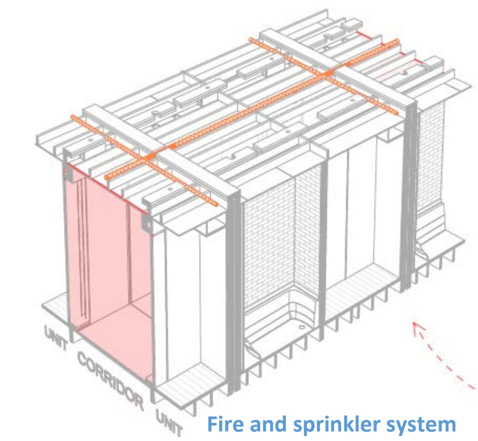
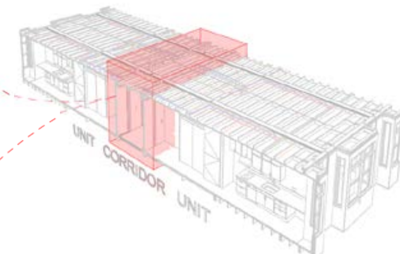


Figure 5.6.2.2 - 38 Harriet St. site

SOMA Studios, 38 Harriet St., is a modular residential project that considers itself as a shift from Project-Based Construction to Process Based Housing and that is creating profound changes to established attitudes, norms and regulations using a process driven system (Kafami, 2013). In this project there is a heavy engaged collaboration between the architect and the developer to create their own repeatable and scalable solution while the clients can plug and play with prototypes for mainstream adoption and remove negative connotations surrounding modular and factory built housing quality to compete in the construction market. The developer promotes flawless execution by having everything 100% pre-built digitally, resulting in 100% conflict resolution, and 0% change orders to guarantee time and cost (Takagi, 2014). They can achieve this through full scale collaboration and coordination with the use of BIM platforms to create predictable outcomes, reduce conflicts and risk, to achieve success. The influences of this project that were interesting include the constricted site situation modules (Figure 5.6.2.2), layout of and the functional design for small living situations having an area of 30-sm (300-sf), placed within





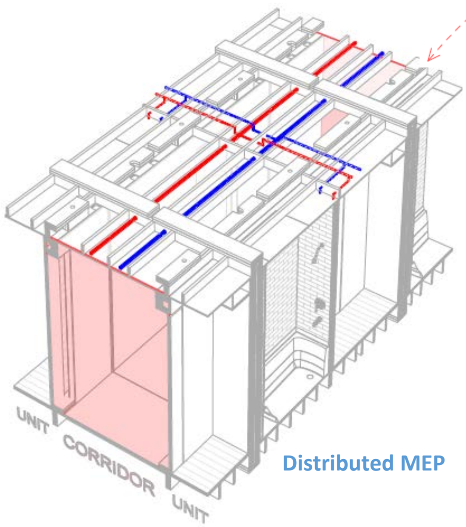


Figure 5.6.2.3 - Double loaded corridor with the services and sprinklers

a dense urban community and a constrained, in-fill development site (Figure 5.6.2.2). What initiated the project was to test this emerging technology for multifamily housing and save time doing it. When speaking with the architect on the project, he mentioned the design process and design criteria began with maximizing the site (based on square foot zoning) to yield the most units. This resulted in a double-loaded corridor plan (Figure 5.6.2.3 and Figure 5.6.2.11) and other basic building code requirements (ie. stair size, location, elevator, accessibility, fire egress etc.). When designing for small housing, accessibility codes were a strenuous process, especially with clearances for kitchens and bathrooms to make sure they were leveraging as much as possible to maximize space use. They were down to inches in providing required clearances (Figure 5.6.2.4). Luckily, modularization meant the factory could build to such tight tolerances (Lowney, personal communication, 2014). Once the plan was locked down, they came up with a durable façade design.

The modules were custom designed for the site and then mass produced in the factory. The manufacturer ZETA, has 91,000-sf of factory floor and can produce 300-400 homes annually.

The modules for this project include wood construction and are 3.65-m (12-ft) x 8.8-m (29-ft) with a ceiling height of 2.75-m (9-ft) and a window height of 2.15-m (7-ft) high (Figure 5.6.2.4). Each module is designed and delivered with built-in finishes to make the space more functional and less congested.

“The design and production needed to be highly coordinated,” said Takagi from Zeta. “Everything, including structural hardware like tie-downs as well as mechanical, electrical and plumbing systems had to be micro-engineered to optimize the unit’s interior space. Modular construction was well-suited to this job” (Takagi, 2014).

Figure 5.6.2.4 - Functional module design layout for small living, maximize use of space with minimal clearance

From a design perspective, the project had to overcome a number of challenges, their objective was to create efficient units in a small space. In addition to the persistent coordination, every space within the unit was designed for optimal use and storage, for instance, multi-purpose spaces and storage in the walls, floors, and ceilings (Kafami, 2013) (Figure 5.6.2.4). The modules were prototyped in full scale to test the type of living situation and how it could be improved before the production phase began. When speaking with the architects they mentioned the project was a heavy developer-led design Panoramic Interests had already been developing the "Smartspace" concept when Lowney Architecture were brought on board, the prototypes really maximized the use of the small units (Lowney, personal communication, 2014).

The architect's interior design intent includes soft textures and materials to present a feeling of comfort in small spaces (Torres, 2013). The module designs offer two twin beds, and a queen bed, each including in-unit laundry (Figure 5.6.2.2). The design schedule took two weeks for site design, four weeks for design development, and 8 weeks to complete the construction documents (Lowney, 2014). It took less than three months for the module prefabrication process and four days to install all four floors onsite Figure 5.6.2.5. A total of six months from ground breaking to completion. 'However, since this was a pilot project in many regards (ie. the first urban micro multifamily modular building) there were some items that took longer' (Lowney, 2014). Traditional construction time for this project was estimated for 13 months.

Figure 5.6.2.5 - Four floors of modules stacked in 4 days onsite

Therefore the overall workflow of the project had more emphasis at the beginning of the project compared to typical construction project where the focus and majority of the time is spent during the end construction phase. The architect mentions the only items left to do on site were a result of whatever could not be done in factory. This included the foundation, utility stubbing and utility connecting to modules (in corridor ceiling), roofing, and exterior envelope was left for onsite work. However, the thesis project will include the exterior envelope in the factory production, it depends on the process of assembly and how you seal the mate lines between modules.

The architecture firm did not design for the assembly or sequence, they worked with structural engineers who came up with the structural detailing for fabrication. This resulted in the only major problem the architect had because there was no direct instruction or illustration to guide the project, difficulties explaining the site scope to the on-site general contractor.

They connected the modules vertically with a detail using pre-installed ATS tie-down rods Figure 5.6.2.6, which are essentially long threaded rods connecting all of the stacked modules down to the foundation Figure 5.6.2.6 (Mullinax, 2013). They are threaded together on site at each level. First, they installed clips from the floor rim to the plates below Figure 5.6.2.7. Next, they installed hold-downs and many sheet metal straps between the modules and the podium which vertically connect all the module floor and ceiling mate lines Figure 5.6.2.8, which helped make sure the modules were level. They also installed wood structural panels across the horizontal and vertical mate lines for shear, and then installed the wood structural panel bands and straps across the mate lines at the roof Figure 5.6.2.10 (Torres, 2013). While the exterior is being connected, the interior will also be connected, Figure 5.6.2.11 will illustrate the critical areas of connection the project has (Figure 5.6.2.11).

Structural Details Designed for Rapid Building Erection

Minimal Connections Required During Set

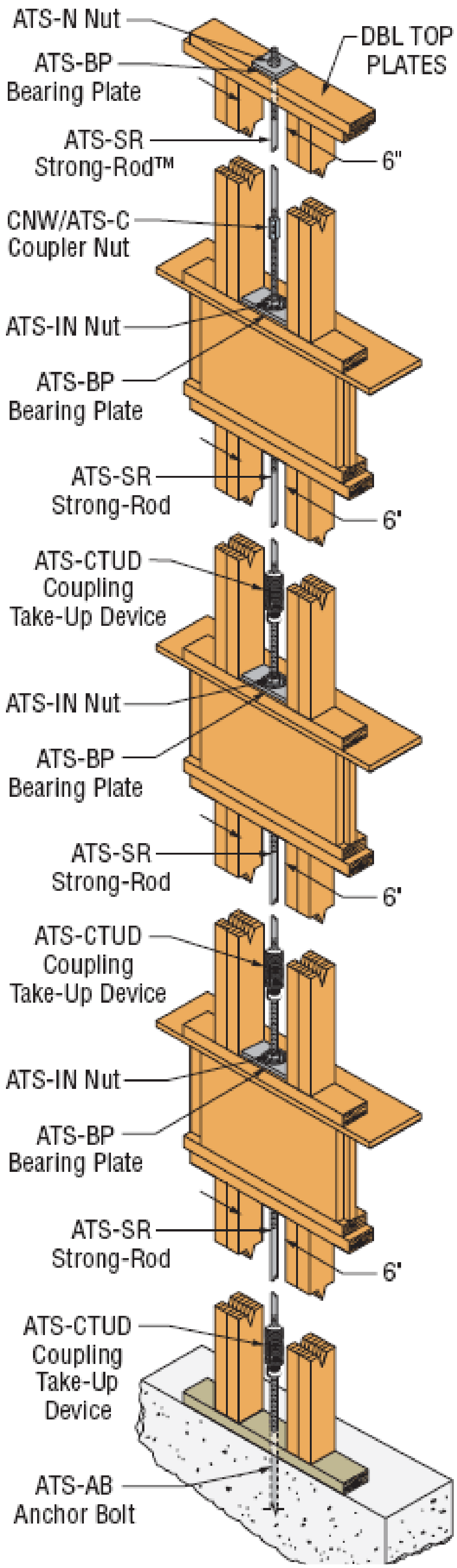


Figure 5.6.2.6 - Modules connected vertically four floors

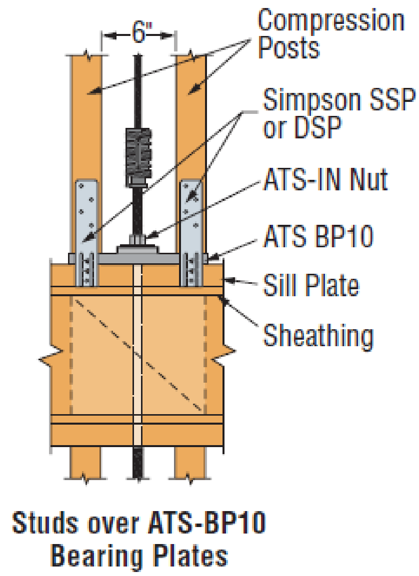


Figure 5.6.2.7 – Detail connection plates

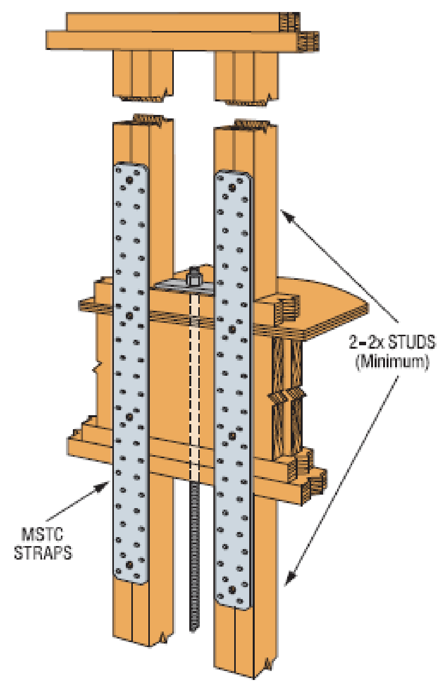


Figure 5.6.2.8 - Metal straps to tie down modules

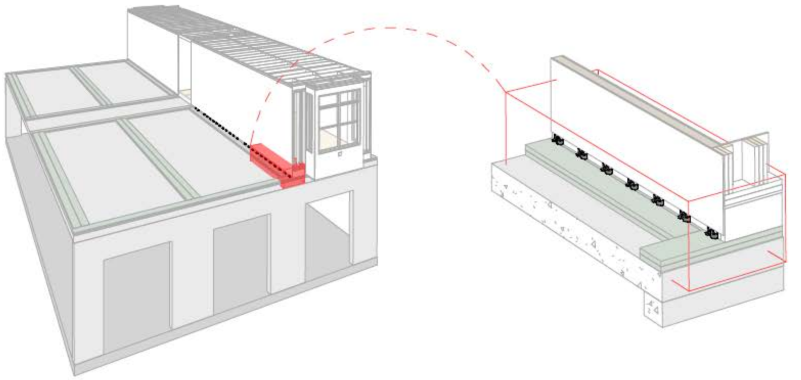


Figure 5.6.2.9 - Install clips from floor rim to plates below

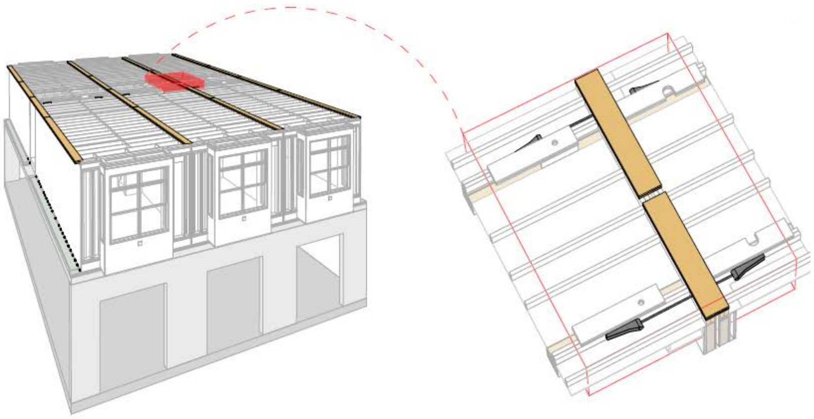


Figure 5.6.2.10 - Install hold-downs at ceiling mate lines

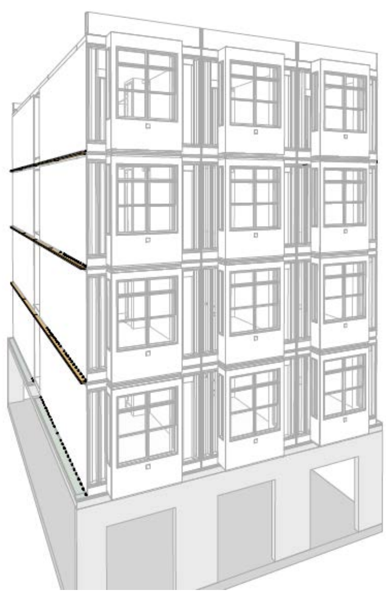
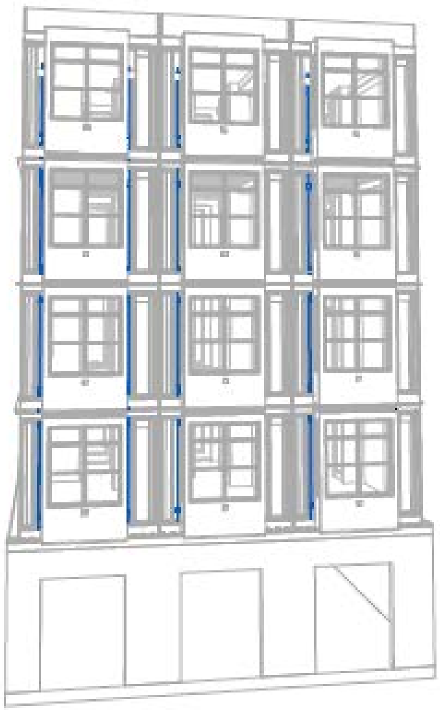
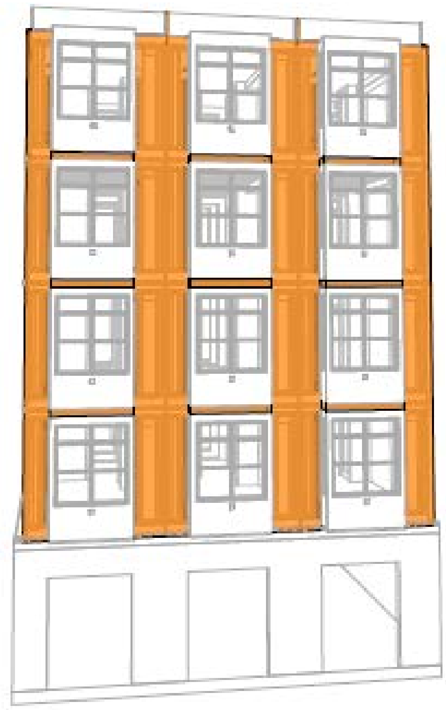


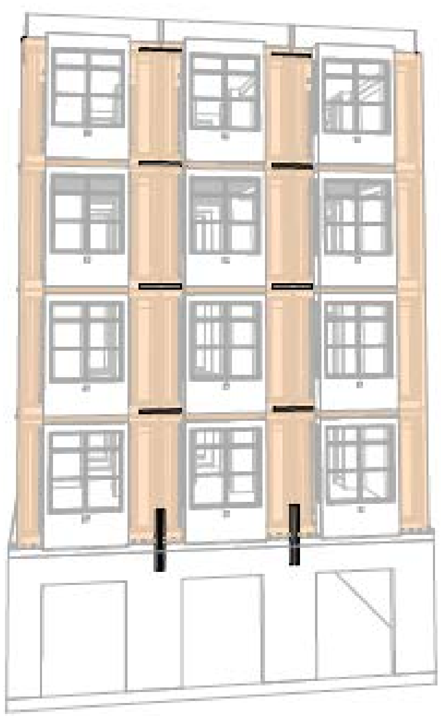
Figure 5.6.2.11 – Project near completion



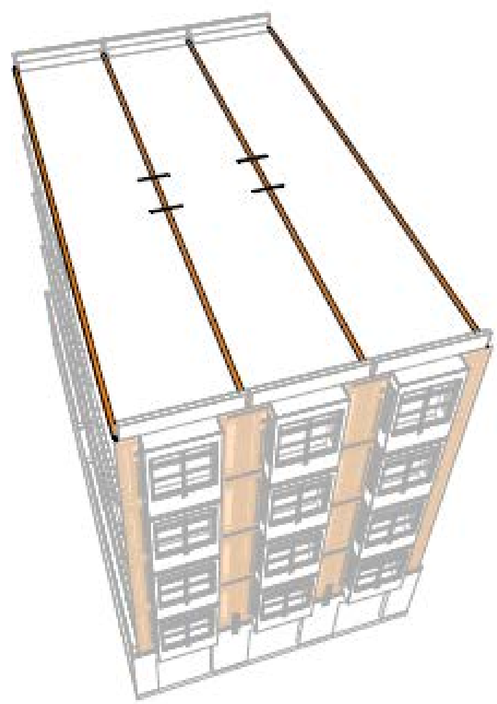
1. Connection of pre-installed threaded rods



2. Shear plywood installed across horizontal and vertical mate lines



3. Install straps between modules and to the podium



4. Install plywood bands and straps across mate lines at roof

Figure 5.6.2.12 - Exterior structural connections after set in place

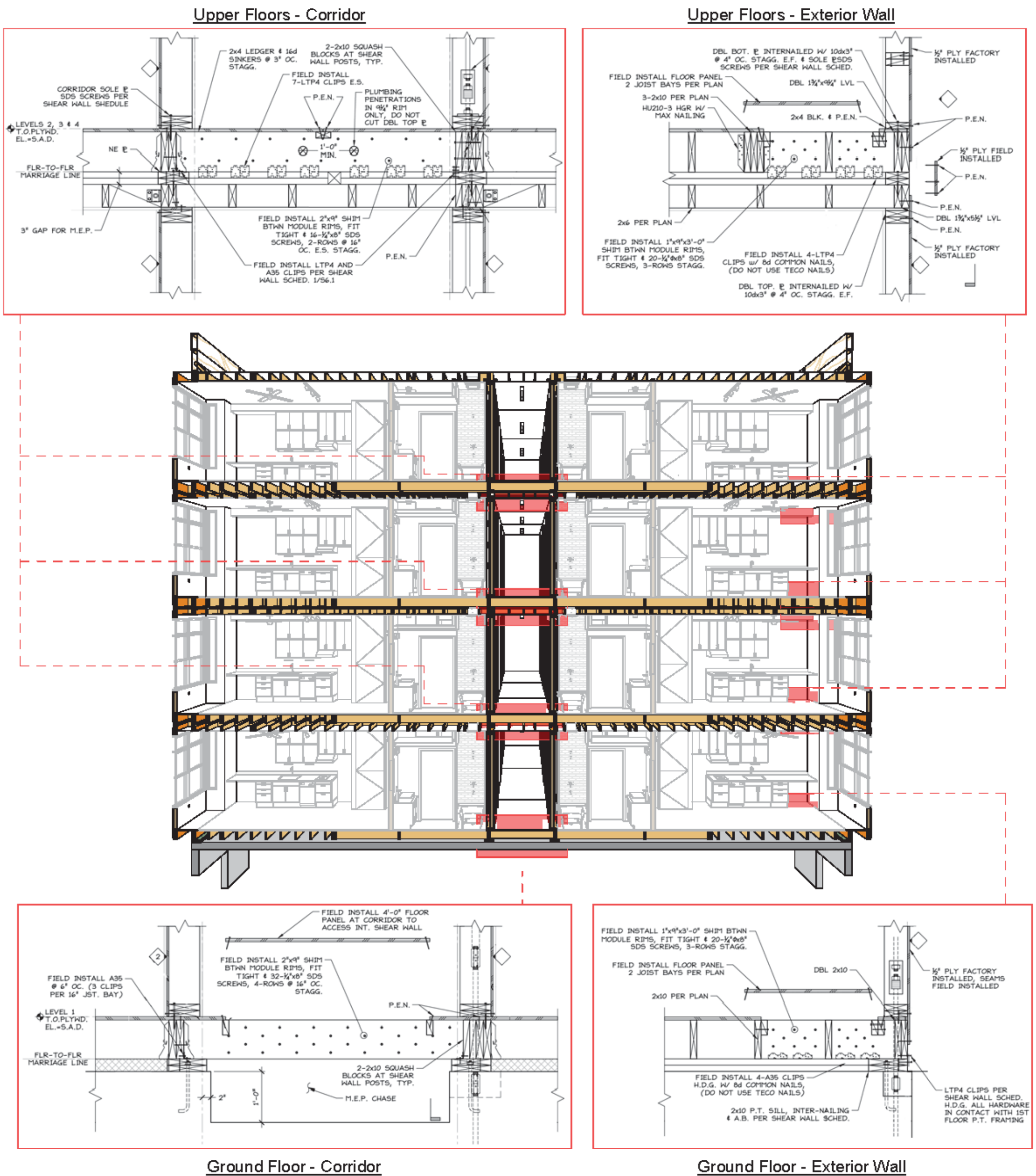


Figure 5.6.2.13 - Interior structural connections after set in place

Pro	Con
• Factory located within 100 miles of site • Micro Housing design catered toward existing and growing demographic • Factory control allows for superior product • Quick assembly process • 50-90% less waste used on project due to controlled factory setting and procurement	• Outside of target demographic, not marketable • Urban setting limits size of project

5.6.3 Precedent Three

Project name: T30 Hotel 2011 – 2011

Architecture firm: N/A	**Number of floors:** 30
Construction company: Broad Group	**Number of unit types:** N/A
Manufacturer: Broad Sustainable Building (BSB)	**Unit size(s):** N/A
Location: Xiangyin, China	**Project size:** 17,000-sm (183,000-sf)

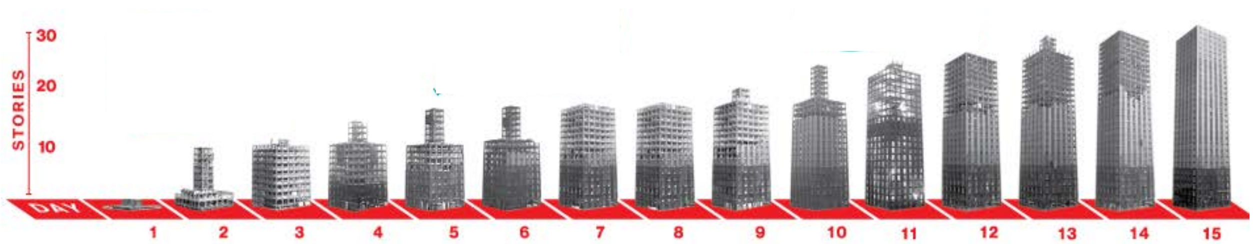


Figure 5.6.3.1 - T30 Hotel assembled in 15 days


Figure 5.6.3.2 - T30 Hotel complete

The influence and attraction to include the T30 tower into the thesis was for its record holding speed erection time of 30 floors in 15 days with foundation being laid ahead of time (Figure 5.6.3.1), and accuracy of construction with the use of detailed processes of assembly and design to increase speed. In other countries, the most advanced prefab construction methods can reduce building times by a third to half, said Ryan Smith, an expert on prefabricated architecture at the University of Utah. The builders of the T30 Hotel did reduced it by one-half to two-thirds off the normal schedule (Kaiman, 2012). The building and its project schedule shows how important accuracy, coordination, and organization must be in order to achieve a quick delivery and assembly time, otherwise, the project would have not have achieved the goals set out.

Although this precedent is not an enclosed modular unit, the influence lies in the techniques and achievements in the projects speed, factory processes, assembly accuracy, and structure. Broad's chief executive officer Zhang Yue was previously an artist, before working with air-conditioning systems, and now has moved into pre-fabricated buildings, this previous knowledge provided him with a different mindset on how to approach the industry and achieve innovation within the industry and company goals (Lin, 2012). Broad Sustainable Building is a design-build contractor/modular manufacturer and is currently building 8 new factories to meet the builders demand for more projects of this nature (Lin, 2012). Zhang started researching how to build cheap, environmentally friendly structures that could also withstand an earthquake. He had given up on traditional methods and decided the best way to cut costs was to take the building into the factory, therefore, to create a factory-built skyscraper, BSB had to abandon the principles by which skyscrapers are typically designed (Hilgers, 2013). The whole load-bearing structure had to be different (Hilgers, 2013). To reduce the overall weight of the building, it used less concrete in the floors; that in turn enabled it to cut down on structural steel, the result was the T30.

The T30 Hotel is 30 stories high with 358 rooms, consisting of a structural steel frame and curtain wall, BSB has claimed the tower is five times more energy-efficient than a standard non-prefab building (Jiang, 2012) because of the amount of detail dedicated to the design development phase of the project. This provided greater attention to detail in design and processes of production and construction for efficiency and functionality of the overall project. 90% of the building was built in the factory (Jiang, 2012), the assembly line involved an intrinsic and complex integration process of various elements that were planned and prepared previously in the design development process. Zhang Yue was focused on building design, for instance, bolting together frames side by side and on top can achieve the lateral stability that is needed across the entire structure. The production of the structural design include an innovative column shape and serve as linear vertical trusses to achieve the bracing required, (these linear columns are used in both planes of the building) (Figure 5.6.3.3). It is difficult to believe that the bolting together of such frames side by side and on top of each other gives the lateral stability that is needed across the whole structure, but the columns themselves serve as linear vertical trusses and employ a high degree of bracing (Wood, 2012). Prototypes of the design were built to test the production and assembly processes for the stability and structural integrity of the building to withstand high magnitude earthquakes (Jiang, 2012) (Figure 5.6.3.4).

Figure 5.6.3.3 - Linear columns used in both planes act as truss

Figure 5.6.3.4 – Large scale prototype to test structure

The structural floor system consisted of a steel truss module, and was produced on a jig that can flip the floor face down so that the ceiling can be applied to the floor below, then flipped back to work on the floor assembly for a simpler and more accessible installation. The truss-framed floor module measures 3.9 meters in width, 15.6 meters in length and 450 millimeters in depth and comes complete with all electrical and mechanical systems, and all the connection plates were ready for attachment onsite at each module interface (Wood, 2012) Figure 5.6.3.5, numbers 1 and 2. The frames are welded in the factory and the connections are bolted onsite. The construction generated a fraction of the waste compared to traditional methods of this size because the process was clearly detailed and completed in the factory. The project task left for onsite work consisted of each floor module being lifted into place with all the vertical elements and material to finish the build for that unit, Figure 5.6.3.5 numbers 3 and 4. Once the floor is assembled into place, the vertical is raised and bolted into place in preparation for the next module, Figure 5.6.3.5 number 5.

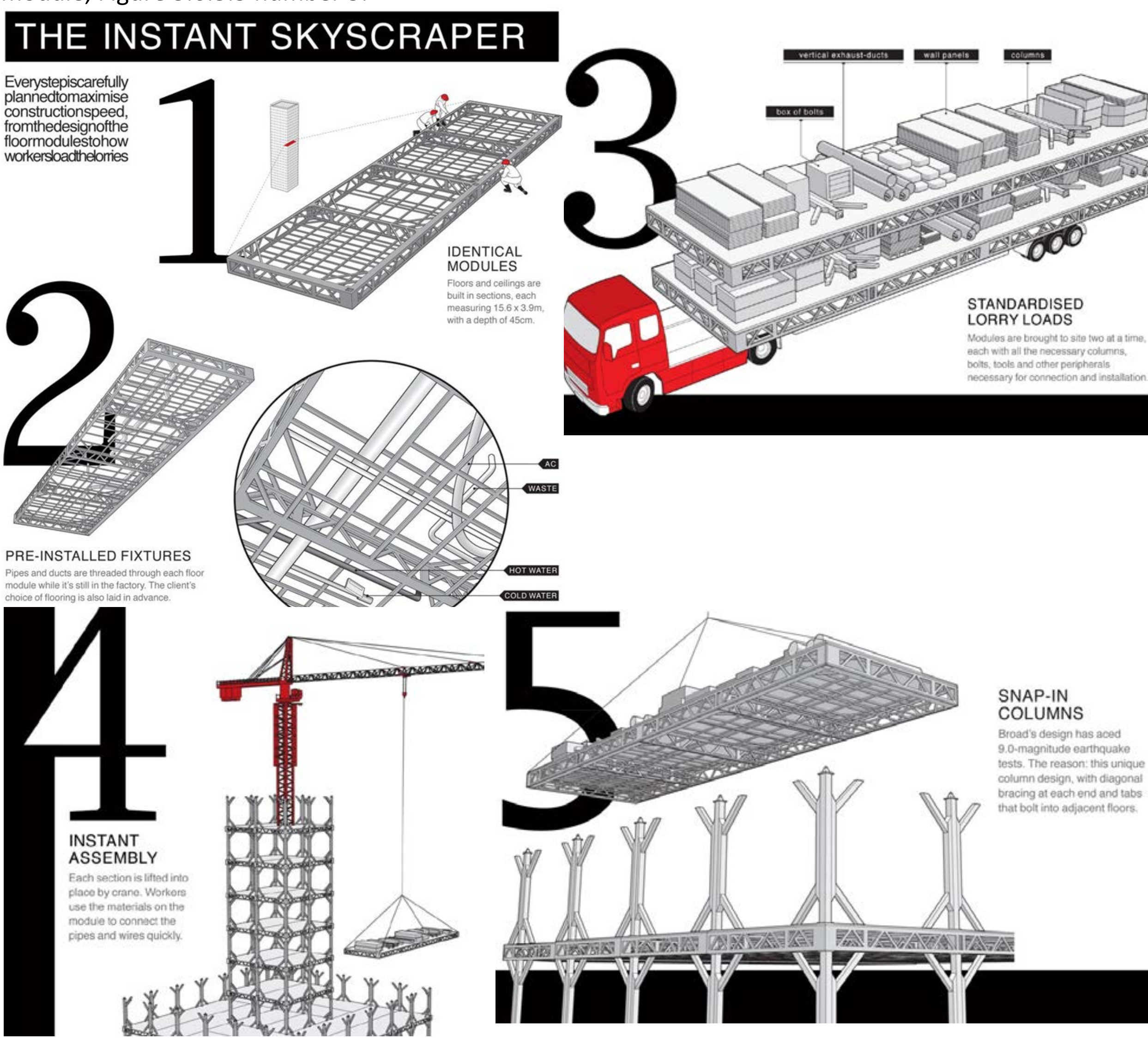


Figure 5.6.3.6 - Organized materials, vertical structure raised, floor mod set in place, and bolted together

During assembly, the floor module was designed to anticipate and assist in placing the component to structurally connect and receive the next floor module with the use of tapered pins that were used as locators for the next slab to fit into the column with speed and precision to be bolted and fastened (Figure 5.6.3.6). 'The design detail to assist assembly was critical to the construction phase since there can be virtually zero tolerance when fastening the floors with such a fast paced schedule' (Wood, 2012). Although the concepts of limited risk and high quality are valid, it is too soon to tell for sure (Kaiman, 2012).

Pro	Con
• $17 million US to build, 30% lower than traditional construction cost • Accelerated schedule – 2 floors per day typical • High standards of quality – assembly method ensures quality checks and standardized processes • High market demand – International franchise adopting the product • Low embodied energy from conservation technologies/techniques • High energy efficiency with 1% construction waste • Ease of construction and assembly processes, (simple concepts, assisted designs) • Strong in-house workforce and deeply indoctrinated	• Standardized look – aesthetics generally plain • Nonstandard interior design – irregular shapes etc. • Chinese production is cautionary, may not apply to North America at this time • Strong in-house workforce and deeply indoctrinated has the potential to become isolated with no outside expertise

5.6.4 Precedent Four

Project name: The Ballingdon Bridge 2002 – 2003

Architecture firm: Michael Stacey Architects	**Number of floors:** NA
Construction company: Costain	**Number of unit types:** NA
Manufacturer:	**Unit size(s):** NA
Location: Sudbury, UK	**Lot size:** 800-sm (8,611-sf)

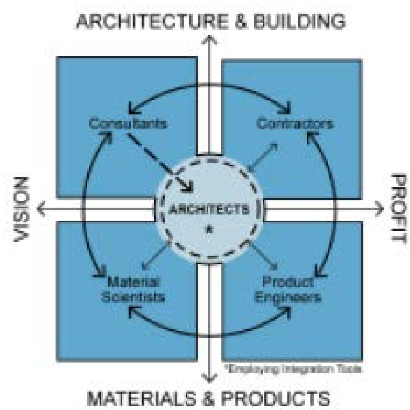


Figure 5.6.4.1 - Kieran Timberlake's integrated design

The third precedent is a bridge project by Michael Stacey, the Chair and Director of Architecture at the University of Nottingham, his research includes: digital fabrication, form finding in components and architecture, offsite manufacture, façade design and procurement, and emergent materials.

This project was chosen because of the principles the project follows and shows how conventional craft compares to digital prefabrication. The Ballingdon Bridge project was based on a research methodology, and is characterized by the attention to detail. Having an integrated team was essential to the successful delivery and quality of this project. The means and methods of the digital design and construction process followed Kieran Timberlake's integrated design diagram (Figure 5.6.4.1), which includes collaboration with consultants, contractors, and material scientists on the cast components and finishes.

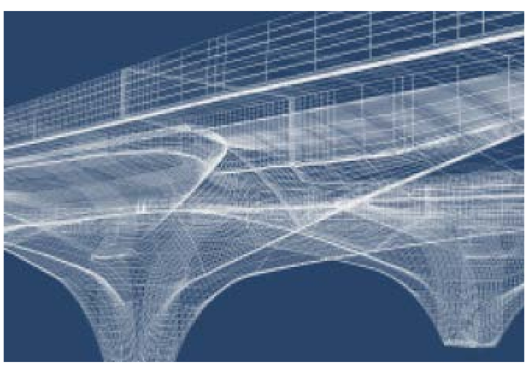


Figure 5.6.4.2 - The digital geometry of the bridge

'It is also an example of fast construction and slow architecture, combining rapid production technology and the qualities of architecture' (Agkathidis, Bettum, Hudert, & Kloft, 2010). 'The digital geometry of the bridge (Figure 5.6.4.2) went through a number of design iterations, which resulted in a unique and site-specific form within architecture and was facilitated by the use of rapid prototyping and digital fabrication. Without this digital geometry generated by the architects, it would have been very difficult to realize this bridge' (Agkathidis, Bettum, Hudert, & Kloft, 2010). The structure of the form has a dynamically changing three-dimensional design which was formed from precast concrete. The precast units were manufactured by hand crafted timber moulds (Figure 5.6.4.3), and checked with laser-cut templates; no two adjacent sections were the

Figure 5.6.4.3 - 17 hand crafted timber formwork

same, resulting in 17 craftsmen and formwork components. This process became the most time consuming and expensive part of the project, which could have been avoided in a number of ways. The development in digital architecture have become re-engaged with the means and methods of construction and resulted in a renewed engagement with making, craft and industry, with strategic planning of production and assembly to utilize manufacturing fabrication machinery such as fully utilising the laser cutter to produce the actual formwork, CNC or hot wire to shape foam formwork, or sourcing a subtractive or additive fabrication machine that uses technology of water jet cutter or a printer to recreate the form in its exact three dimensional space for complete precision, can potentially eliminate inconsistencies, laborious work, overhead costs and time in preparation of the formwork and procedures.

Figure 5.6.4.4 - Ballingdon Bridge

The problem resonates from the predominant traditional construction techniques in formwork. The aspirations of a holistic design, process, and integrated team should require the utilization of automated machinery to maintain accuracy of the design intent in complex geometry and take control of the repetitive and labor intensive processes. This means the integration of assembly in the factory and onsite are required as part of the holistic design process in the digital model. This should include the ethical and ecological responsibilities of architects to inform the design process.

The thesis objectives and knowledge gained from the precedence will contribute to people's lives and the culture of contemporary society through the informed use of technology, knowledge of humanity. The study of architectural theories and a detailed understanding of fabrication processes and assembly through the use of digital design, will inform the built environment and create an impact on architecture

The impact on architecture when using a modular design and offsite manufacturing make it possible to create high quality and cost effective architecture, delivered with the shortest possible site time. The technological development in modular design has generated a vast resource for the creation of architecture in design, manufacturing, and assembly, with an unmatched level of opportunity to progress from concepts into physical realities when compared to design and processes without modularization.

5.7 Challenges in Modular Construction

5.7.1 Design Implications to Be Considered

Physical constraints should be researched and taken into account during the initial design process in order to turn them into benefits in design. The limitations of modular size and weight must be accommodated by the designated shipping method and path of procurement. Considering construction methods and processes early on in the design process will establish design guidelines such as, overall dimensions of the module size and its structural properties, design, and assembly in the factory and onsite. The height, width and length of the modules are subject to transportation constraints. Other design implications include:

- The modular unit has to conform to the transportation limits (A Guide To…, 2014).
- Typically module designs can create structural redundancy of overdesigned structures.
- Openings on the exterior of the module can be limiting, however, variances can be achieved by increasing the size of the structural members.
- A decentralized Mechanical, Electrical, & Plumbing (MEP) system is the most common system of distribution in modular design, this allows for a higher quality of environmental control and can allow for alternative design choices (Garrison & Tweedie, 2011). Therefore, each module is self-contained and regulated, this allows for a variety of forms and layouts in the design of the module. The architect may design access points within the module for MEP hookups.
- Accuracy of complex interfaces in irregular shapes can be difficult, however, advances in engineering, manufacturing, and computer design have benefited the modular industry with good design, and the combination of the three can provide illustrated instructions for easy assembly.

5.7.2 Constraints

Handling big projects requires a lot of planning for contingencies. 'An important part of the modular process is interface management; because it directly influences the outcome of the project' (Kafami, 2013). Interface management is defined as the digital or physical interaction between the various components created to assemble the modules; frequent meetings and open communication between all parties are important for this to work. 'Proper interface management requires the scope of each module to be defined early on to test connections and have a successful project' (Kafami, 2013). Since modular

design requires a defined scope of the means and methods early in the planning stage, some owners may see this commitment as inflexible and as a constraint because of the inability to make changes later in the project (Bernstein, 2011). For some owners, increased design and engineering costs are considered barriers (Hutchings, 1996). Using prefabricated components can have a limited range of sourcing options and competitive bidding, which is seen as a constraint and a risk factor (Bernstein, 2011).
The biggest concerns in modular construction projects usually revolve around Logistics, Assembly and Sequencing. A paper titled *Modularization: A Pioneering Approach* (Brookfield, and Cooke, 2011), states how important the logistics are to define the manufacturing and transport constraints. Key points are broken down under the headings Logistics, Assembly, and Sequencing:

Logistics:

- Identify alternative manufacturing centers
- Consider and prepare for different levels of skilled labor
- Survey all transport routes for physical constraints: power lines, bridges, roads, turning, etc.
- Site access, crane locations and lifts onsite, heavy lift footprint onsite, and laydown areas onsite
- Survey site – zoning, climate, environmental issue, permits, safety, impact on surrounding areas
- Define the volume of the transport maximum and optimum, these will dictate module sizes

Assembly:

Assembly and the workforce onsite require good planning and control. The availability of truck beds may also play a factor on the flow and workforce that can assemble the modules. This issue is researched and adopted from the Leadenhall case study in section 6.8.1, on how to manage and adapt the workforce for delivery and assembly into the thesis project.

Sequencing:

With a detailed work schedule for sequencing, the module assembly will allow for shorter durations of equipment use in the field. Proper sequence for construction minimizes handling of equipment and modules. Some technical considerations in pre- assembly include:

- Consider the equipment being used onsite and offsite
- Include the structural system into the design to manage and assist the installation sequence
- Maximize access for onsite work by including flooring, handrails, electrical access for cable installation, and stairs into the modules

- Consider alignment issues
- Consider construction sequencing and module placement
- Consider crane movement
- Consider the placement and disassembly of temporary steel if required
- Configure connection details that suit the sequencing and the project

As design, production, and assembly become more complicated from sophisticated design software, prefabrication and modularization methods are rising in popularity due to the increasing demand for cost efficiency and safety in construction (Kafami, 2013). Every project can be entirely bespoke, the more variables and constraints detailed into the project the better the outcome will be, utilizing machines instead of hands to achieve consistent results for the project to be built as designed. This has encouraged the research to conduct interviews with leading professionals in the modular industry to discuss the challenges mentioned above who had dealt with these issues first hand, in order for me to make an educated assessment into how I can transform the constraints and challenges into benefits for the thesis project

5.7.3 Reasons for Not Using Prefabrication/Modularization on Projects

The McGraw-Hill Construction reviewed reasons for not using modular/prefabrication on projects in 2011 and reported the biggest issue is not starting a project with modular design from the onset. Having modular design in mind from the beginning will make the entire project far more efficient and more advantageous than attempting to include these techniques further into the project. The later modular design is introduced, the more room there is for error and expenditures. Awareness and knowledge of modular design and construction is the second highest reason for not using modular design on projects, because either the architect or owner are not educated in the matter, questions and concern of quality, components, structure, and cost arise (Bernstein, 2011). Other issues that refrain from modular design and construction include the availability of a trained workforce, local manufacturers and the path to site. If modularization is incorporated from the start of a project, it will eliminate most of these factors. What predominantly necessary here is the need to spread awareness and educate the industry on the processes and wider applications of modularization. The more that companies learn about modular construction, the more they are accepting of it, and architects can find more creative and innovative ways to design, manufacture, and assemble in the future by being equipped with the right knowledge (Kafami, 2013).

6. Project: Design Analysis

A Workflow Strategy for Design

Prior to the strategies for design, the theories primarily discussed in sections one, two, and three, are summarize to reflect on the influences that have guided the paper.

- To create a closer and stronger relationship between the digital and physical transition in architecture and construction, to elevate design in all aspects of the project.
- The thesis project will demonstrate how to approach a design that contributes to the production and assembly of a multifaceted project with accuracy before it is physically built.
  - The thesis approach is to directly engage with the means and methods of construction through design, and control the process through details and illustrations.
  - Integrating Design, Manufacturing, and Assembly to be applied in the beginning of the project phases for efficient design and more holistic overall process.
- The project will show an understanding of integration and collaboration with other trades and industries for a reiterative influential processes and expertise to make informed design and logistic decisions into the design development phase.
- The organizational model will enhance the capabilities of architecture to discover new opportunities and expand the role of design in all aspects of this project.
- Highlight potentials for architecture and architects within restructuring the industry and position themselves within a larger market.
- Restructuring the building process can help owners and developers engage with architects on an individual level.

What matters in design? Is it the description of the artifact or the description of the process to make the artifact? To answer this, the processes that brings the artifact into life will need to be traced (Rehim, 2000).The act of designing has a better chance of improvising and reflective learning, when the process is traced (Lobel, 2008). The verb design implies certain associative leaps and intuitive calculations that are made based on seeing, thinking and doing. The noun design indicates the outcome of a process that can be analytically rationalized into series of discrete procedures. The Architecture, Engineering, and Construction (AEC) industry employ digital technology in the service of both the process and product of design (Lobel, 2008).

At the conception of a new project, the design process should study the context and unveil the opportunities buried within the project.

The design will begin to influence change in the means and methods of production and assembly through the thesis project by impacting how we approach a project from the beginning. This concept follows the theory of Kisho Kurokawa, his work was influenced by the attention to detail, and the process of his work followed a sequence 'from parts to a whole, and not from the whole to the parts' (Kurokawa, 1959) that had stuck with him from ancient Japanese architecture. Kurokawa believed in a hierarchy that focused on the autonomy of parts to be an integral part of his design and forms.

Intimate knowledge of production and its assembly repeatedly informs design and relates to its method because the process is a continuous and iterative sphere of influences between design, manufacturing and assembly as found in the custom script of Figure 4.2 during the initial research. The way in which the building is constructed can be as much a driver of design as anything else.

To do this, the thesis project is putting more stress at the beginning of the project during the design development phase and has approached design from a small scale perspective from section 6.7 Site Parameters to section 7.13 Interior Mate Line Assembly, to consider the design potentials in details, structure, and processes of construction by introducing manufacturing and assembly into design from an architect's perspective. The process follows a similar process to the B2 Atlantic Yards workflow coordination diagram of phases in Figure 5.6.1.3, it moves from detailed connections, to mechanical services, structural members, bays, and structural design, to wall assemblies to construct a module. The module is then assembled to connect with other modules to make a unit. A unit is considered an apartment that can consist of a number of modules depending on the size and area desired. Once the units are assembled and configured to other units they create the subfloor, then each subfloor creates the building. The workflow of the project, client needs, design constraints, and the project parameters will be considered when covering crucial phases of the project to establish design solutions with the aim to reveal new opportunities in architecture whilst contribute to people's lives and the culture of contemporary society to benefit humanity.

Collaboration with any contractor outside of the design team is also necessary to integrate into the design process from the beginning of the project so that the design team can benefit from their expertise and so the contractors are well informed, in order to have the same goal in mind and to keep the design intent.

Therefore, through the informed use of technology, the design team can use the knowledge gained to create detailed outlines and instructions to regulate, guide, and maintain production and construction sequences through the integration of design, manufacturing, and design into design development phase.

With the growing complexity in geometry and structures in architectural design, are rapidly advancing far greater than any existing construction techniques today. Therefore, the problem lies in linking high level digital technology with low level construction techniques to become a holistic design and process. However, digital platforms today can run rapid feedback on simulations of an object or process before anything is physically built to prevent issues on a project. The ambition to translate digital into physical in architecture and construction will support new trajectories into the discourse of architecture to make beautiful buildings through the art and science of architecture to elevate us all.

6.1 How to Procure a Modular Building

To procure the project and for design development to achieve a successful project on time and on budget, it involved collaboration from a number of disciplines from the beginning to anticipate any projected issues within the project. A number of professionals where interviewed to understand the modular industry, this includes an architect and project coordinator from &co Architects who discussed their views on modular design when compared to the original construction used on the existing building and what kind of issues they ran into during construction on site. A digital fabricator from Vector Praxis, who discussed topics of digital design and their abilities to manufacture and fabricate components from a detailed 3D model designed down to the nuts and bolts, as well as, provide some information on the B2 Atlantic Yards case study currently in construction, since they were part of the design team, structure, and logistics of building the modular unit. A number of visits with a modular design specialist and modular manufacturer at the permanent modular construction facility in PCL, went over logistics and details of modular design and building code regulations as the project progressed. A mechanical engineer who provided a brief explanation of the requirements and distribution of the HVAC for modular design. A crane lift specialist from Western, assisted with the position placement and choice of crane for its limitation on lifting and boom extension for mobile and stationary cranes. The Ministry of Transportation Ontario (MTO), outlined delivery logistics and processes required for permits, along with the shipping conditions and guidelines. Interaction with all parties gave an understanding of the processes and integration required in this field of work. It is important to have all parties meet and collaborate on a project from conception and during interval stages of the project to discuss the projects direction and outcomes. It takes the agreement and participation of all parties involved to ensure success. Forbes explains ‘it is up to the building industry to act as the driver for change’ (Dailey, 2014).

6.2 Design Considerations

The stress on design development and the application of small scale design considerations from conception are crucial when applying modular design. This is necessary in order to plan, organize, and design details with accuracy and precision during the digital to physical transition, to aid in the assembly process, and preserve the architects design intent. The project is designed with the consideration of manufacturing and assembly. This involves the design team to constantly collaborate with the other disciplines so that there is at minimum a general understanding and relationship with most aspects of the project so that there is unanimity in order to make informed design decisions. Advances in Computer Aided Design (CAD) and Computer Aided Visualization with the use of Building Information Modeling (BIM) are immensely helpful to inform many aspects of the design, workflow, and construction. A specific design and a well-rounded knowledge of the industry are needed to review construction processes from start to finish in order to identify obstacles and design effective solutions to prevent errors or delay.

6.2.1 Current and Future Considerations

In this regard, an analysis and exploration of the effects modular design and construction has on architecture (and vice versa) shows there are a number of benefits that can be applied to current and future issues when analyzing the design considerations.

i. Current design considerations
    - a) Small urban infill
    - b) Small housing/living design
    - c) Limited space and access onsite
    - d) Onsite assembly and complex construction
    - e) Reduced labor
    - f) Accelerated and assured schedule

ii. Future design considerations
    - a) Small urban infill
    - b) Small housing/living design
    - c) Limited access to site
    - d) Limited skilled craftsman
    - e) A change in the construction industry and condo development
        - a. Homeowner participation
        - b. Flexibility of space
        - c. Division of shared land property
        - d. Adapt and grow

6.3 Project – Informed Critique

The types of design tools and the production of design employed in the AEC industry are defining new meanings, both intellectually and physically through digital intelligence and manufacturing. What seems to be neglected is designing for assembly, where the rationale of assembling building components is part of the design criteria at the beginning of a project. In traditional construction projects the areas of missed opportunity lie within the "transition" period during the handover from digital models and drawings to production and construction, there is a high level of understanding on how the project is to be directed and built during the planning and design phases when produced by the Architect and Engineer etc., once the plans are "handed off" to the contractors they then have to reinterpret the design, directions, and goals of the project from the beginning. Ignoring the transitions between digital to physical handover (Figure 6.3.1), can lead to misinterpretation and miscommunication of information, this will also result in lost opportunities to create a closer relationship of architecture and construction, linking together file to factory techniques and processes to maintain the architects design intent. When all three systems of design, manufacturing, and assembly are integrated as a whole from the beginning, the term file-to-factory can be repurposed as factory-to-file, by creating a shared iterative relationship between design concepts, methods of production, and assembly sequences (Marble, 2012). Intimate knowledge of production and its assembly informs design and results in many different design iterations to consider. Taking time to predetermine the construction issues during the design phase makes it quick and easy to solve problems sooner rather than later in the project where costly mistakes can occur.

Complex design and logistic projects today should consider an architecture firm that is equipped with a multidisciplinary background of expertise at their disposal, who can be involved with the fabrication, assembly, and construction process (Sheil, 2012). In the past the industry has not seen these methods implemented to this level of detail because the technology was never quite there. Now that offices are becoming more comfortable with the digital tools and their means for communication and organization of information, the ability to work on every aspect of the building simultaneously is attainable.

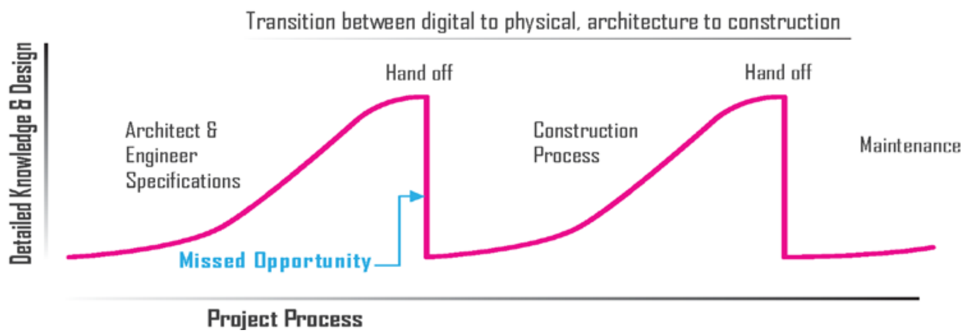


Figure 6.3.1 - Transition between digital to physical, architecture to construction

6.4 Project – Objectives

- To create a closer and stronger relationship between the digital and physical transition in architecture and construction, to elevate design in all aspects of the project.
- The thesis project will demonstrate how to approach a design that contributes to the production and assembly of a multifaceted project with accuracy before it is physically built.
    - The thesis approach is to directly engage with the means and methods of construction through design, and control the process through details and illustrations.
    - Integrating Design, Manufacturing, and Assembly to be applied in the beginning of the project phases for efficient design and more holistic overall process.

There are four main objectives to consider that have accumulated from the material previously investigated. The first is designing for an efficient and more holistic overall process, in which the design development is given more priority and produces in a much shorter time. This will be tested by devising solutions to an existing buildings project parameters (section 6.7 to section 7.13) using modular design and construction. The second objective is to design for the majority of the project to be completed in the factory. The third is establishing design decisions from the knowledge gained from manufacturing techniques and assembly procedures that will ease the production, field assembly, and minimize site work for greater control of the project phases and a stronger relationship between architecture and construction. The fourth is the accumulation of the first three and is applied throughout the project, this entails the processes and principles outlined earlier, which includes the relationship between the digital to physical transition, as well as implementing small scale design from the beginning; this requires the control, knowledge, and ability to translate idea into form, intent into reality. These aspirations are sought after to make an impact on the industry and to look at new opportunities in the discourse of architecture for the industry to prosper.

The following will describe the design criteria and showcase the design parameters discovered from the project with the chosen site. The design parameters are outlined by the specific site and project limitations and the design criteria become part of the objectives which guide some of the design decisions directly.
Firstly, to speed the projects schedule, the thesis project building's design will not include a basement, only a crawl space, therefore, the onsite foundation preparation is minimal and all of the typical basement services will be relocated to the roof. The foundation is one of the most critical areas of the project since

this is the only major portion requiring onsite work and it's where all of the modules need to rest, so the accurate completion of the project relies on the foundation; therefore, keeping the process and design of the foundation simple will aid in its success. Additionally, the building's design will include components of mass production for quick production techniques, for example, patterns in design such as location of MEP, service walls, kitchens, bathroom pods and window arrangements on the exterior. However, the design of the spaces will still allow for customization for more desirable units to the homeowner. Since the thesis project design will not be able to rely on tangible evidence for the manufacturing portion, investigating similar projects like the Atlantic Yards B2 and their production methods as precedence will aid in selecting the most efficient production processes in a factory setting as well as, organizing the trades working on components so that there is no downtime.

Secondly, for lean production processes, equipping and organizing the assembly line with the required materials and tools into appropriate sections will eliminate any downtime during the production phase. The design of the assembly draws on the language of the automotive industry, describing the module as a 'chassis' because it is built on a jig that is premeasured for installation components to be assembled, it mainly uses one type of assembly line for the build and acts more like a car than a traditional house frame because it is predesigned with all of the services such as (insulation, wiring, plumbing, etc.) and built with dedicated room to receive others if needed. The modules are built with all the efficiencies and quality found in an assembly line and is built as designed. By using automatic assembly equipment and repetitive assembly-line techniques, factories assemble component parts more efficiently and with greater consistency. Designing and organizing of the factory floor itself is influenced by the precedent projects that have accomplished this successfully using the latest technologies, for instance, designing a flexible jig that can adjust for various wall assemblies. The jig will be marked out precisely for the varying wall sizes using a CNC machine to outline and label each piece necessary for installation; this will allow designers and project coordinators to implement quicker production procedures and strategies for trades to work simultaneously with gravity on a rotating surface. The building's interior design will abide by the sizes set by each module so that as many finishes can be completed in the factory as possible, with fewer components to be exposed to the elements. This includes bathroom pods and service walls, the interior walls will border the space of the module to create an enclosed module, minimizing work onsite such as mate walls when connecting two modules together. Each module is strategically designed to have the least amount of mate walls necessary (if any) for quick construction time. The more time spent on design to enclose each unit, the quicker the assembly and construction work will be to seal two modules onsite.

Thirdly, designing for assembly both off and onsite to achieve efficient designs with accuracy and precision are required to ease the construction process. To ensure accuracy and precision of the digital to physical transition, prototypes are used as a precursor to analyze the pros and cons of any phase before moving forward, and to facilitate the modular design solutions that were created and adapted for the project for ease and efficiency during the assembly and construction process. Besides the overall project view, attention to the small details for the placement of the modules onsite was mandatory to establish a predetermined system for installation. The modules are designed to assist the assembly process to speed up the construction and labor time by designing a structural system where speed and minimal effort is needed to fasten each connection, designs were implemented to locate and position the immediate module precisely. The onsite construction has been designed to have almost all of the structural connections and mechanical-electrical-plumbing (MEP) connections to be accessed and fastened from the roofs of the modules so that the site trades can work with gravity, and work simultaneously with the erection crew. All of the coupling connectors for the piping and sealants are precut and shipped with the module for efficient labor. After the building is set, further maintenance of the services can be accessed inside the building from the main circulation area and corridor to the unit to create fewer disturbances for the residents inside the unit. The core circulation and services are all placed in one module for more efficient design, manufacturing, and assembly, both off and onsite.

When the modules are placed onsite, the gap between each module is normally left open. Up until now, building inspectors have accepted this, even for fire rated floor assemblies, but if this system of modular construction is to become more common practice and is to be used for larger projects, then this calls for an innovative design solution to the seal between modules to create more sustainable buildings. Gaskets are strategically designed into each module to seal the exterior of the modules together by using an access panel from the interior after the modules are in position to close the gap. This will allow easy access for workers during the final finishes of the building.

Fourthly, the time spent designing the module and layout along with the component details of connections and assembly will ensure quality craftsmanship with accuracy and precision in the factory, and quick and efficient assembly during construction onsite. The architect’s involvement throughout the project will ensure consistency and reduce any confusion for trade workers when dealing with complex multilayered designs and their components. The process and application of the fourth objective will be shown throughout the remainder of the thesis to track and monitor the theories previously introduced.

There is in essence a convergence whereby crafts people can become an industry of one (Campbell, 2006), and the architect, once a remote fabricator, can now directly control the manufacturing process. The roles of crafts people and architects are interconnected with the aid of manufacturing technologies available that engage design with the construction and production by using precise components detailed in a 3D model.

6.5 Project Description

For the project to have a basis, it was best to start off with a comparative study of an existing building. The residential modular market was an area that opened itself up to opportunities into adapting the building process of residential towers and integrating the design workflow strategies into small urban infill projects. The project site chosen is 294 Richmond St. East in the downtown core of Toronto, Ontario, Canada. The existing building is a 6 floor, mixed use building (Figure 6.5.1).

The existing building took two years to build, when speaking with the architecture firms project coordinator, he mentioned issues with construction including, site parameters: access to the site, working on a small congested site, clearance of hydro lines for crane lifts, and attempting to match prefabricated floor slabs onto a site built structure were major issues for them. If there were any other issues, they chose not to disclose them with me. Therefore, the project requires a better design alternative to ease the construction and assembly process, and an alternative for accessibility, as well as minimizing labor to alleviate congestion onsite, to produce a faster schedule.

Figure 6.5.1 - Existing Building, 294 Richmond St. E

MAJOR OCCUPANCIY	MIXED USE		
GROUND	RETAIL		
SECOND FLOOR	COMMERCIAL OFFICE		
THIRD - SIX FLOOR	RESIDENTIAL		
BUILDING AREA (m2)	330 m2		1.1.3.2
GROSS AREA	1900 m2		1.1.3.2
NUMBER OF STOREYS	ABOVE GRADE: 6	BELOW GRADE: 1	3.2.1.1., 1.1.3.2.
NUMBER OF STREETS	2 STREETS		3.2.2.10., 3.2.5.5.
BUILDING CLASSIFICATION	RETIAL	GROUP E	3.2.2.57
	COMMERCIAL OFFICE	GROUP D	3.2.2.50
	RESIDENTIAL	GROUP C	3.2.2.43

Figure 6.5.2 - Building code parameters for existing building to compare

For most buildings this size, two years of construction time is unacceptable from a project management point of view. The existing building took two years to build because of the issues discovered during construction. Like most projects in this situation, the complications occurred because they started construction before knowing the problems, not taking the time to strategically design and plan for the construction processes can leave the project vulnerable to errors that could have been easily avoided. It's not only the design development phase of developing the building itself, but being very knowledgeable about the context we are building in. This has become a result of digital design programs being highly advanced in imagery but lacking any actual construction and build processes, which have not been integrated, the problem is that we have an issue in bringing them together.

'There is too much focus on form and not enough focus on performance in helping define form. The power is developing agile information at the speed of design to inform the making of form' (Kieran, 2014). I have followed a process that has dealt with decision-making from concept by examining the details of site parameters as well as the construction assembly process onsite to aid in a design solution and to structure my thought process.

6.6 Schedule

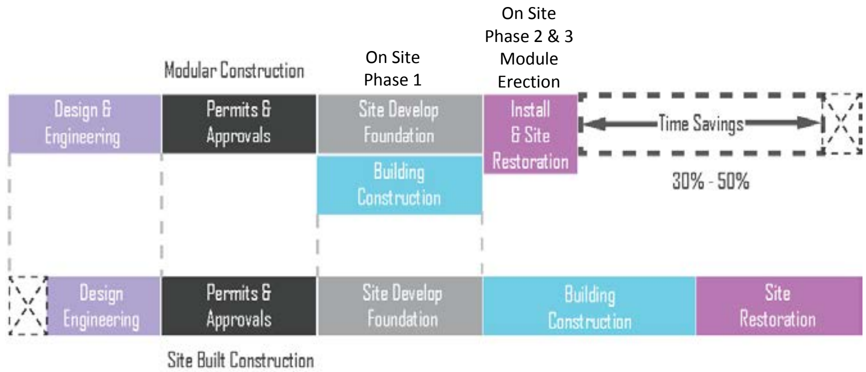


Figure 6.6.1 - Time savings for modular construction

The parameters of a conventional building process (site built construction) in comparison to modular design and construction, show that putting more emphasis on the design development phase allows for design strategies to aid in the construction and assembly processes, therefore, the project produces in a much shorter time with more efficiency and better performance results for leaner construction in phase 2 and 3 (Figure 6.6.1). This can eliminate potential flaws a conventional building process may have during the construction phase and reduce costly design changes (Figure 6.6.2). The permits and approval time can be reduced due to the work being done offsite with an integrated team and holistic process, the close relationships cause faster production and communication times. Also, modular design and construction can have repetitive tasks and specific design regulations in place which can lead to a faster approval response. Typical modular designs do not include full basements and can reduce the site development schedule significantly, and site restoration is reduced because furnishing is done off site as much as possible to the final finished product; and because 3D models are extremely detailed they can potentially be handed off to the building operator to maintain the building.

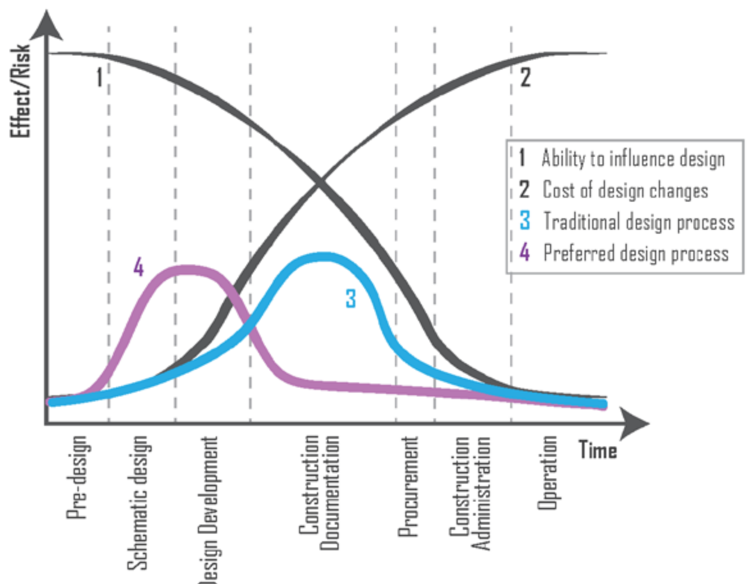


Figure 6.6.2 - Original construction schedule versus preferred modular schedule

Trying to maintain quality on a tight budget and within a strict time frame, with the intent to achieve profit margins, are improved when planning the workflow and processes for the project before construction begins. Executing a plan beforehand provides a safety net to minimize risk and any unknown scenarios that may occur onsite (Figure 6.6.2). This is critical for firms to rethink traditions and become more educated and observant in the processes.

6.7 Site parameters

Site conditions will create significant factors on modularity and in the processes will impact design, organization and schedules. The site is analyzed to preplan a strategy and to note any obstacles found onsite for optimized machine flow, site access, placement of materials and equipment stored onsite. We can begin to map out the process of workers and machines onsite to reduce downtime and be as efficient as possible when assembling.

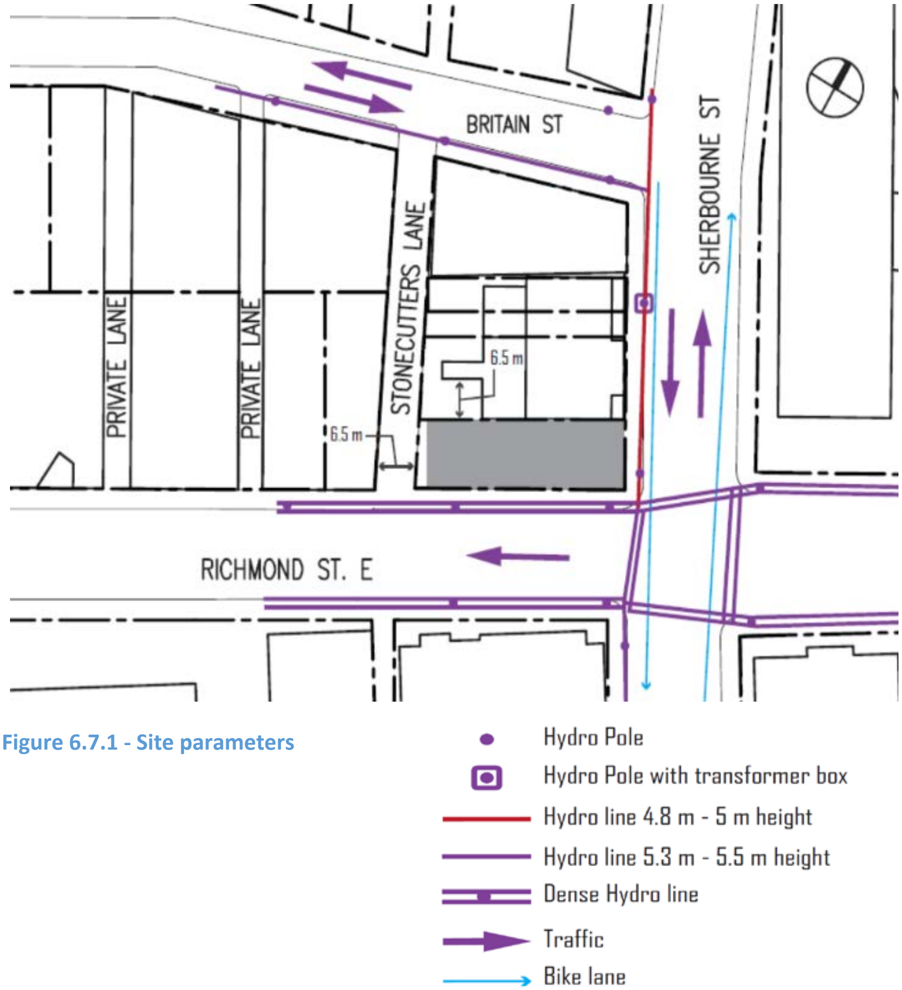


Figure 6.7.1 - Site parameters

This diagram highlights traffic flow and measurements for clearance, as well as access to the site (Figure 6.7.1). The double line represents dense hydro lines that can become an issue for crane operation; the single red line tells us that access onto Britain St. may be limited due to low hydro lines from the hydro pole with transformer box on Sherbourne Street. Therefore, the best access route for traffic of large shipments is to take Richmond St. East onto Stonecutters Lane. The modules must conform to the allowable space given for maximum efficiency in delivery and assembly, without disturbing the surrounding area or inconveniencing anyone until the project is complete. Modular construction can alleviate site issues such as this, and minimize the workers required to build onsite in constrictive spaces. It should be noted to check the local council in the early stages to determine the impact the building will have on the surrounding environment and any future plans that exist in the area. After the site analysis was completed it was discovered that there are no future plans of development for the immediate surrounding area.

6.8 Accessibility

As previously discussed in the site analysis, access to the site is constrained, having the building produced under controlled factory conditions means less time that will be spent on the site. This results in a safer, cleaner site, a faster assembly time, and less disruption to the organization. Another point for modular construction is that restricted space for onsite work is an impeding problem and continuously increasing as we develop in urban settings. This topic is becoming more of a concern in future development because of dense urban areas. 'One of the largest influences in the future of construction is offsite manufacturing' (Bernstein, 2011).

Modular construction seems to be the best response as it is known to alleviate space and minimize the workers required to build onsite. In addition to this, recent projects in modular construction have been so confident that they agree to impossible deadlines, building skyscrapers in a few months to cause less of a disturbance to the area. A recent project shows how this congestion is becoming a common problem in established areas and how modular construction has alleviated the concerns.

6.8.1 Accessibility Precedent – Leadenhall

The Leadenhall building is a 50 story tower in London, UK, by Rogers Stirk Harbour + Partners was just finished in 2013. The site was completely restricted from any onsite construction (Figure 6.8.1.1). Part of the building is made up of modular units, the remaining pieces of the building (the slope) are constructed out of prefabricated parts and assembled onsite.

Figure 6.8.1.1 - Leadenhall building accessibility

With an 84,424-sqm floor area and a tight deadline, the construction sequence had to move fast onsite, with just one crane driver and six people, they completed the equivalent of four tennis court sizes in one day, this was due to the fact that most of what was required was assembling bolts onsite (Films, 2014). Pouring concrete would take three times longer and would need double the man power. There was no logistic space for organization onsite so they worked under just-in-time delivery; a crane was ready to lift as soon as the module arrived, and in some cases they were lifting three story stacked modules with only four workers to guide them (Films, 2014) (Figure 6.8.1.2). It would be impossible to coordinate and assemble every piece on this type of schedule using 2D drawings. Instead, they created an entire 3D model of the building and structure, right down to the single bolt (Figure 6.8.1.3), to be as efficient as possible and to make sure everything fit. It took 18 months for the digital model to run complete simulations, it was built 37 times digitally, every hour and piece is accounted for months in advance, digitally modeling the sequence guaranteed each component was lifted into its exact defined location right first time (Figure 6.8.1.4). This allowed each machine to be optimized so there was no downtime; every component and every crane lift was given a time slot (Films, 2014). As one trade finishes the next one is preparing to start. It only took 24 people to compete 41 floors of prefabricated modules, this project could not have been done in the amount of time they had and with the constraints they were dealing with, without modular construction. This project is a good example of what the industry needs to prepare for in future situations.

Figure 6.8.1.2 – Prefabricated module guided into place with 4 workers and one supervisor

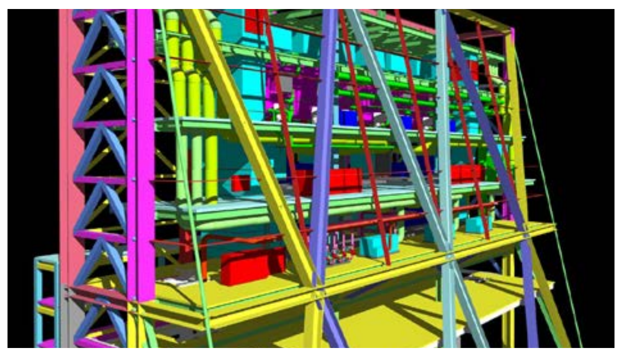


Figure 6.8.1.3 - Detailed 3D model used for simulation of processes and onsite reference

Figure 6.8.1.4 – Digital crane simulation VS onsite placement

6.9 Transportation

With any modular construction, transportation is critical to the overall scheduling of the construction project. It involves careful study and consideration of dimensional criteria, setting out a path and making space allowances. It is important to speak with the local cohort district authorities from the Ministry of Transportation Ontario (MTO). They will advise if and when the item can be shipped and the best route to take. They will help with the necessary claims and forms to file prior to delivery. Once everything is approved and payments have been made they will lay out most of the guidelines required for the load and transportation including, times of day you are allowed to travel, number of escorts, maximum loads and overall sizes. Anything over the maximum size will result in more fees. The modules for this design have a larger than normal width of 5.5 meters wide, with a length of 11 meters and a height of 3.7 meters. Typical width to transport a load on a transport truck is 2.59 meters. But, most companies have what is called an 'annual permit'. An annual permit allows the company to transport larger loads in the daytime ("A Guide to Oversize," 2014). For a 5.5 meter size a special permit is required, it is the maximum width before larger fees incur. A single trip permit is issued to facilitate an oversize move for a one way trip along a specified route for a limited time period. The following dimensions are permitted on single trip permits:

Length - single vehicle 12.50 m including an overhang up to 4.65 m
Width - from 2.61 m to 5.50 m, over 5.50 m (must be submitted to the Permit Issuing Office)
Height - 4.16 m or greater, maximum height permitted on a flatbed trailer is 4.26 m
("A Guide to Oversize," 2014)

The size and location requires two escorts (an additional fee) with flags and signs at the required locations of the load. The shipment times for a load this size is listed, but accommodations can be made if needed, a major concern for MTO is to avoid rush hour traffic times. For large shipments they will notify road crews to clear any obstruction along the way and notify delivery trucks if there will be any construction on the roads. The modules were designed with a larger width size in order to take advantage of the entire lot coverage to maximize the space available. This was a strategic decision; extra fees incurred with shipping will be recovered quickly balancing out the additional cost. The first decision was to not overly complicate the structural design, by efficiently orienting the modules onsite, the structure is at its most valuable location in which a better outcome is achieved, this is shown under section 7.1 Building Configuration.

Secondly is having the module itself enclosed as much as possible, therefore, the object is not exposed to the elements during delivery, meaning minimal time is taken from the schedule for onsite finishing touches, the more components to attach, means more joints to seal, more complications, and more time. Thirdly, perhaps the most beneficial reason, is the floor layout design, the floor area is maximized to achieve more occupied space and comfort in a narrow area for a greater return on investment overall. Therefore, the three major reasons for an oversized load and paying initial extra fees is compensated by a leaner and more efficient structural grid design, faster schedule with no delays and maximum livable space for comfort and greater return on investment during the buildings lifetime.

There are two modular sites that are available for manufacturing and assembling the modules. The first is the PCL Construction Company, at the Permanent Modular Construction site located 22.9 km (19 minutes) away from site at 2520 Haines Road, Mississauga, Ontario. The second is Vector Praxis, located 11.8 km (16 minutes) away at 500 Keele Street, Toronto, Ontario (Figure 6.9.1).

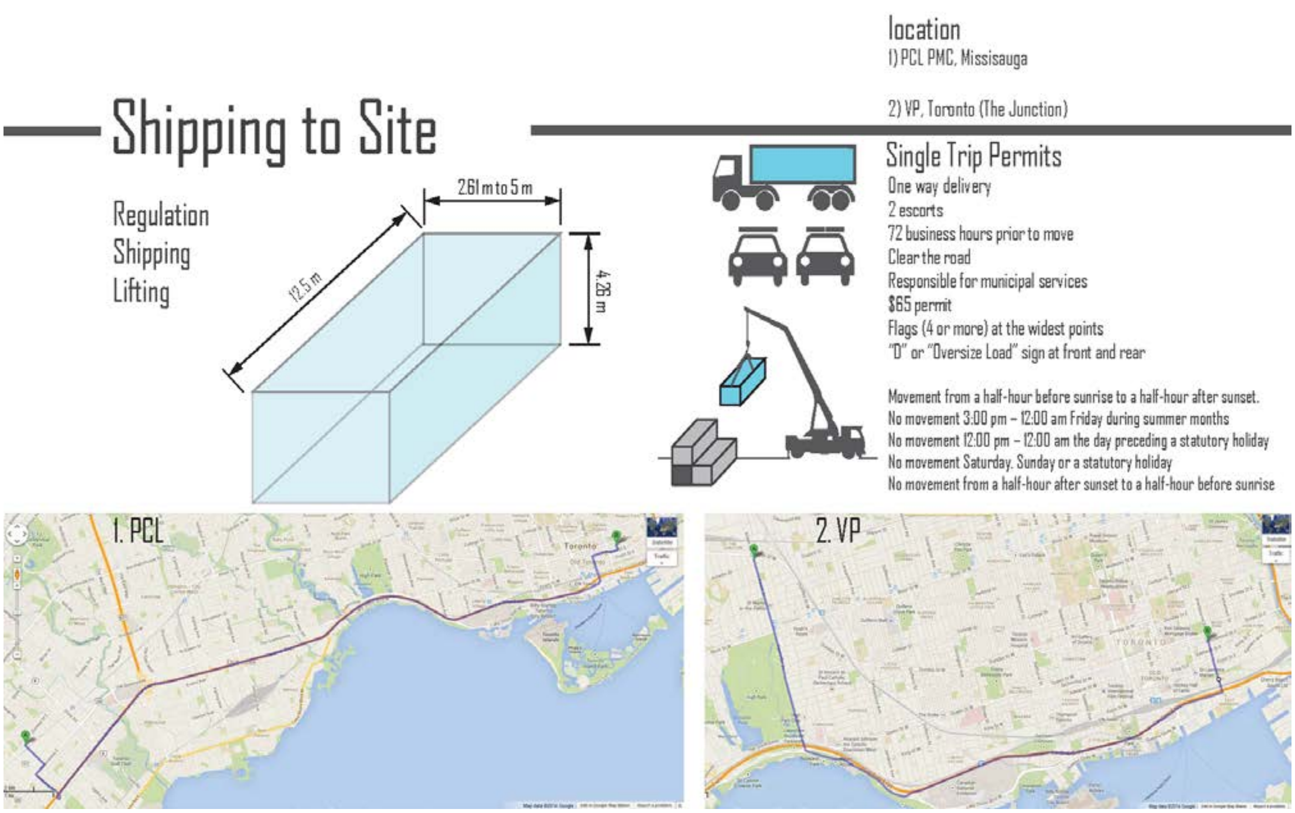


Figure 6.9.1 – Shipping and Ministry of Transportation Ontario

6.10 Crane Specification

After consulting with a crane specialist and senior engineer from Western Mechanical, I was advised to stick with one mobile crane for the entire assembly. Initially the plan was to bring in a mobile crane to set up a stationary crane in the building to alleviate space onsite, and then disassemble it by a mobile crane when the job was complete. However, the crane specialist said the project can be done with one mobile crane with little risk and effort. The choice came down to using the smallest crane possible that was still able to do the job to minimize costs. A tower crane costs an incredible amount of money and it would likely take a larger mobile crane to assemble a tower crane. Since cranes are charged on an hourly basis, a larger mobile crane is expensive, but not nearly as expensive as a tower crane (M. Carney, personal communication, May 07, 2014), tower cranes are justifiable for large projects that take a long time. The purpose of using modular construction for a building is to reduce construction time onsite which means the plan should not require a stationary tower crane (M. Carney, personal communication, May 07, 2014). Therefore, it was determined that the crane specified would be the LTM 1250 crane (mobile, hydraulic, see Appendix A2 - Crane Technical Data). Although these modules are not the heaviest type; the ideal months for heavy lifting with any crane are during June and July where wind loads are usually under 10km per hour in Toronto, anything over that can cause difficulty. Since modular principles try to achieve the most amount of work offsite, strategic and logistic crane operations are an integral part to the project (Figure 6.10.1).

Figure 6.10.1 - Crane statistic

7. Project: Design – Manufacturing – Assembly (DMA)

After reviewing and analyzing the project parameters in section 6, learning the workflow strategies for design is revealing the guidelines and shaping the overall project. The background knowledge and the benefits of modular design and construction are outlining the project and positioning the design team in the right direction by being equipped with the proper tools, they can integrate all of the previous knowledge with the specific parameters given with the site and apply them to the details of the project to achieve a noble and more informed design.

7.1 Building Configuration

Job site condition and accessibility should be in coordination with delivery crew and crane operation to analyze all of the influential processes and design decision making when using modular construction.
The building configuration of the modules were carefully considered and given a method of assembly. The first thing to consider is the surrounding environment and the direct relation to the existing building on the north property line. There is an existing building along the north property line adjacent to the proposed building (highlighted in red in Figure 7.2.1). This realization determined the design had to incorporate fireproofing between the two buildings in order to adhere to fire code regulations. Precast concrete tiles are built onto the back wall of the modules on the north face. With the given site, a number of module variations were tested and designed for structure, circulation, and the most optimal space 12 times (Figure 7.1.1), and the interior layout variations were tested and designed 29 times.

The first iteration shows a north to south orientation which utilizes the floor space after the corridor and circulation are considered. However, only two out of six units achieve the greatest amount of exterior surface, in addition to this, the structure is not in its most efficient layout when considering other possibilities.
The second iteration shows ample common space between the residents, however, the layout can only accommodate four units, and only two out of the six units attain the greatest amount of exterior surface.
The third iteration shows the greatest amount of exterior surface between three of the six units and has the most utilized occupiable floor space, however, to support all of the floor space, the center module will not be entirely enclosed.

The fourth iteration is similar to the first except it skips every other module and then bridges across to save on the repetitive materials; however, it does not utilize most of the floor space after the corridor and circulation are considered. Bridging across leaves all units exposed to the elements which requires a lot of time for onsite work compared to the rest, which is counterintuitive to the project. Plus, only two out of the five units achieves the greatest amount of exterior surface, in addition to this, the structure is still not in its most efficient layout when considering other possibilities.

The fifth design iteration was chosen because three out of the five units have the most sunlight exposure compared to the unit's surface area and potentially has the most functional space in terms of its structural bays and lateral bracing. Even though the two north modules have a small surface area to sun exposure it can be design to have light shelves to extend the light source or connect the two modules north to south.

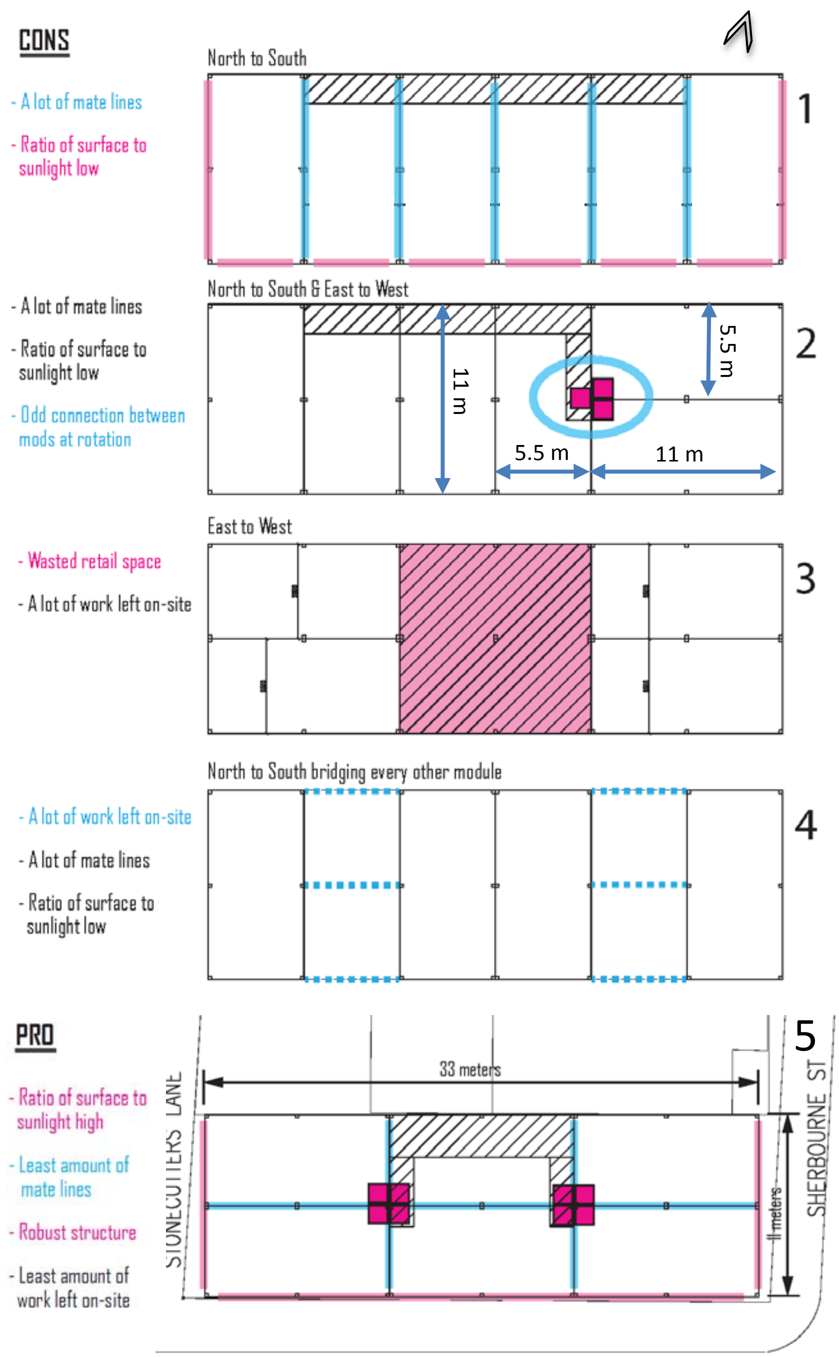
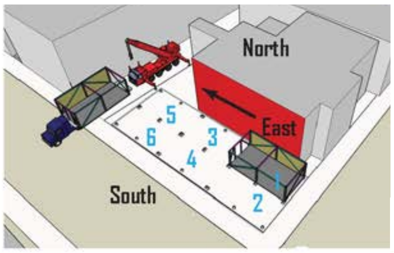


Figure 7.1.1 - Top five module iterations, building orientations

7.2 Module Placement Onsite

With the building configuration chosen, the sequence of the modules placed onsite begins with the mobile crane. The first module is placed in the north-east corner of the property, the second module is placed on the south-east corner, the third on the north (center) of the property and the fourth on the south (center), the fifth module will be placed on the north-west of the property, and the sixth module on the south-west of the property to finish up the first floor. The pattern is repeated for the remaining floors moving consecutively from east to west (Figure 7.2.1). Each module is structurally stable for erection process.



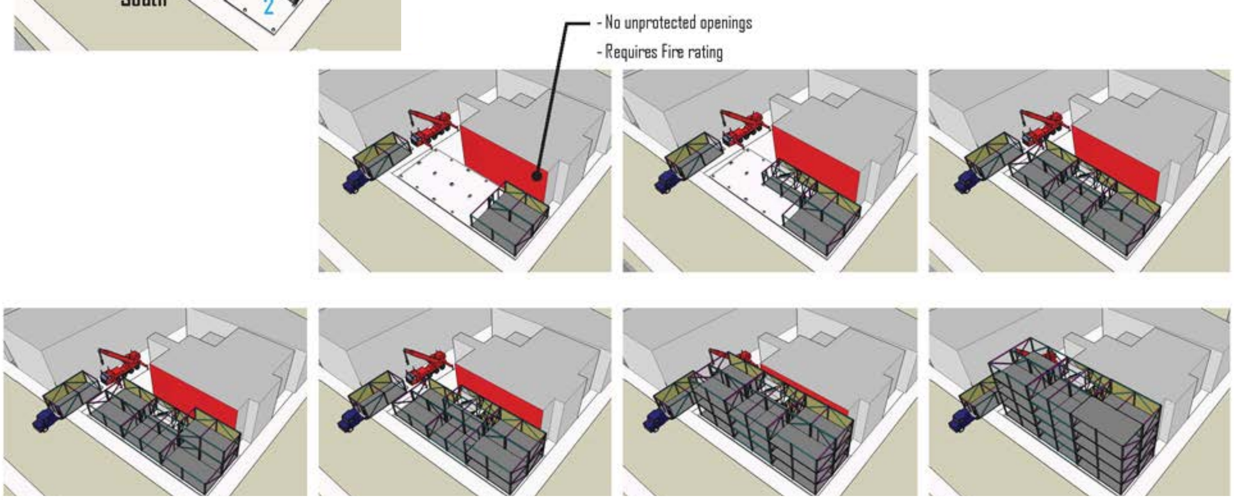


Figure 7.2.1 - Module placement from building configuration

7.3 Module Orientation

These are some of the modular orientations considered when moving forward with the design. Note that this is not the entire buildings massing, these are only a few scenarios that were pertinent to the specific site parameters of the project to stage and analyze for the best possible site design considerations that engage with the broader culture (Figure 7.3.1).

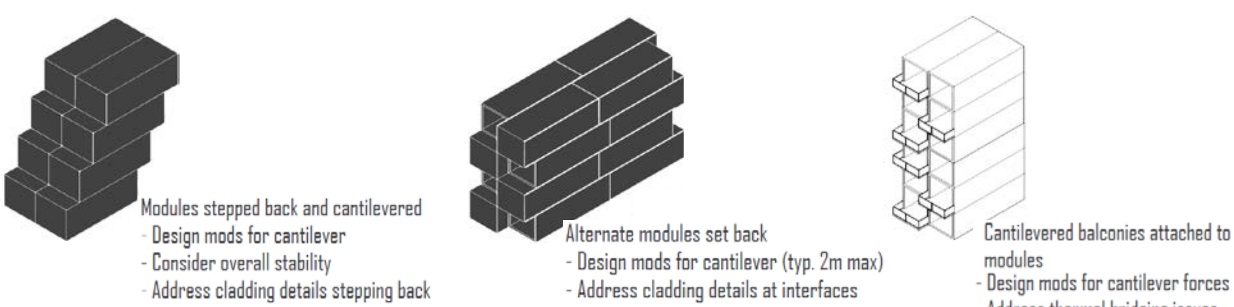


Figure 7.3.1 - Module orientation

7.4 Structural Stability

The Atlantic Yards B2 project had subcontracted the structural work, since this building is the first of its kind, I believe the company's response resulted in a typical brace frame solution around the building and didn't take enough time to come up with a more efficient structure. Time dedicated to developing a design that was specific to the project would have also assisted the assembly. Opportunities were missed to create a leaner, more efficient design for the project. Therefore, I explored how to design for a more efficient brace frame solution. A discussion with a professional who chose to remain anonymous, worked on the Atlantic Yards project and went over my alternative structure because the thesis design was similar to the B2 Atlantic Yards modules. Knowledge from the case studies in section 5 has instigated that a modules structural integrity is efficient enough to withstand being shipped and lifted by crane.

The term robustness refers to the additional structural capacities of modular buildings in order to withstand road vibration and vehicle braking when being shipped, and the craning forces when being lifted. 'Modular buildings are built to be stronger structurally than a similar insitu building. The benefits of robustness include increased strength and durability, seismic resistance, and future additional loading capacity' (Lawson, Grubb, Pewer, Trebilcock, 1999). Theoretically, the structure of the thesis project is robust enough to withstand future expansion to adapt and grow for a multifamily buildings future needs. Therefore, overall stability can be provided by the modules themselves, or by an external structure such as the B2 Atlantic Yards. From this, I was able to come up with an alternative where the brace frame is designed in concentrated areas. To do this, a rigid connection for every corner of the module would make the entire building stable enough to reduce the brace frame with a vierendeel truss which spans to the modules corner posts to carry the vertical loads to the foundations (Matchneer, 2013). Consequently the ends are the only required connection points (Lawson, Grubb, Pewer, Trebilcock, 1999). The structure is supported by the modules corner steel posts in which loads are transferred via edge beams to corner posts. The posts consist of Square Hollow Sections (SHS) for their high buckling resistance because compression resistance of the corner posts is the controlling load factor. The corner posts must align and be connected throughout the building. Resistance to horizontal forces require bracing within the walls of the modules and hot rolled steel members located in the lifts and stair area. Modules are tied at their corners both horizontally and vertically so that they act together to transfer wind loads. When modules are tied together they become more robust (Lawson, Grubb, Pewer, Trebilcock, 1999) and the walls of the module are supported with braced frames to minimize any deflection. Thus, a full set of modules stacked in a grid formation connected with a rigid connection will in theory have enough stability suitable for buildings between 6 to 10 stories.

Since all loads are transferred through the end columns, openings and glazing can be configured without consideration of shear forces (Lawson, Grubb, Pewer, Trebilcock, 1999). If the brace frame is concentrated in the right areas, for example, the bottom four corners for the first few floors, then, the brace frame can be reduced in the upper part of the building if needed (Figure 7.4.1 to Figure 7.4.3). The subfloor group of modules are connected horizontally and act as a floor diaphragm, this will distribute lateral loads back to the braced frames;

When a fully enclosed module is stacked or placed side by side the structure is doubling, at first this can be seen as a constraint as more material and more space is being used, therefore, a deeper understanding of the structural behavior is required or else the structure can become overly designed. However, the structure can be seen as a benefit for stability and assembly when planning ahead, there is also the benefit of running the services in the cavity space between two modules if the design allows, and with the available computer technology, simulations of the design can be tested for the most efficient structural size and thickness of each member.

The grid structure for the thesis project can allow the module orientation to be flexible because the width and length of a module will be the same as the column bays, therefore, modules can potentially be placed north to south or east to west as shown in section 7.1. This design decision opened an opportunity to explore a variety of unit configurations and floor plan layouts. The structure in modular design is an important influence to the design, construction, and assembly.

> ‘The more detailed the surrounding information is, the more concentrated
> the components can be, and the clearer it can be to direct design’
> – Mark Burry (Burry and Burry, 2010).

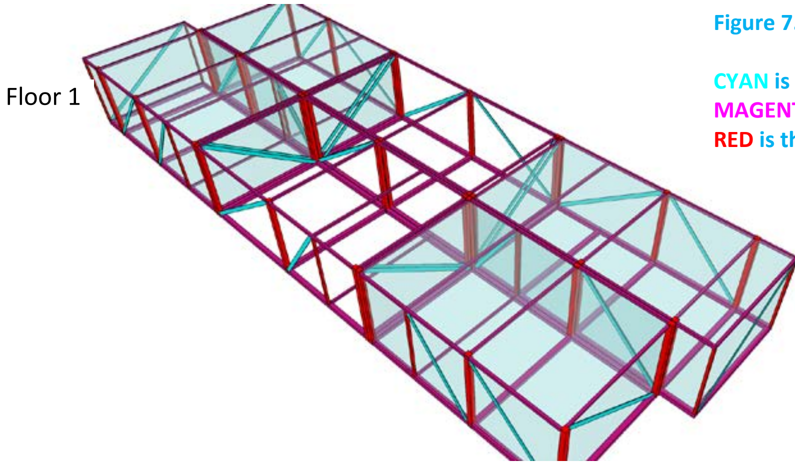


Figure 7.4.1 - Brace frame of bottom four corners

CYAN is the lateral bracing
MAGENTA is the horizontal mainframe of the module
RED is the vertical mainframe of the module

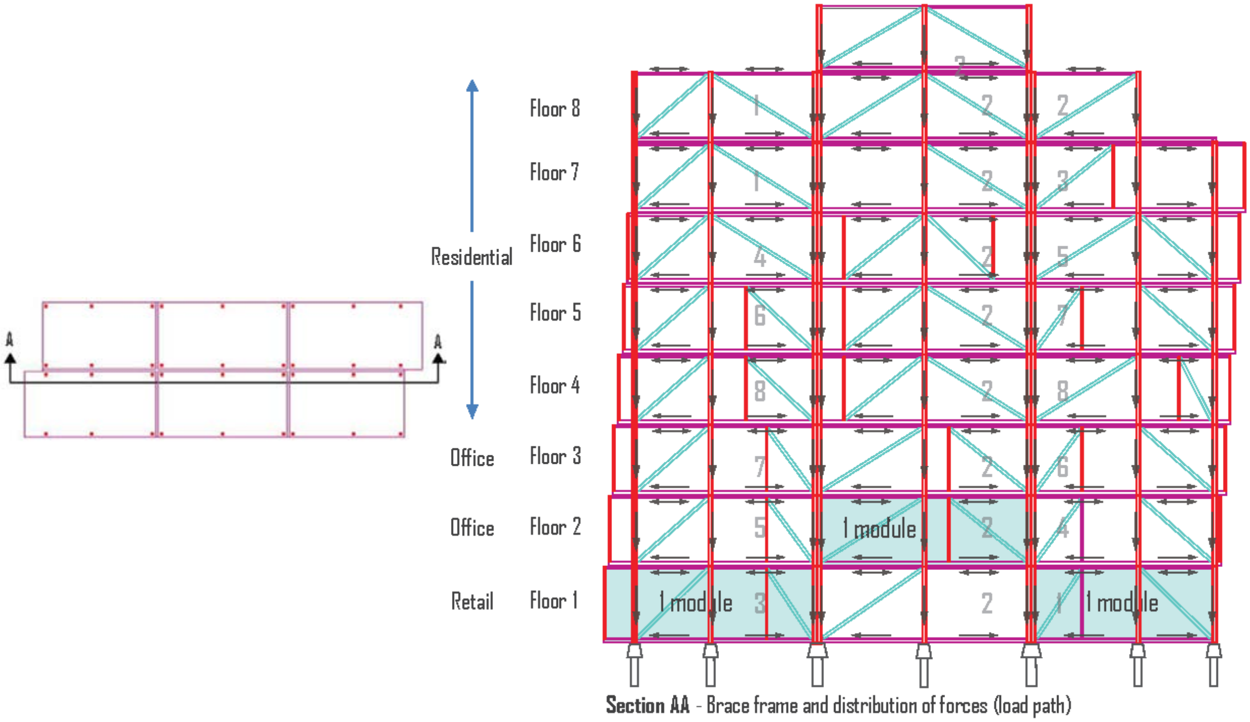


Figure 7.4.2 - Brace frame and distribution of forces (load path) in stacked modules of the building structure.

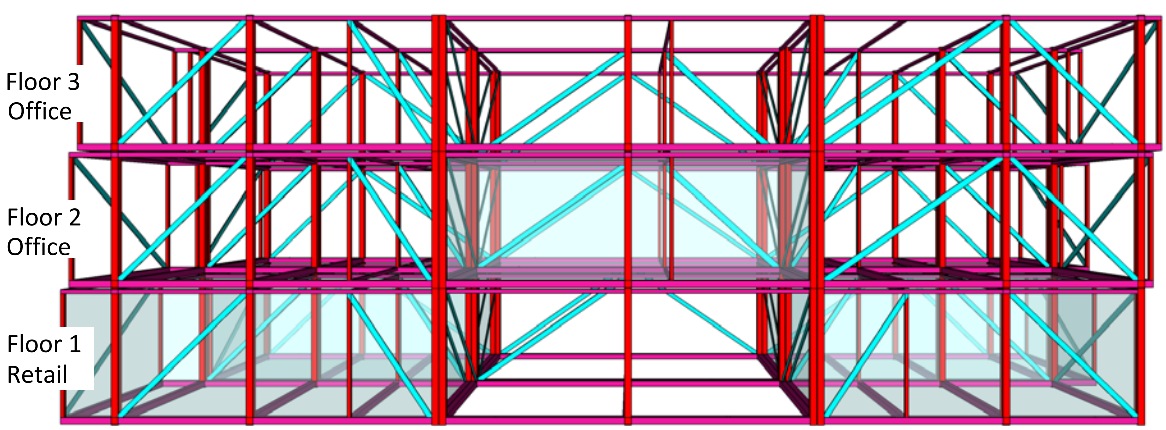


Figure 7.4.3 - Brace frame of the first three floors

7.5 Module Design

The steel frame uses square hollow section for the vertical and horizontal members. These are welded together at the intersection of the corners. The design of each module has both a floor and roof structure. Floors are designed to have purlins welded onto the main frame with corrugated steel and cement board instead of poured concrete to minimize weight and help with crane capacities. The roof consists of purlins and corrugated steel so that workers onsite can stand on top during installation. The lateral bracing is welded to the main frame for slimmer wall thickness (Figure 7.5.1, Figure 7.6.7, and Figure 7.7.1) as opposed to the design in B2 which is placed on the outside of the modules main structural frame as a secondary structure throughout the entire building (Figure 5.6.1.8), creating thicker walls.

The module design for the thesis project has resulted in a rectangle shape; the resulting shape was formulated because of the small lot (11m x 33m) restrictions, therefore, the rectangle shape was necessary to take advantage of every square meter on the small lot so that the homeowner can feel comfortable and not confined by a smaller space with an odd shape. This allows the space to be flexible and adaptable, creating an irregular shape can restrict the livable spaces with unusable or uncomfortable angles or curvature.

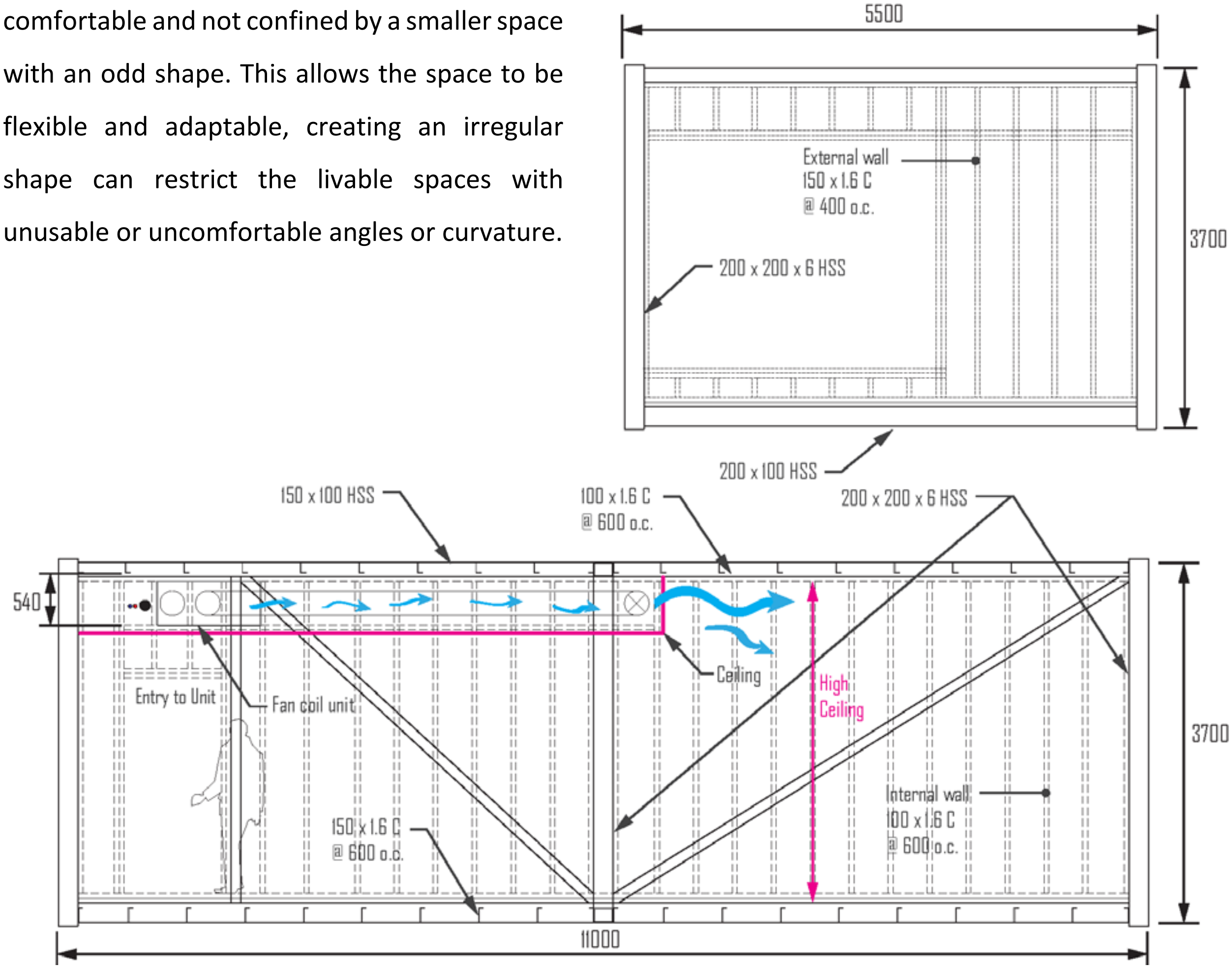


Figure 7.5.1 – Module Structure components, HVAC unit at entrance of each module, displaying distribution to mid module

The overall dimensions of 5.5m by 11m also fits within the allowable transportation sizes on the road. The design of the module will take advantage of the height by putting the services in the ceilings structural frame, this allowed more floor area given the narrow width between units. Describing the module frame as a 'chassis' during the manufacturing relates it loosely to automotive techniques than a traditional house frame because it is predesigned with all of the services such as (insulation, wiring, plumbing, etc.) and built with dedicated room to receive others with as many universal connections as needed.

The thesis project structure is designed to be leaner and more efficient in terms of lateral bracing compared to B2 Atlantic Yards, where no additional support is required on the outside of the module; the major difference between the two in design, is my design involves placing the structure within the modules main frame and reducing the amount of lateral bracing to critical areas.

Building modular units in a controlled setting in general, can take on any shape desired. The structural system is flexible enough to accommodate any conceived architectural form as the perimeter of a module can have any imaginable relationship to the structural frame (Figure 7.5.2). Almost any architectural form can be modularized; however, as stated earlier, best results are achieved when designs are initially conceived as modular. This is another force that is leading the industry to more prefabricate modular designs, for instance, to achieve the intended design composed of complex geometry, it requires more accuracy and quality which is more suitable in a factory setting. One major influence that makes it easier to conceive this process is the control that builders have in factory conditions: not exposed to the elements, work with gravity, and all the resources and tools are in close proximity to them at all times. Building modular units in a controlled setting will likely yield to the highest cost and schedule benefits (Bernstein, 2011). It is stated that production of a modular unit can be complete in as little as 90 minutes minus interior walls, floors and fixings and still achieve a high level of accuracy to ensure a simple construction process onsite (Matchneer, 2013).

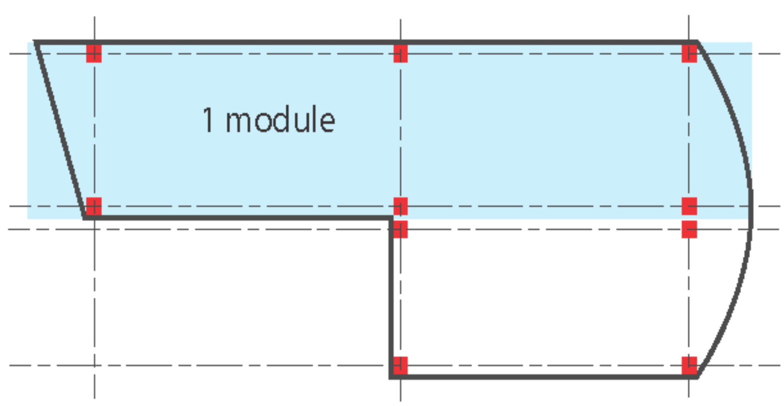


Figure 7.5.2 - Perimeter of module can take any architectural form

7.6 Module Assembly

After researching connectors, the most efficient process required a connection that is universal for the purposes of faster production and a simpler repetitive method of assembly for the builders. The design to join the modules together include a rigid connection and is located at the top and bottom of every column of each module, six columns and 12 connections all together (Figure 7.6.9). The connection consists of a threaded rod that is passed through the column of each unit stacked vertically, a single plate that consists of a tapered pin welded to the plate as a guide for accurate placement is slotted through the threaded rod to position the module and plug into the tubular steel frame column, it is then post tensioned and locked by hand using a washer and nut to fasten. The next module is then stacked on top to sandwich the plate in between two modules, this rigid connection works in both the horizontal and vertical direction, creating a continuous member that will transfer the loads to the foundation (connections are shown through Figure 7.6.1 to Figure 7.6.15, a detailed section of the connection is shown in Figure 7.6.10 and Figure 7.7.3). This connection detail was influenced from the SOMA precedent of the threaded rod, and T30 Hotels pin detail to speed the assembly process onsite, this project has merged the two to adapt to modular construction. The connector element is available to suit 1 to 4 configurations depending on the type of module configuration. The connector system is integral to the overall building's construction and its design is carefully measured and tested. Designing a rigid connection for every corner of the module would make the entire building stable enough to reduce the brace frame at a height below 10 floors if the building design required. This connection does not require site welding, and allows for all of the work to be done standing on the top of the modules so the builders can work with gravity.

The connection detail is designed to be applicable to all module assemblies of the building, this influenced universal and versatile effects in larger implications of design through its singular connection and instills a sense of harmony in the project and overall theories presented in this thesis.

1. Pile foundation with concrete cap and base plate (Figure 7.6.1)

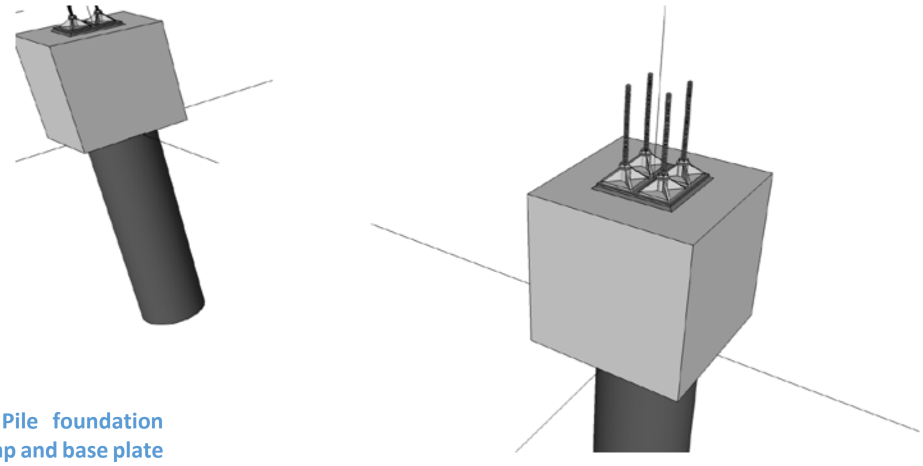


Figure 7.6.1 - Pile foundation with concrete cap and base plate

The foundation consists of a drilled shaft caisson and a crawlspace since there is no basement. The threaded rods and base plate are anchored into the concrete foundation. No matter how precise the digital planning of the model and fabrication processes are in the building industry, the success of the assembly depends on the manual process of excavating the foundation (Papanikolaou, 2008). Therefore, there is always a risk of error, but this too can be minimized, for example, precast concrete members, surveyors, digital scanning, and soil tests can be measured to reduce many of the risks associated with it.

2. Long nut added to receive and extend steel rod through first module (Figure 7.6.2)

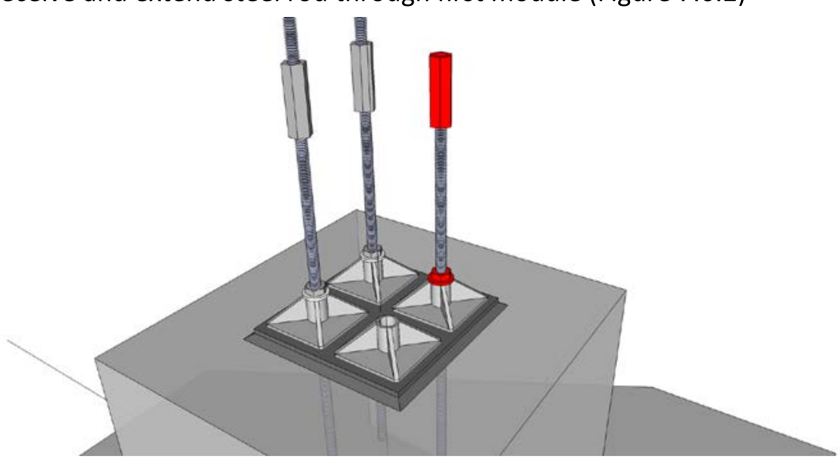


Figure 7.6.2 - Long nut added to receive and extend steel rod through first module

The tapered pins are welded onto the baseplates in the factory, the washer and nut are fastened and tightened onto the rod, the long nut is then added, ready to extend another threaded rod for the first module to be set in place (3.7 meter high). The tapered pin fits inside of the column to come and is a design element to assist and guide the module into its final position to reduce setting time and increase accuracy. There are two pins labeled as floating pins that have a slightly larger tolerance to allow for error.

3. Module #1.1 guided into placement (Figure 7.6.3)

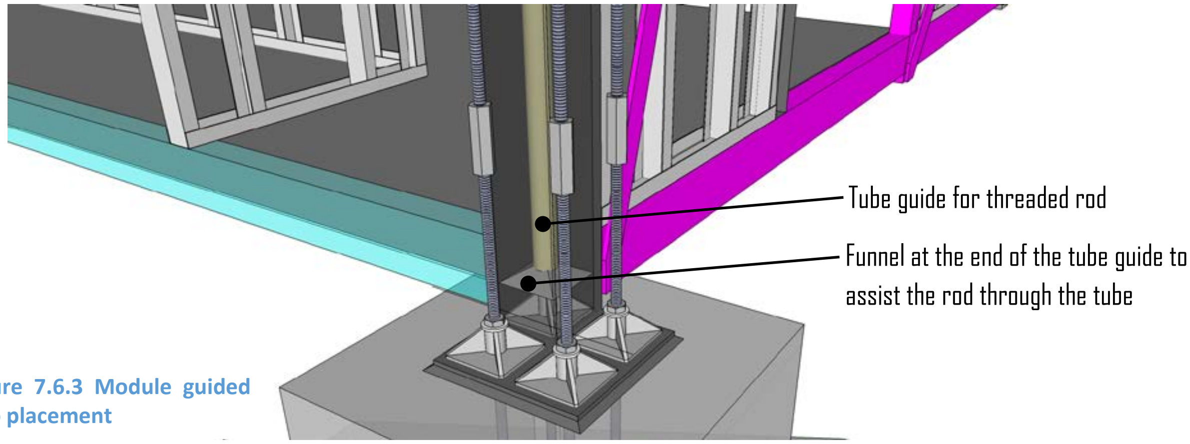


Figure 7.6.3 Module guided into placement

The structure is translucent to show the interlocking system. A guiding tube component was prefabricated within the column to aid in the guidance of the free standing threaded rods. The ends of the component are set further inside the column to leave clearance for the pin, the component is also tapered and acts like a funnel to guide the rod into a plastic tube. The tube has a large tolerance to accept the width of the long nut, there is no structural importance to the prefabricated tube component, and its only purpose is to assist the module placement when setting it down through six rods.

4. Zoomed out view showcasing the full length of the tube guide prefabricated inside the column to feed the steel rod through the column (Figure 7.6.4 to be updated)

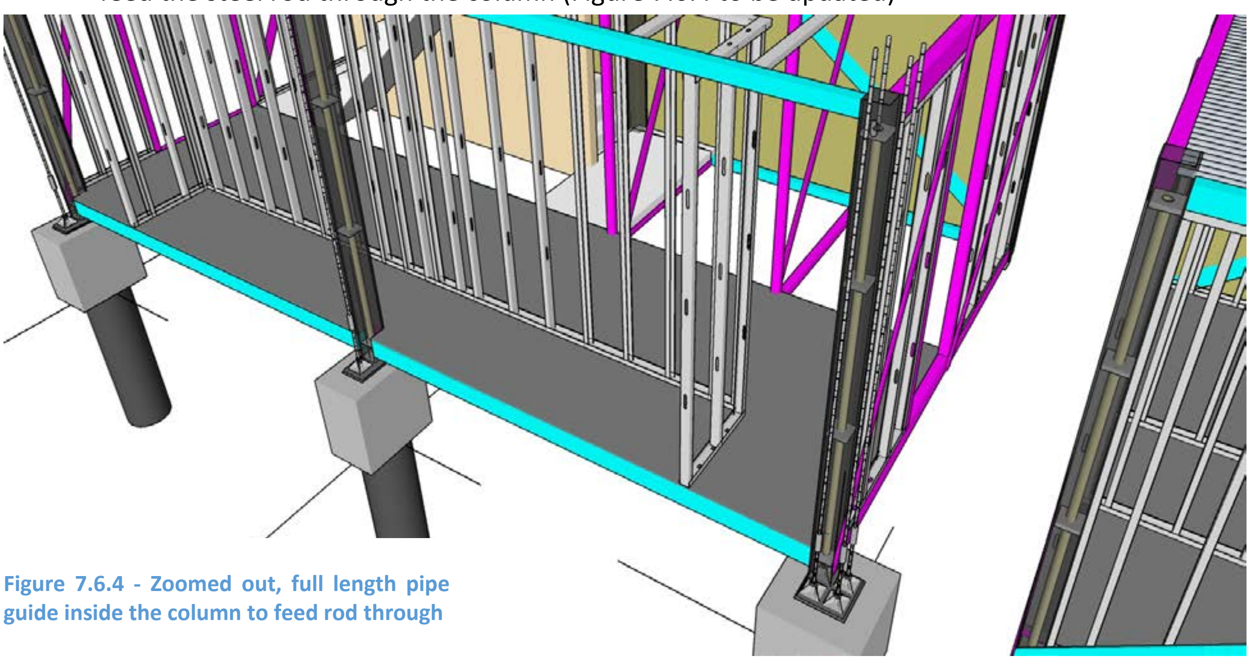


Figure 7.6.4 - Zoomed out, full length pipe guide inside the column to feed rod through

The modules are shown as an exoskeleton to showcase the structural properties. Note, is not the order of the module assemblies, the purpose of these images are to represent the module connections onsite.

5. Module #1.2 guided onto base plate (Figure 7.6.5)

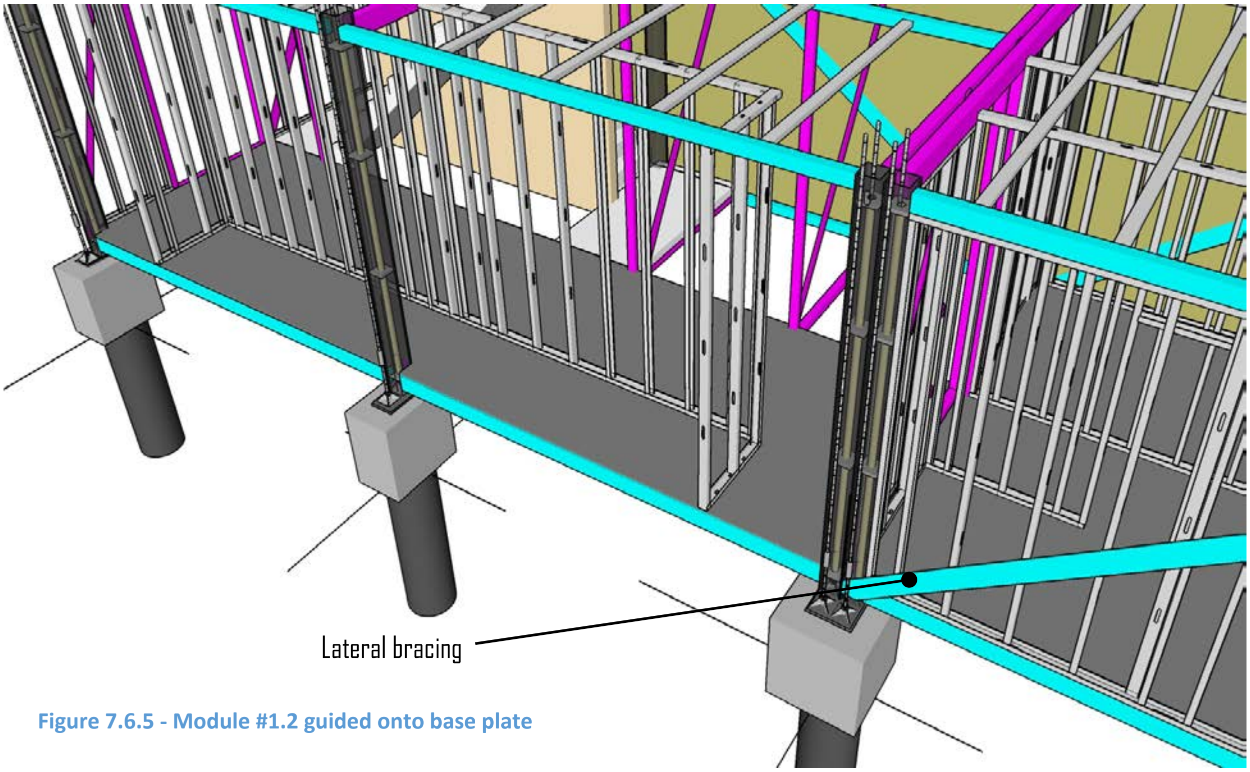


Figure 7.6.5 - Module #1.2 guided onto base plate

The second module is in its final resting place. Here is a glimpse of lateral bracing welded to the main frame east to west and placed in an unused space between two modules.

6. Close up of pipe guide and two modules side by side (Figure 7.6.6)

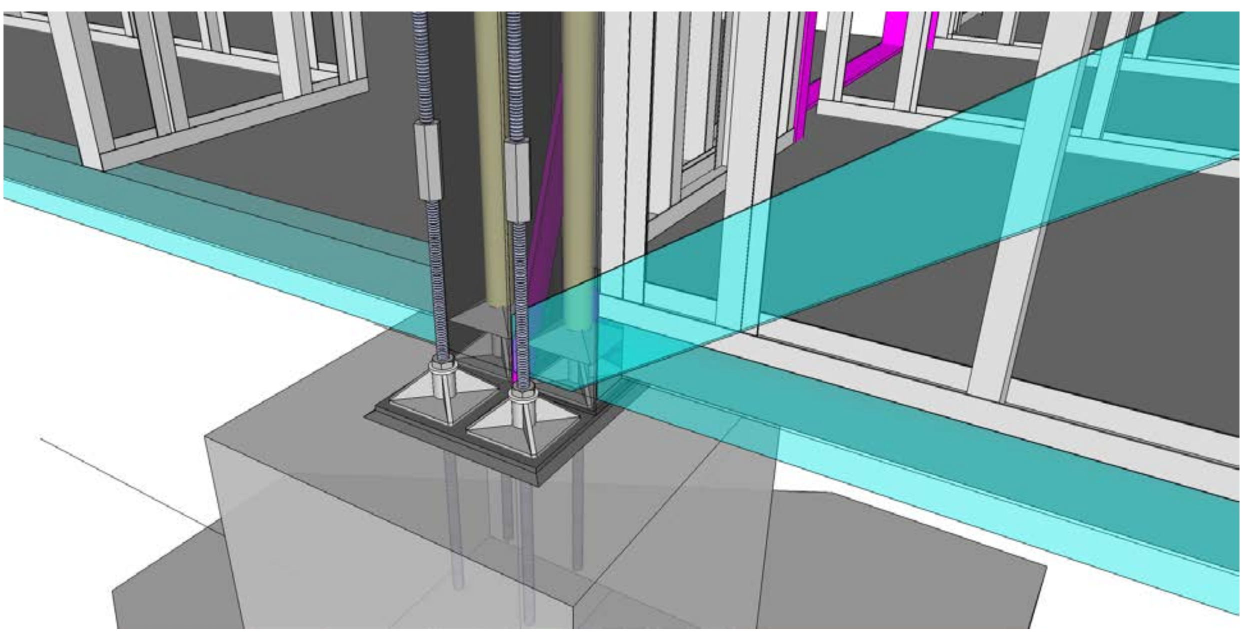


Figure 7.6.6 - Close up of pipe guide and two modules side by side

7. Module #1.3 placement (Figure 7.6.7)

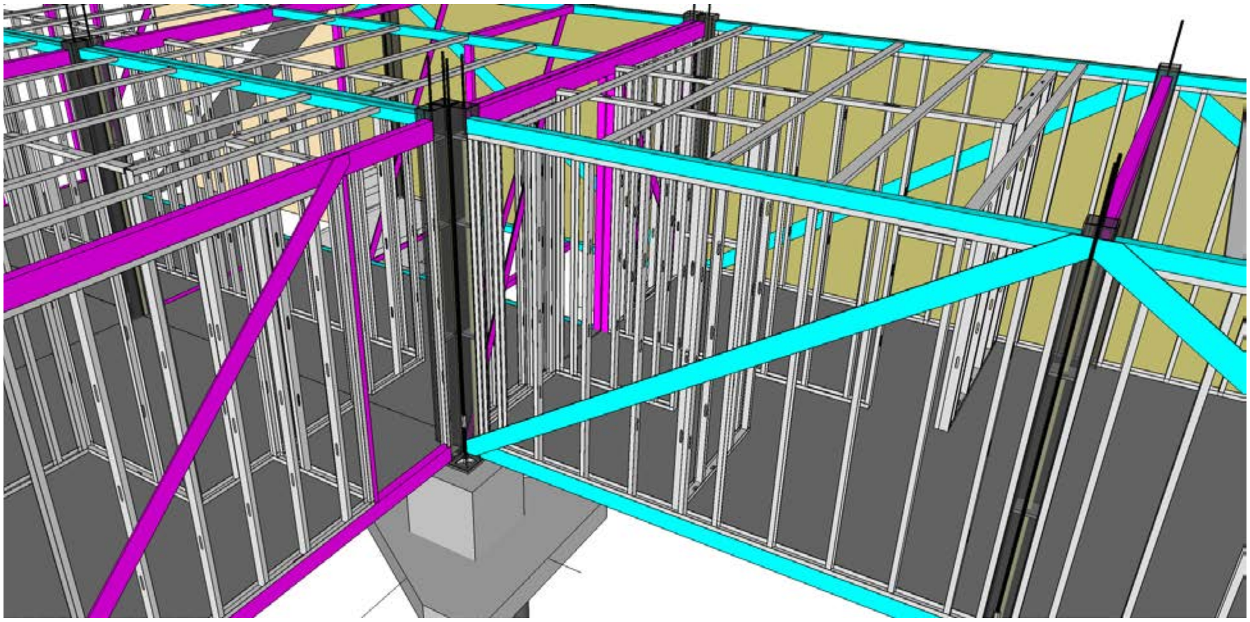


Figure 7.6.7 Module #1.3 placement

Module three is in its resting place, showing lateral bracing north to south with an opening left for a door.

8. Module #1.4 placement (Figure 7.6.8)

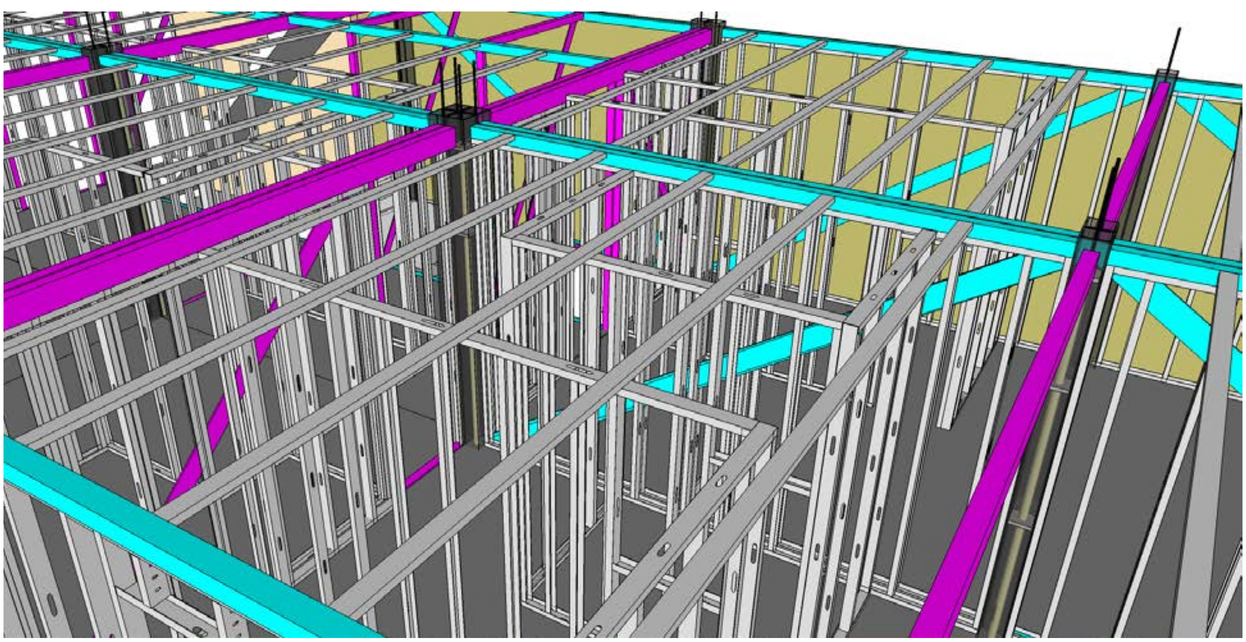


Figure 7.6.8 - Module #1.4 placement

All four modules are in place and ready to receive the connection plate.

9. Connection plate placed onsite to connect all four modules side by side and allow for stacking of second floor modules (Figure 7.6.9)

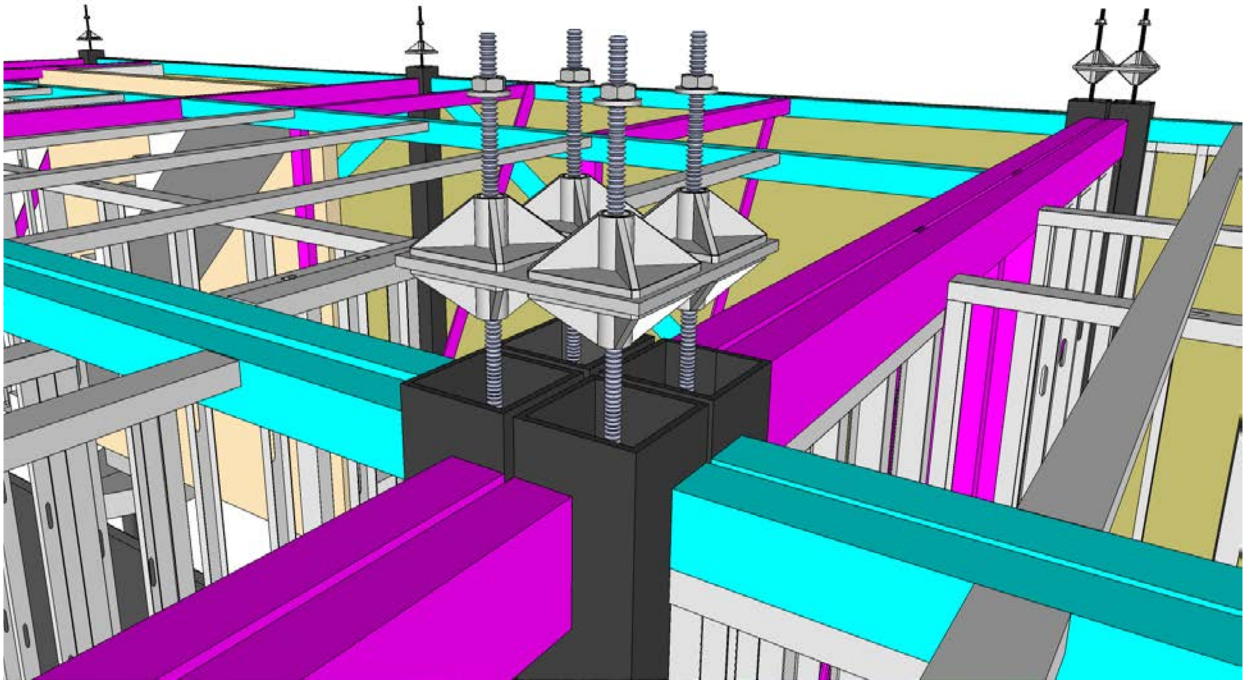


Figure 7.6.9 - Connection plate to connect all four modules side by side and allow for stacking of second floor modules

The tapered pins are welded to the bottom and top of the plate so it can adjust the four modules below to the correct position, and be able to receive the next four modules that will be stacked on top (Figure 7.6.10 and details in Figure 7.7.3). This may take some readjusting, for example, using a bodger (bodging technique) to align the holes to the connection plate to receive the next set of columns. Prefabrication techniques will ensure precision accuracy, a small tolerance is provided for any error. All that is required is a couple of washers and nuts to post tension the modules. No welding, casting, or bolting is required to ensure the perfect position.

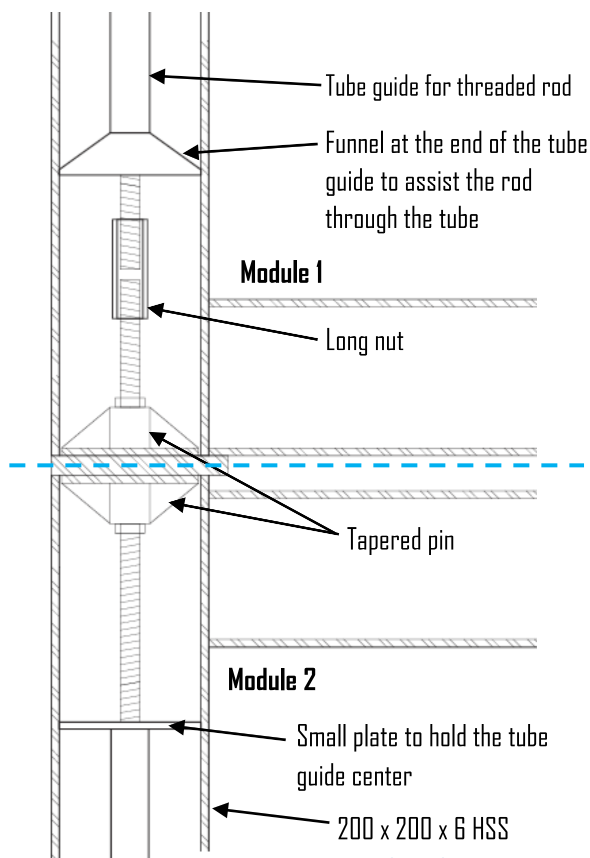


Figure 7.6.10 - Steel stacking connection

10. Connection plate in place (Figure 7.6.11)

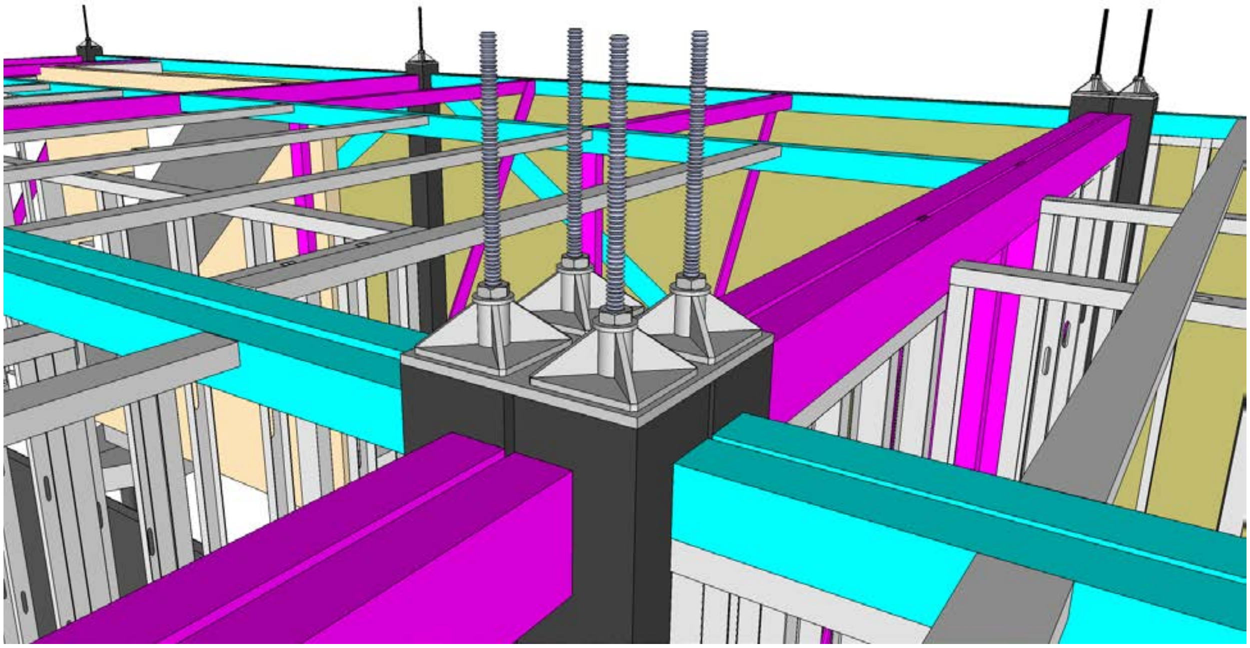


Figure 7.6.11 - Connection plate in place

The washer and nut are fastened ready to receive the long nut.

11. Long nut added to extend steel rod through second floor Modules (Figure 7.6.12)

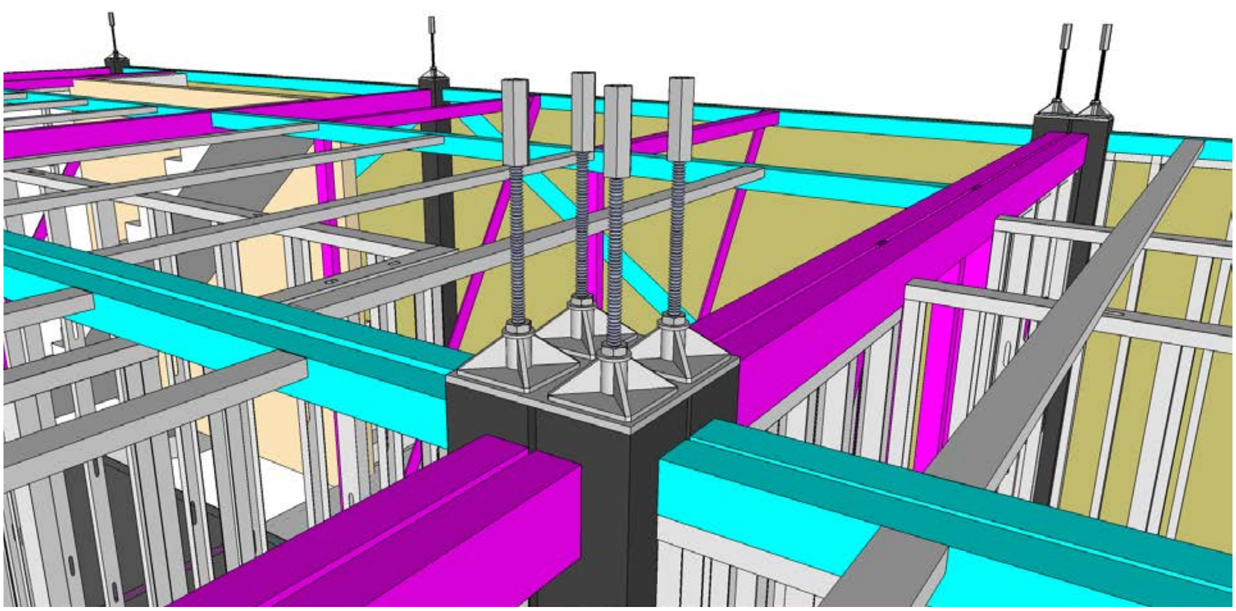


Figure 7.6.12 - Long nut added to extend steel rod through second floor Modules

The long nut are in position ready to receive the extended steel rod.

12. Corrugated steel deck (Figure 7.6.13)

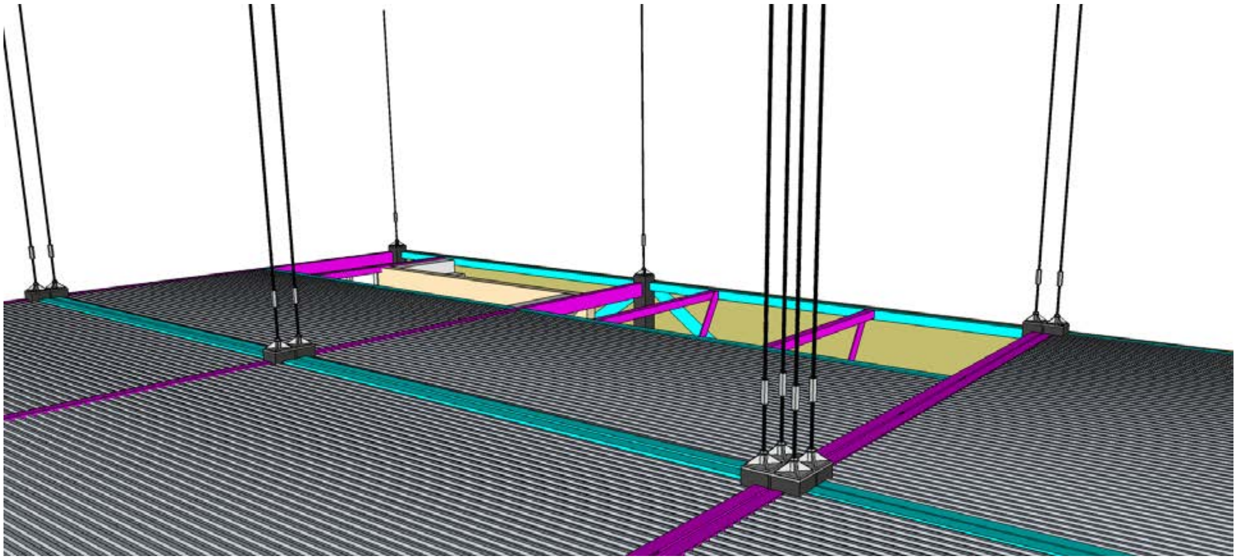


Figure 7.6.13 - Corrugated steel deck

The prefabricated corrugated steel was hidden in the previous images to clearly show the exoskeleton structure. The corrugated steel is used for onsite construction workers to walk on when assembling the next set of modules. Note the steel rod is now extended (3.7 meter high), ready to receive the next floor of modules.

13. Second floor Module #2.1 is resting in its final place (Figure 7.6.14)

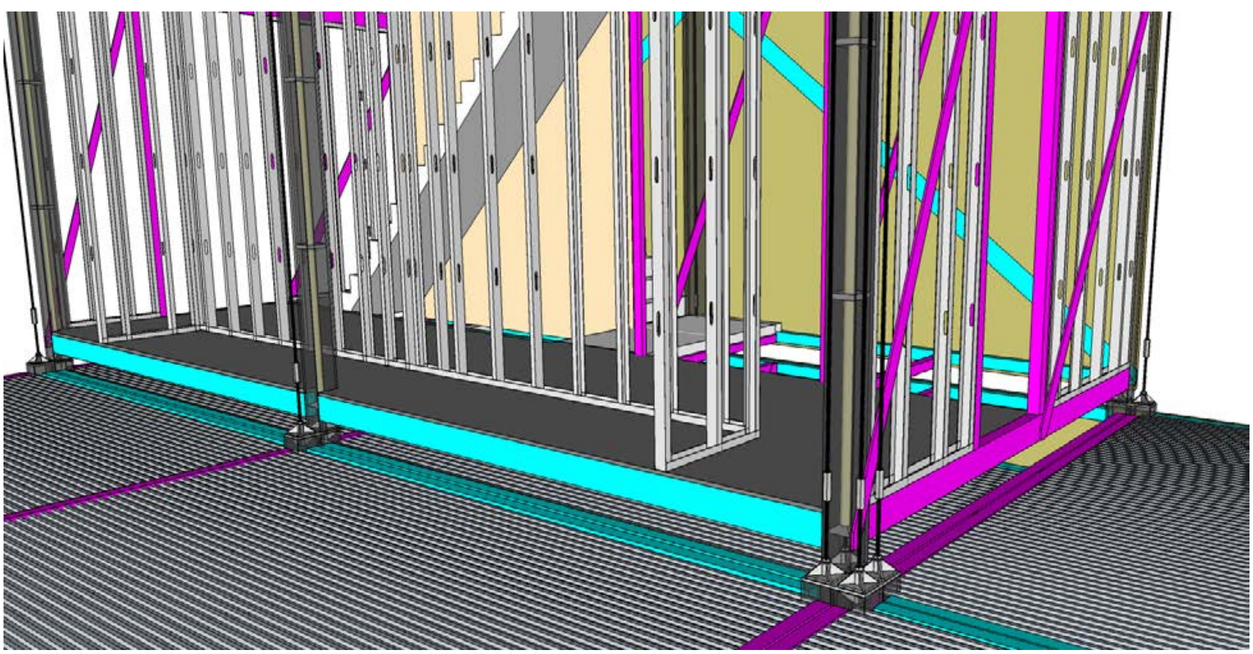


Figure 7.6.14 - Second floor Module #2.1 is resting in its final place

14. Second floor Module #2.2 is being placed, the process is repeated (Figure 7.6.15)

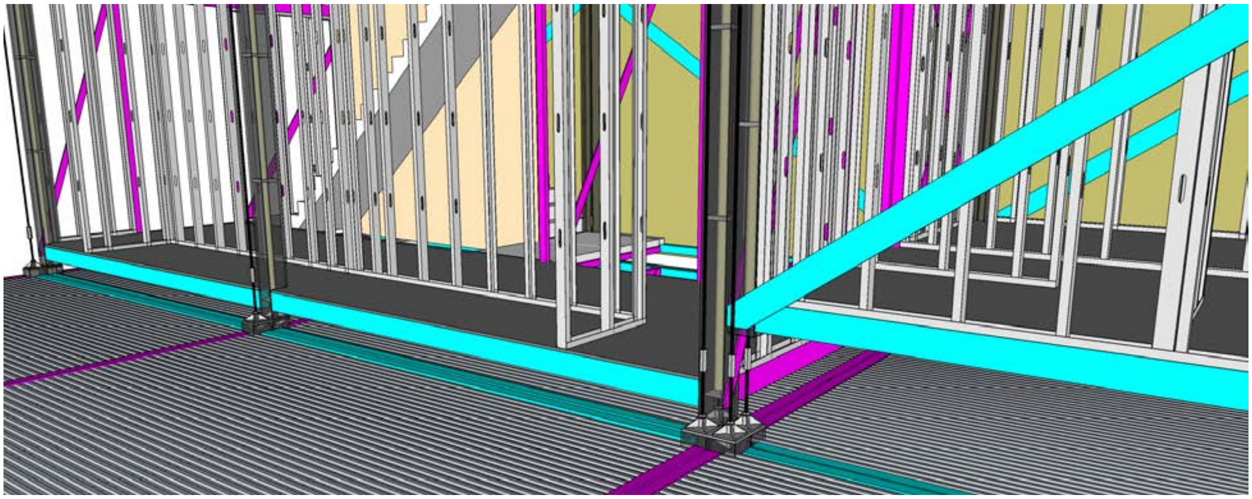


Figure 7.6.15 - Second floor Module #2.2 is being placed, the process is repeated

The project will use just-in-time delivery as referenced in the Leadenhall UK building in section 6.8.1. To aid in the installation onsite, four to six people will be guiding each module through the extended rods, to do this, they will feed rope through the columns of the module before it is lifted, once the module is hoisted by crane and ready to be placed, the excess rope hanging through the bottom of each column will be tied to the tip of the extended rods. That way the workers can easily guide the rod through the column of the modules when they pull on the rope (Figure 7.6.16). This system was influenced by the Leadenhall building and the Atlantic Yards project to determine how much workforce is needed to aid assembly. The actual rope procedure is something that was invented for this project to ease the assembly.

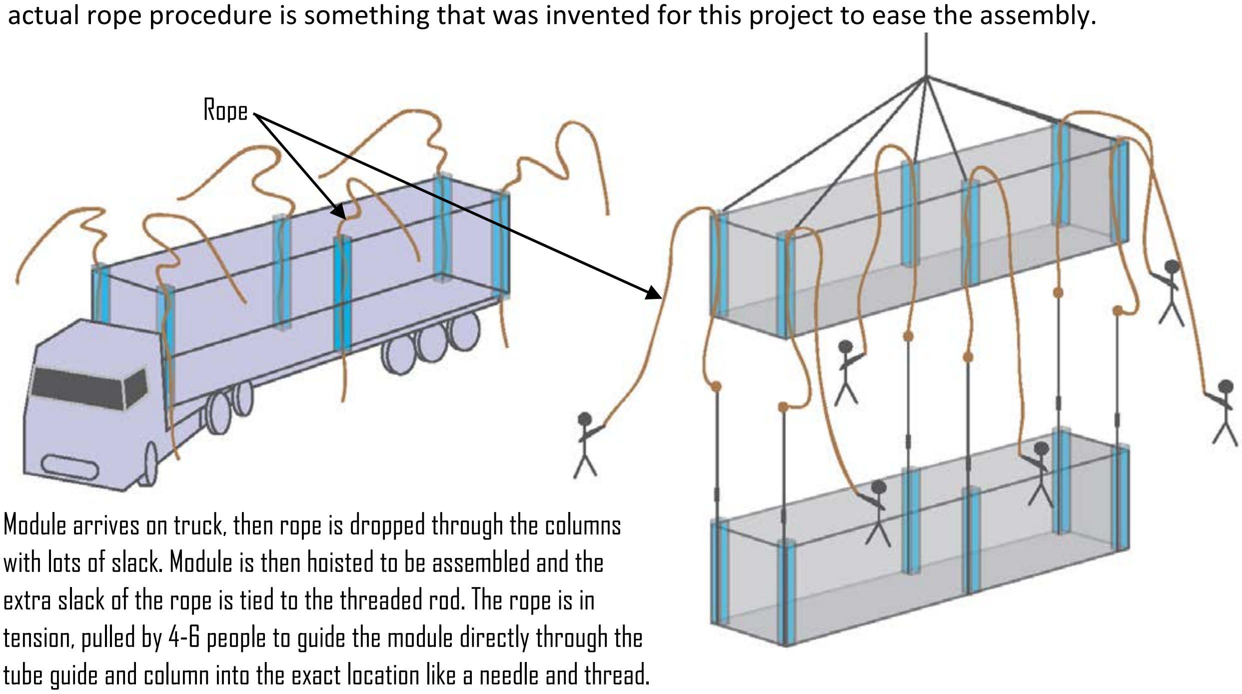


Figure 7.6.16 - Rope threaded through column to guide the extending rods and set the module in place

7.7 Gasket Sealant and Fire Ratings

Another issue discovered in the Atlantic Yards B2 project was the issue of sealing the modules together once it is in set in position by the crane during assembly. The modules would rip the gasket apart have significant weight, when setting the module adjacent to another module it comes down with friction and rips the gasket apart. Therefore, the design calls for an innovative solution to seal mate lines between modules. This is still something modular fabricators are trying to resolve. When the modules are placed onsite, the gap between each module is normally left open. Up until now, building inspectors have accepted this, even for fire rated floor assemblies, however, if this system of modular construction is to become more common practice and is used for larger projects, then this calls for an innovative design solution to the seal between modules to create more sustainable buildings. Gaskets are strategically designed into each module to seal the exterior of the modules together by using an access panel from the interior after the modules are in position to close the gap. This will allow easy access for workers during the final finishes of the building. The design set in place to solve this flaw will be to set the gasket behind the mate line, once the module is set in place by crane and installed, the gaskets do not touch, a site worker can access an opening from the interior and operate a simple mechanism like a bolt to tighten that will extend the gasket past the mate line to seal the two modules firmly together (Figure 7.7.1). This will cause unsightly access panels, however, this can be disguised with a design feature wall to avoid any unsightly panels to satisfy both the developer and resident. Other areas that are more accessible will use a pressurized foam gasket, areas such as the stair tower has a split into the stair to receive the next module and then sealed afterwards.

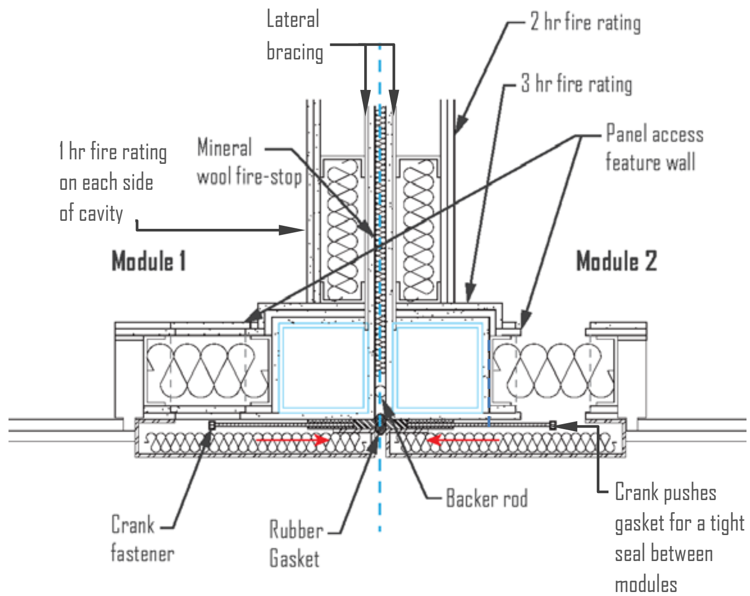


Figure 7.7.1 – Panel access for crank operation to seal gasket

The sealant when stacking the module does not need any mechanical component since there is no friction caused during installation, the weight of the module itself will compress and seal between the two as it rests on top (Figure 7.7.2 and Figure 7.7.3).

Fireproofing is designed with a backer rod fire stop sandwiched in between the two modules and layers of gypsum. The cavity between modules is safeguarded with the added benefit of one layer of gypsum in case the smoke or fire spreads through the building (Figure 7.7.1) this should be considered because the modular industry is getting into larger and taller projects. The exterior requires a three hour rating around the column and a two hour rating for walls, using layers of gypsum.

Each module is presumed to be independent and requires a fire separation between each one (Figure 7.7.4). Since each module is considered independent, the module configuration was open to a number of design interpretations. This has opened the opportunity to experiment with the types of units the building can allow by connecting the module in all axis (NSEW, up, down, diagonal) (Figure 7.7.5).

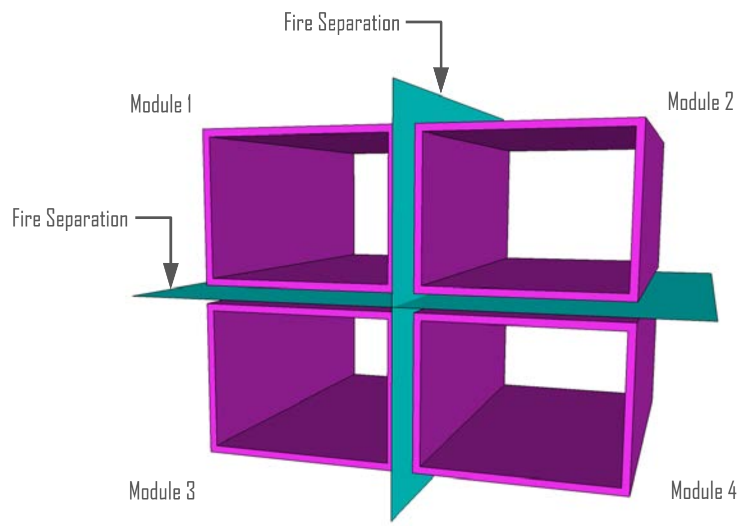


Figure 7.7.4 - Fire separation between each

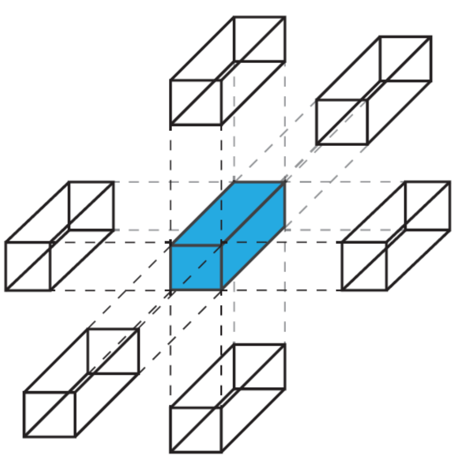


Figure 7.7.5 - Module configuration is open to a number of design interpretations and all axis XYZ

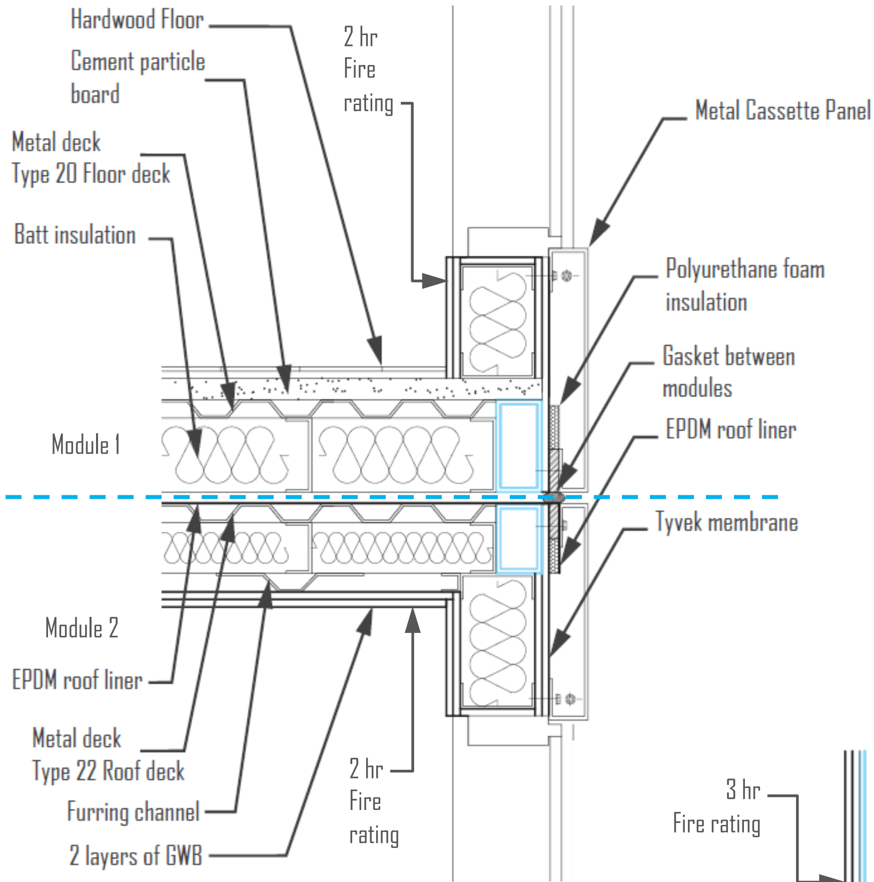


Figure 7.7.2 – Section through beams between two stacked modules roof and floor assemblies

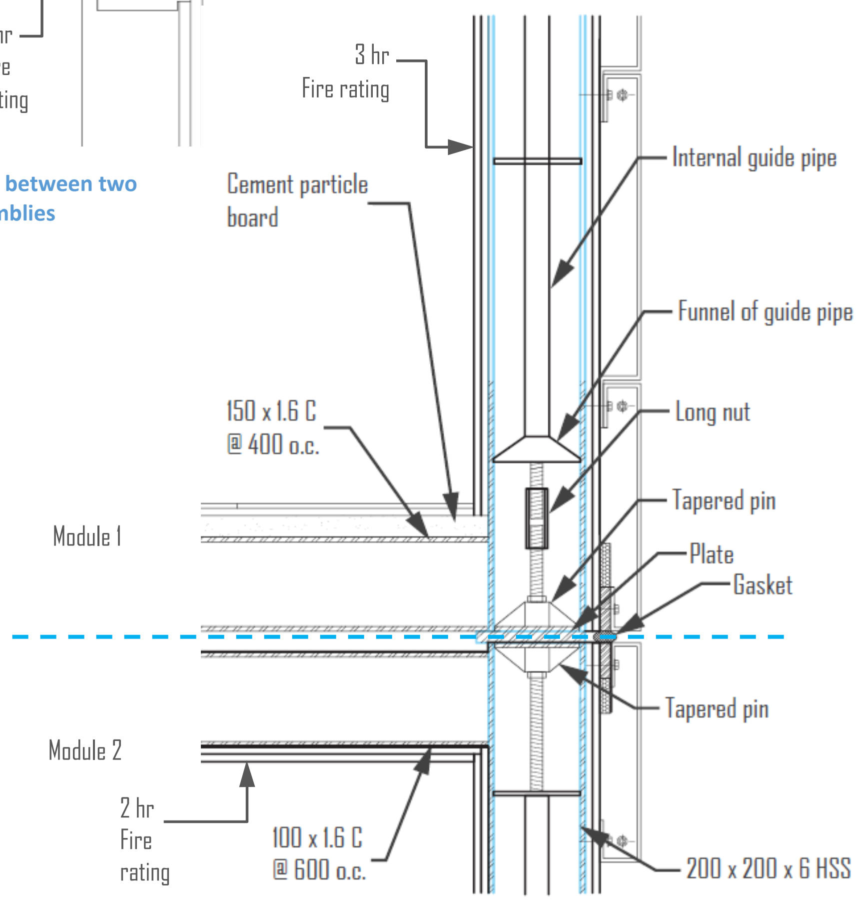


Figure 7.7.3 – Section through column between two stacked modules connection details

7.8 Exterior Cladding Material

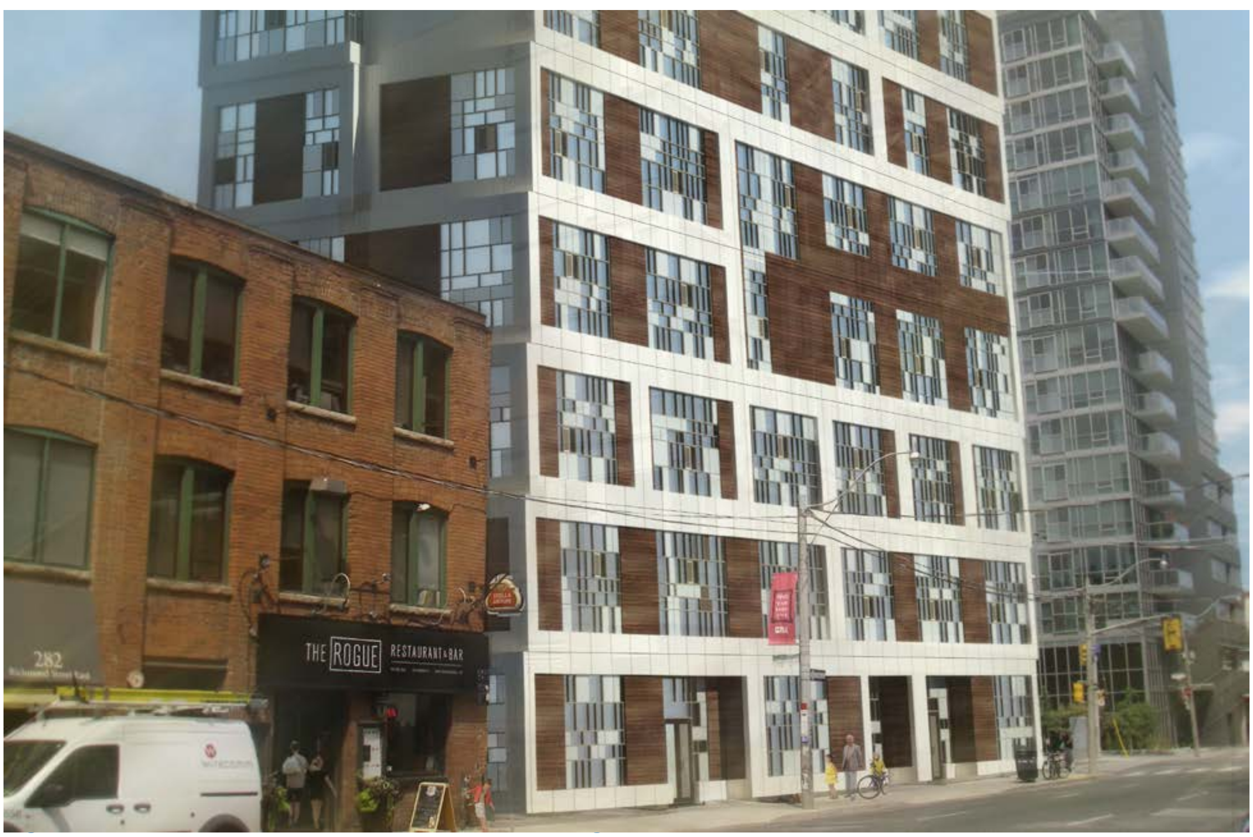
Figure 7.8.1 - Material quality, prefabricated versus onsite

The cladding material chosen includes variations of polished metal on the exterior. The quality of prefabrication techniques will be represented in the finishes to play on its strength. The clear reflection of the finish and smooth seamless lines will surpass any onsite construction build of its type. The illustration shows the comparison of a prefabricated, highly polished reflective material and one built onsite with a similar material which has a "funhouse" effect (Figure 7.8.1). The exterior cladding also includes a highly engineered wood material to match the varying coloured bricks of the surrounding buildings in the area, this style is a personal expression that pays homage to the more common European use of wood design within a similar climate. The interior consist of similar material of metal and wood, the metal is complemented with warm wood tones and textures that provide a comforting environment to the resident. Therefore, the materials chosen for the exterior and interior are design features that express an industrial loft look with the ambience of a warm residential feel.

The panels chosen were implemented into the digital model with precision for optimal use and less waste. The panel's product information has been implemented into the design to work with or even influence the façade to fit accordingly, so few, if any of the material needed to be modified. To achieve this, some of the openings in the façade were readjusted to fit the material sizes and spaces accordingly.

The exterior engineered wood panels were chosen to match the varying colored bricks of the surrounding buildings in the area (Figure 7.8.2 and Figure 7.8.3). The form and pattern of the building, design features, and materials, were all chosen to highlight modular design with the ambience of a warm residential feel and an industrial loft look.

Figure 7.8.2 - Exterior render, lobby entrance



7.9 MEP Mate Line Connection

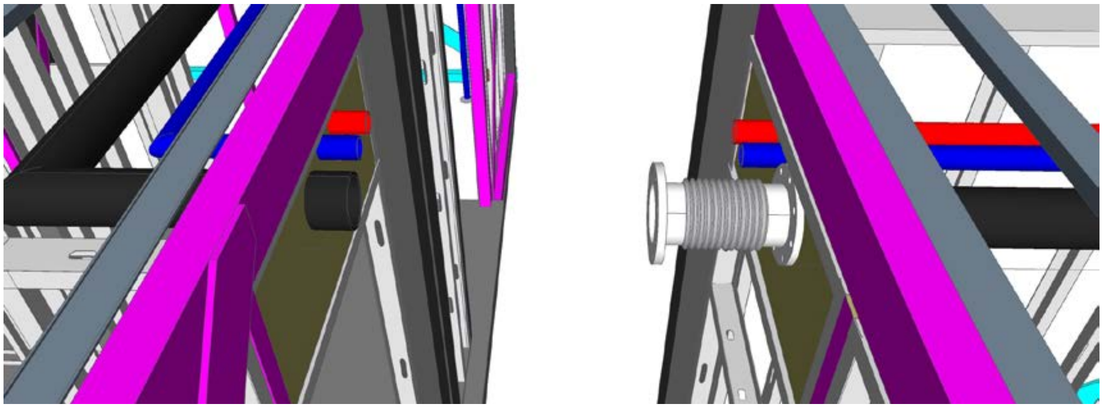


Figure 7.9.1 - Perspective view of MEP coupling connection

The project was designed in a way that will assist assembly to speed construction and labor time, this includes the coupling connection for the services between two modules (Figure 7.9.1 and Figure 7.10.1). Access of coupling services between modules and mate lines are located on the top of the modules so the workers can assemble using gravity to ease the process and connection while working simultaneously with the “just-in-time” schedule of placing the modules into position as they go. Each piece necessary for the installation is already precut and packaged along with the module so there is less confusion onsite.

7.10 MEP Distribution

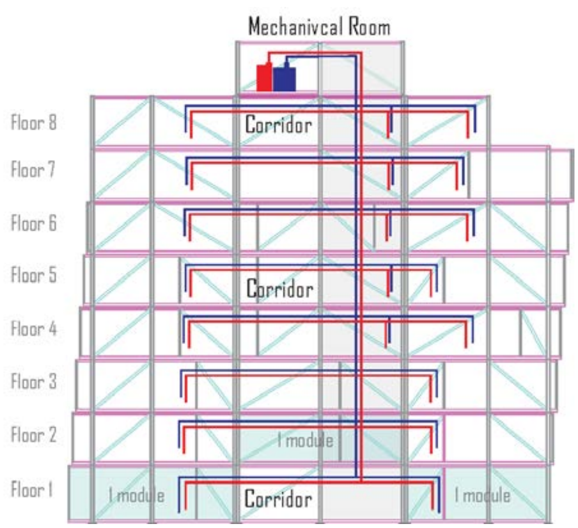


Figure 7.10.1 - Diagram of MEP distribution

Prefabrication of complex MEP systems can be mapped out precisely in BIM beforehand to maximize space required for other components like ductwork. As technology gets more advanced, so do our buildings, typical walls are beginning to look like motherboards in specific cases, but this could soon become a standard, if so, it would be impossible to build onsite.

By installing as much as possible offsite it can greatly reduce the project schedule. Not unlike the Leadenhall building, the 294 Richmond St E project has the services placed at the north end of the building because there are no unprotected openings on the entire wall (Zoning and Unprotected Openings Appendix A1). The design intent is to have the north end of the building with no unprotected openings as the “service” area and the south end as the "served" area. The stacked north-center modules are considered the core circulation of the building (Figure 7.10.1), serving as the spine of the building with the circulation and service distribution that is entirely built in the factory for quick and efficient design, manufacturing, and assembly. This design decision leaves each unit independent from one another, therefore, if maintenance is needed for a specific unit, or if future development occurs in the building, the design would not displace the existing homeowners. Access to services after the initial installation on the roof can be reached from the corridor so there is less of a need to enter the unit and disturb occupants.

All MEP services travel parallel to the elevator shaft and are dispersed to the units from the circulation corridor and back (Figure 7.10.2). The objective is to speed the installation process by not having as many openings between the other modules, the fewer openings and connections there are, the fewer problems can occur. The module units are then "plugged" into the core to receive the services (Figure 7.10.3). The design took advantage of the height by putting the services in the ceiling which run through the corridor space and branch out into other interior rooms, it comes to a stop at the living room to create more ceiling height, since the units are narrow it gives the sense of more space and allows for maximum floor space.

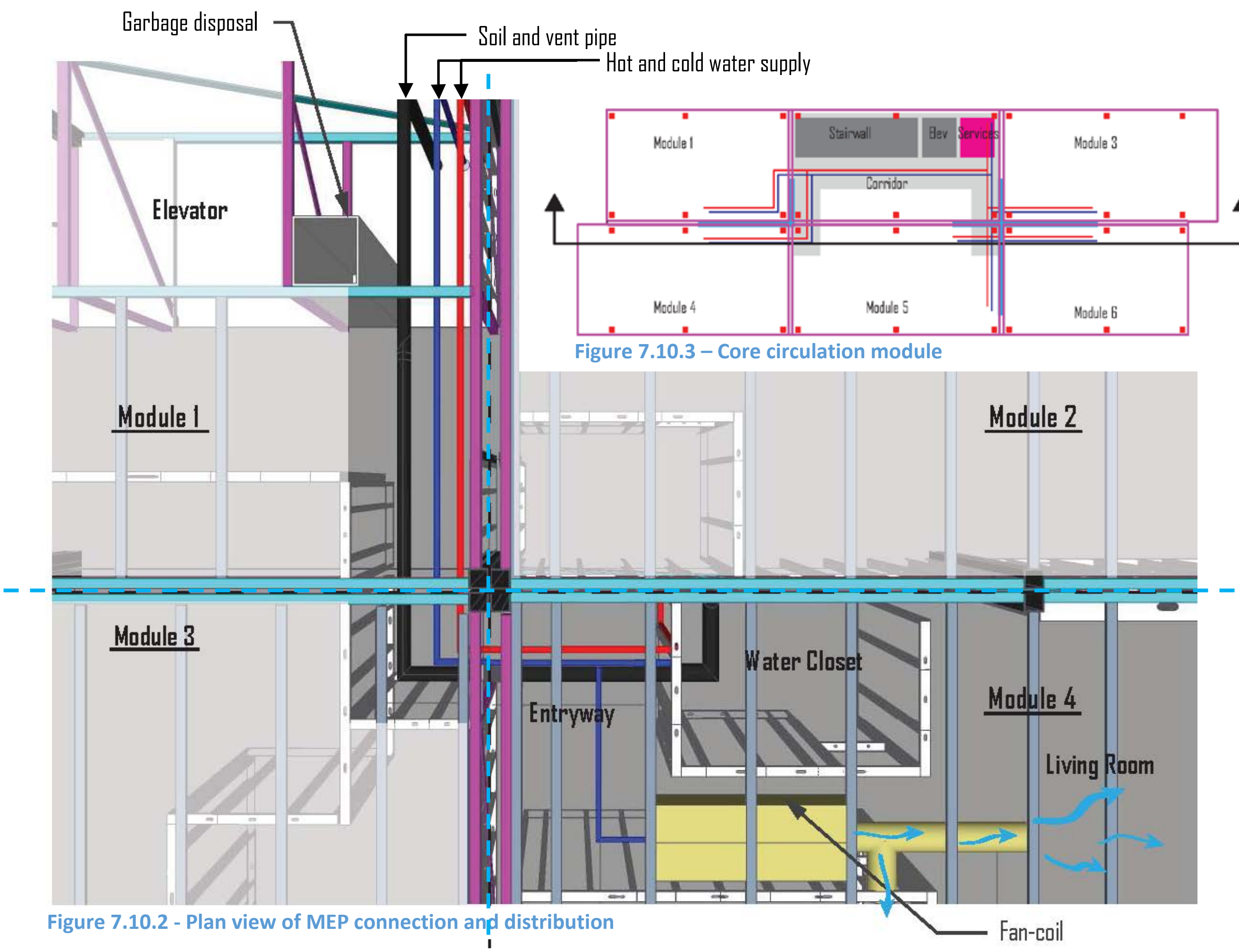


Figure 7.10.3 – Core circulation module

Figure 7.10.2 - Plan view of MEP connection and distribution

7.11 Design of the Module Configuration

This section of "module configuration" is a subgroup within "unit configuration," design criteria and patterns were found within the details previously reviewed. For clarity "module configuration" is the number of components to include within one module and also how that module can connect and relate to other modules. "Unit configuration" can be considered an apartment unit when considering how many bedrooms a unit will include, this can comprise of a number of modules to make one unit. This hierarchy can be seen in the B2 Atlantic Yards workflow coordination diagram of phases in Figure 5.6.1.3, where they label the module a 'pod link,' the next phase is 'unit groups' which is the assembly of the apartment unit and then 'floor groups' which is the entire floor assembled. Although they are interrelated, it was broken down into two subgroups for clarity and detail in the design process.

Until the very end of the last century, exact repetition was the only way to achieve economies of scale (Moe, 2012). This was dominated by the modular industry because they can utilize this type of economy effortlessly compared to onsite construction. As a result, exact repetition lead to perceiving modular design and construction as a commodity. However, this barrier has been lifted by advances in digital techniques, as well as the techniques for building and assembling modules. Modular design and construction is not restrictive in terms of design or layout when considering the module configuration, but in order for it to work you must design for assembly and have a good understanding of the design parameters and context of the specific building. Modules can come together in a number of ways to create an incredible variety of spatial forms including large span spaces and open-sided modules that can be combined to expand the design possibilities for modular construction. The diagram shows a number of possible combinations and orientations of modules (Figure 7.11.1). An incredible diversity of form can

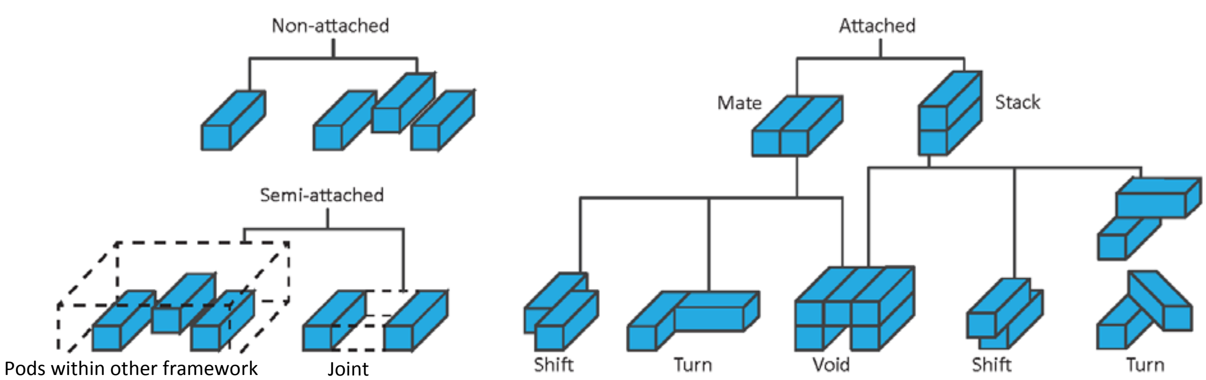


Figure 7.11.1 – Module design configurations

be derived from these very few elemental types of interfacing modules. Almost any building can now be divided into modules, certain project types like multifamily, schools, hospitals and offices will receive the greatest economic benefit and will have significant advantages compared to conventional building (Bernstein, 2011). Today economies of scale can be achieved through mass customization. The term mass customization describes the ability of certain products with pre-designed features to be customized. Digital design, computer numeric control (CNC) fabrication technologies, and various systems approaches allow mass customization to replace exact repetition as a means of achieving economies of scale (Marble, 2012). With the thesis workflow implemented architects can use this workflow to create custom designs and achieve an industrialized economy of scale.

Since modules have a solid "shell" they offer ample design choices inside of the building. It can be tailored to meet any specific need and the exterior can take any shape when pieced together to create the form. However, the more components exposed to the elements, the less that can be finished offsite, meaning, the more closed a module is, for instance, all four walls, floor, and ceiling, the more work can be completed offsite with all the final finishes complete. Having an opening can expose the module to the elements during assembly, this requires some extra work to seal the openings during delivery and require some final finishes to be completed onsite. Being aware of these features at the beginning of the project means the architect can design layouts to prevent as many openings as possible that will be exposed to the elements with the intention to keep as much work to be completed offsite.
That being said, modular construction has far less materials that are exposed to the elements than traditional onsite construction, which is believed to be a testament to their durability (Hutchings, 1996).

With the given site, 12 iterations of module floor layouts were investigated for structure, circulation, and the most optimal space, the top five were displayed in Figure 7.1.2. The small urban site allowed the module orientation to be flexible according to the grid structure. This became a test bed for design and assembly processes to try different module configurations to see what building forms, layouts, and assembly scenarios could be achieved. The form I resulted in used both types of 'shift' in module configurations (Figure 7.11. for the purpose of highlighting modular construction and also metaphorically representing a shift in the industry. Although the building form can be different, the workflow system can be implemented on other sites, with the adjustment of the module shape and size since the length of a module can reach 20 meters on average. The interior layout variations were tested and designed 29 times. The challenge was to design for the most optimal space and to maximize floor area with such a narrow space, as well as considering how the services will be distributed, connections, and assembly, influenced the final interior layout and form. Since there is almost no limit to the type of module configurations the building may take on, it became an exploration test as many scenarios as possible so that the architect is aware of the different types of living scenarios and arrangements a unit can have. Therefore, building 298 Richmond St. E. will represent as many configurations as possible; this will be shown in Figure 7.12.3 and in the layout of the floor plans. The form of the building, design features, and materials, were all chosen to highlight modular design. The modules are stepped back to highlight each individual module, in addition to allowing the units on the north end to receive more southern light exposure, this is seen best in Figure 7.12.6, floor six, and Figure 7.12.7, floor 8; the modules alternate by stepping forward to regain the floor area and allow views into the city. Any module on the north end that may be blocked from southern exposure was considered as a connected two module unit on the same floor north to south; since the total building is only 11 meters deep, with high ceilings, the light can travel through to the north end of the building easily. If the two module unit north to south was not possible for any reason, light shelves would be placed on the east or west ends to distribute the light accordingly (Figure 7.11.2).

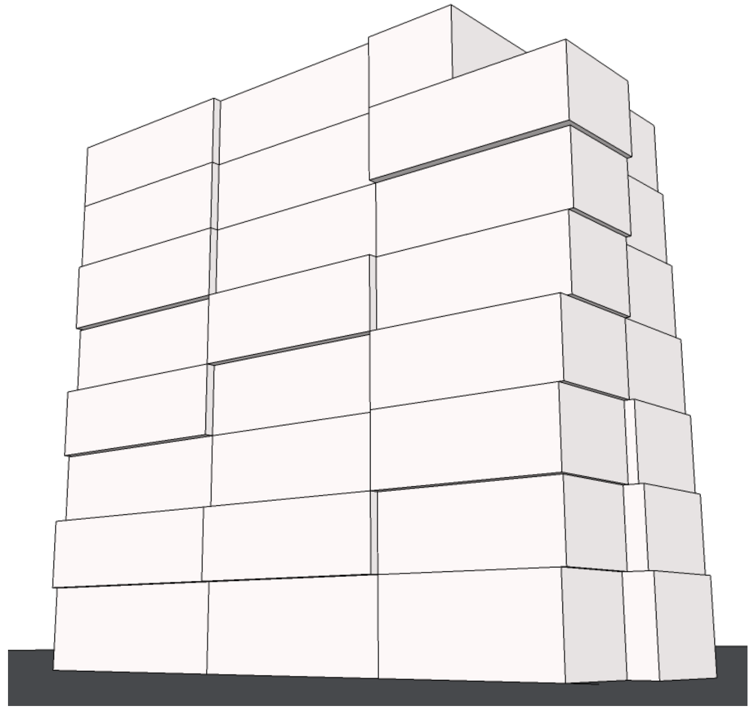


Figure 7.11.2 - Schematic form influenced by the details

7.12 Design of the Unit Configuration

I used the size of the modules to construct most of the interior spaces so that they can be fully finished with little work left to complete onsite except seal and patch. The floor plan layout of the residential units became an exploration of 11 units with different variations, in comparison to the existing buildings 10 units that comprised of eight, one-bedroom units and two, two-bedroom units (Figure 7.12.2 and Figure 7.12.3). The first unit design iteration was one module is one apartment unit, the second design iteration includes two modules connected north to south and another east to west on the same floor level. The fourth iteration is a combination of the north and south modules to east or west modules to create a unit. The fifth iteration includes two floor units with two modules stacked on top of each other. The sixth iteration is a combination of all the previous layouts. This became a test bed for different combinations of units (Figure 7.12.1), that are a direct response to the site and an experiment to test all scenarios possible in the building, from the tightest constrictions of a one bedroom which encompasses everything a person needs to live comfortably, to a large two level family unit. This laid out the possible design scenarios that can be implemented into the design so that the architect is well knowledgeable of the unit scenarios and capabilities when working with homeowners to discuss what custom living arrangements will work for them. These experiments were guided by previous knowledge of modular design with the consideration of services through the building, natural light, and unprotected openings for each bedroom. The building units resulted into three, one-bedrooms, five, two-bedrooms, one, three-bedroom, and one, four-bedroom unit. These floor plan design iterations in Figure 7.12.4 to Figure 7.12.11 are the prime examples which can offer a number of different unit configurations.

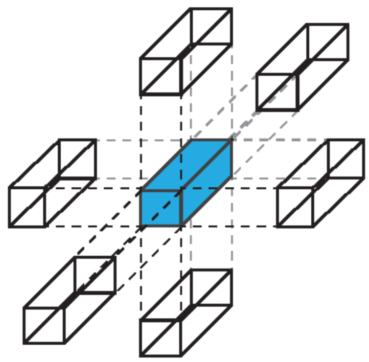


Figure 7.12.1 – Module design configurations

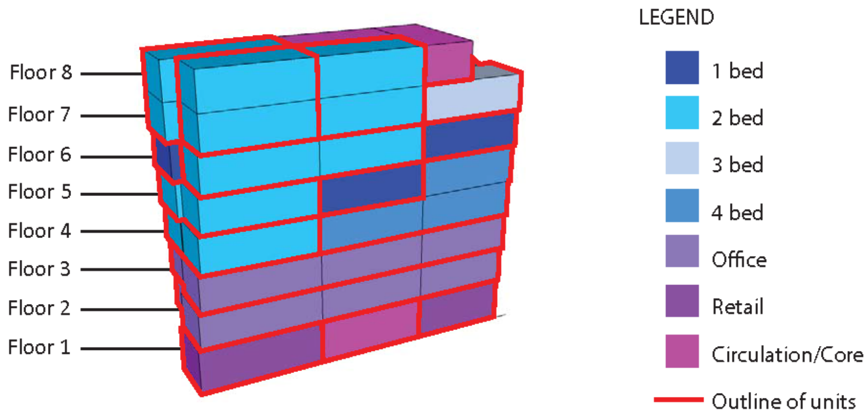


Figure 7.12.2 – Building form with outlined units

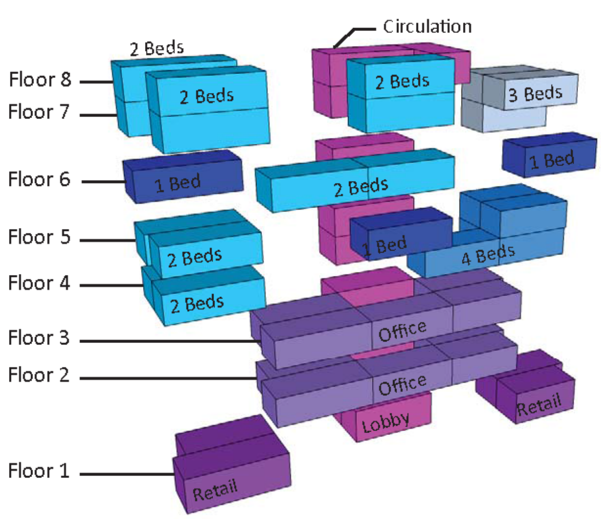


Figure 7.12.3 – Unit configuration, exploded perspective

The ground level (Figure 7.12.4) provides space for a bike area on the west side of the property since there is no parking below grade (consistent with the existing building). The east side of the property is set back to grab the attention of the public from its five story overhang that provides pedestrians some shelter, which is in accordance to suggested neighborhood design guidelines, while subconsciously inviting people into the retail space. The retail stores consist of a coffee shop and dental office (consistent with the existing building). As a design expression I propose to reveal a connection in each of the ground floor public spaces to begin to express the building and embrace modular design, because with most modular designs the average person cannot tell the difference. The common area (currently the lobby) will have the ceiling components exposed to tell the story of the building.

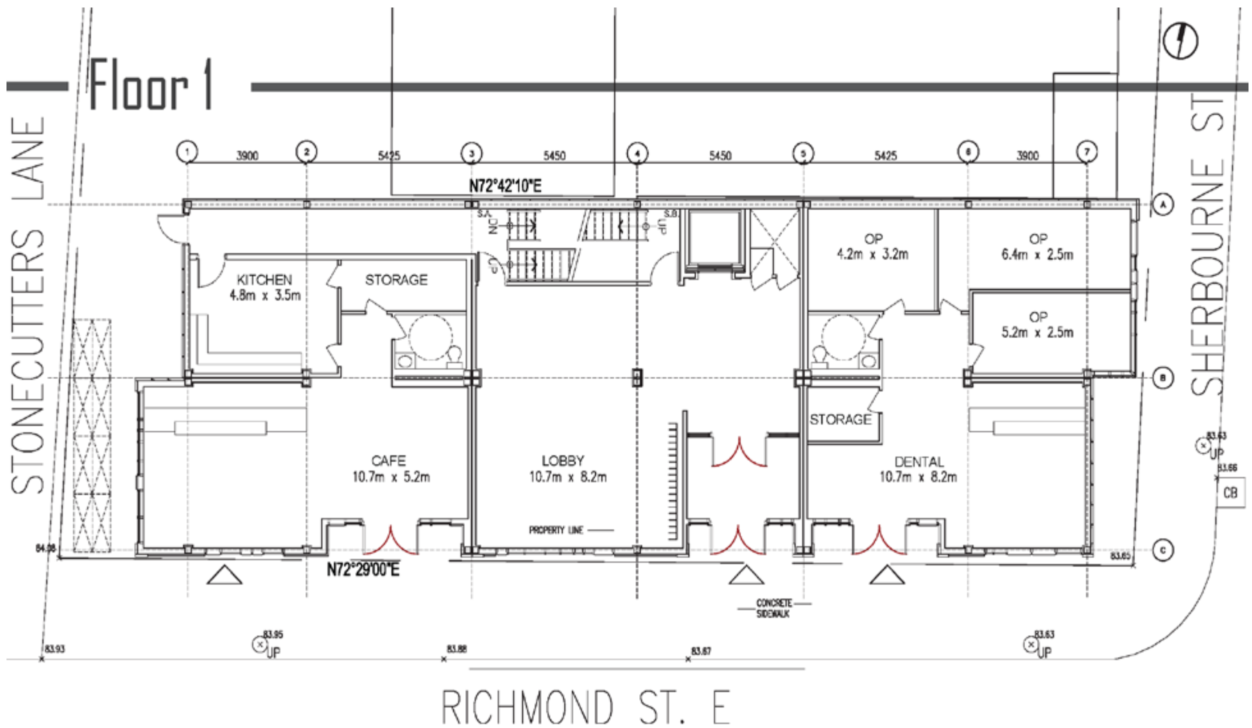


Figure 7.12.4 - Site Plan with lobby and commercial space

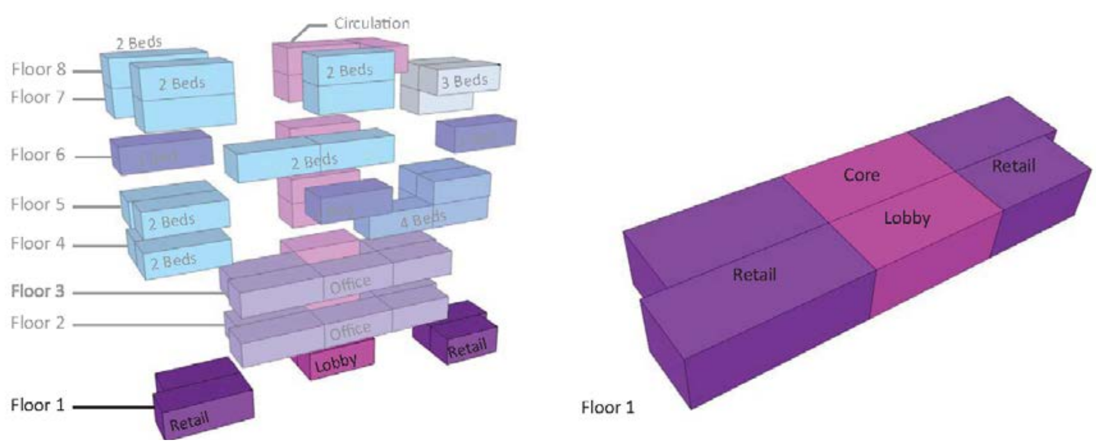


Figure 7.12.4.1 - Floor one spatial configuration

The second floor (Figure 7.12.5), is dedicated to office space, with an open space design with two small rooms in the north-east and north-west corners of the building. The floor layout is a mirror image through the center to allow the option of splitting into two offices that share the same corridor.

Floor 2

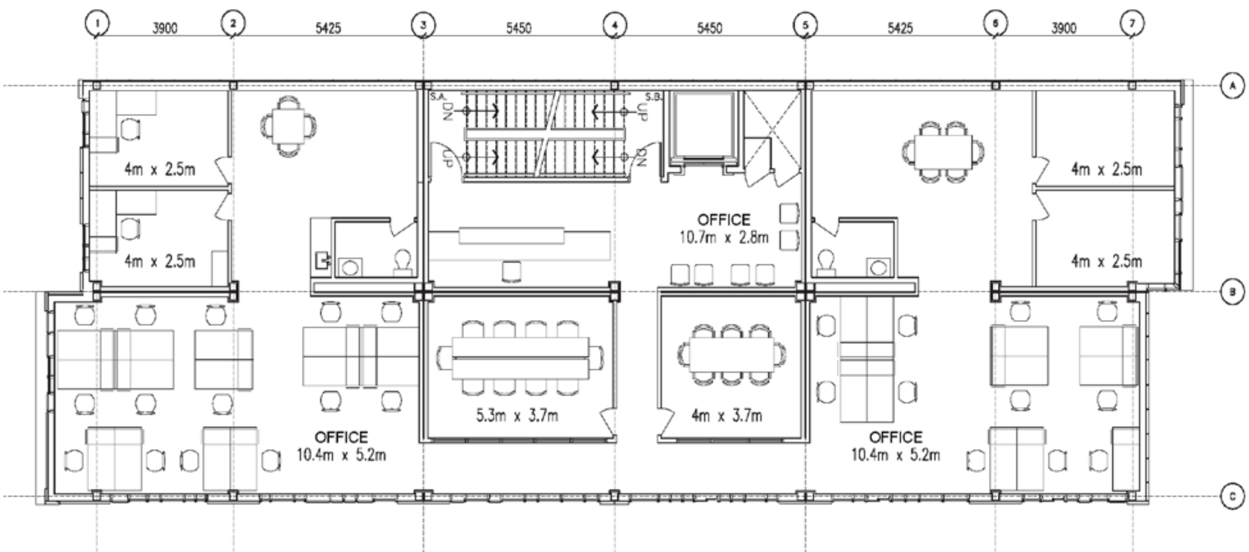


Figure 7.12.5 - Second Floor Plan, office

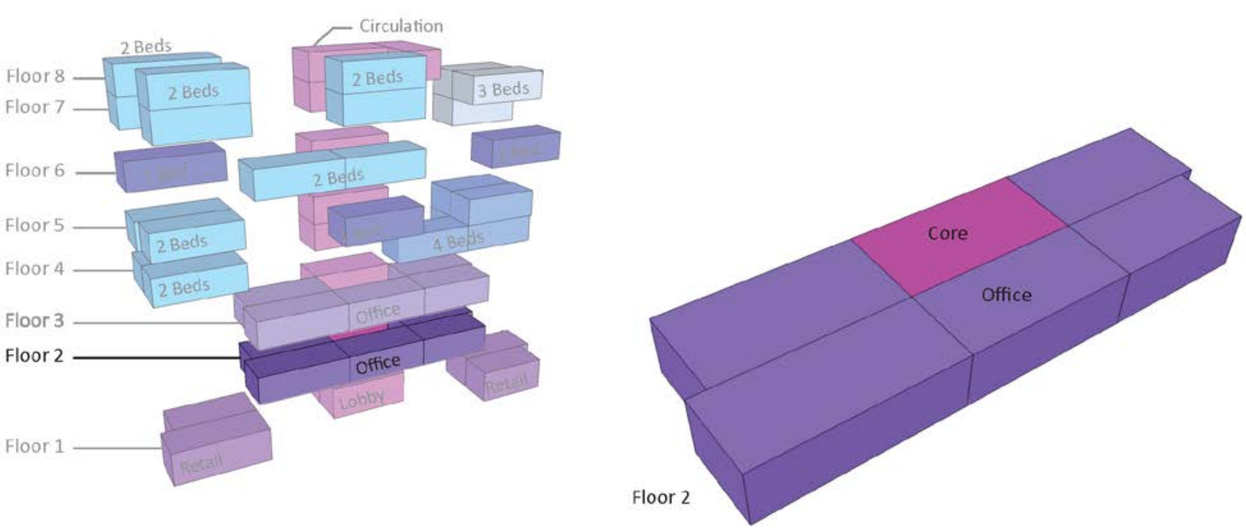


Figure 7.12.5.1 - Floor two spatial configuration

The third floor (Figure 7.12.6.), is similar to the second floor but slightly shifted in configuration. The building consists of a scissor stairwell to save space on the small urban infill.

Floor 3

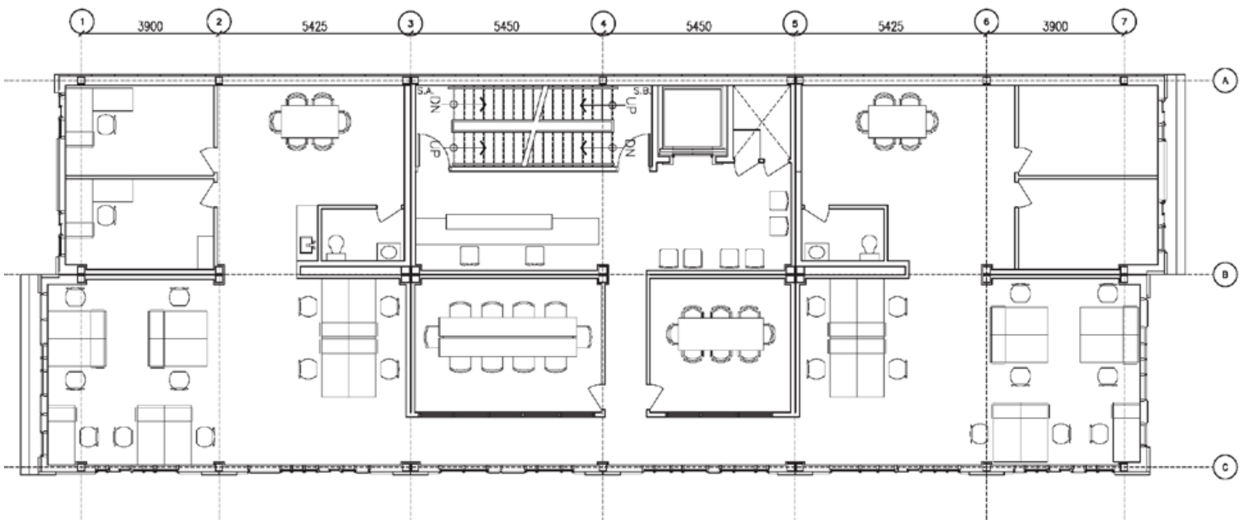


Figure 7.12.6 - Third Floor Plan, residential

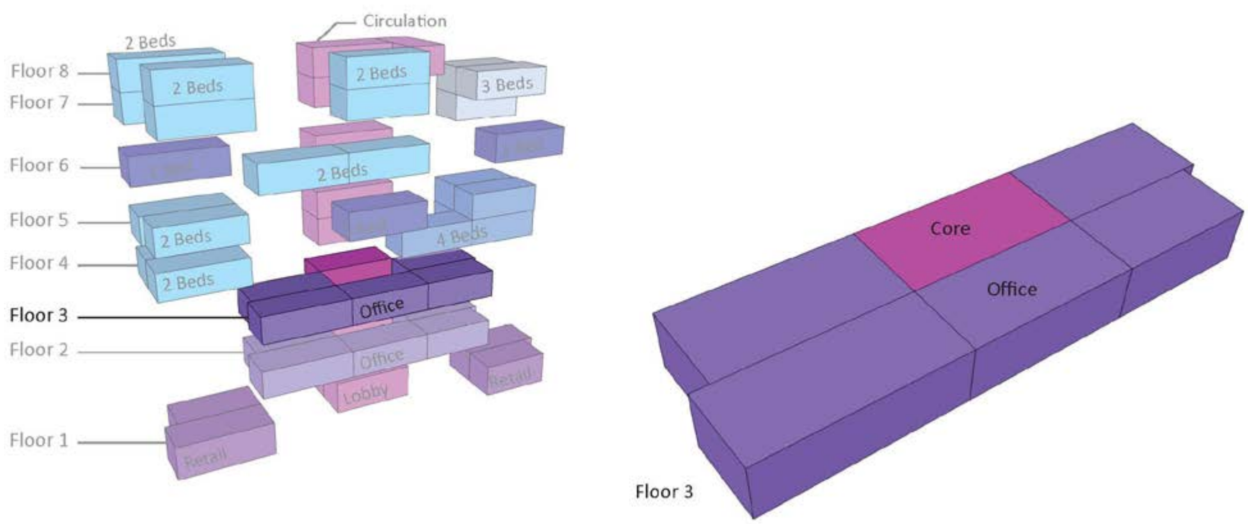


Figure 7.12.6.1 - Floor three spatial configuration

The fourth floor (Figure 7.12.7), contains a two unit module connected north to south to gain full advantage of the southern exposure and a five units, two floor module as an example of double floor heights and flexibility with a combination of both north to south connection and east to west connection. The fifth floor (Figure 7.12.8), the south center module is the only area that requires more finishes onsite because it takes advantage of the open circulation space, by giving more space to the unit that would have been unused otherwise.

Floor 4

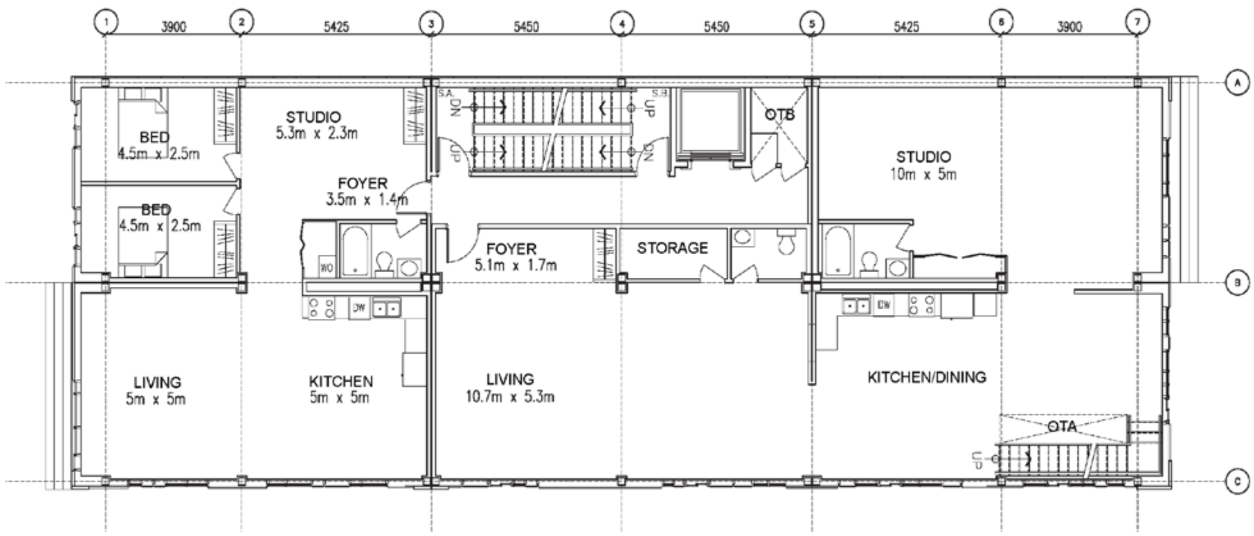


Figure 7.12.7 - Fourth Floor Plan, residential

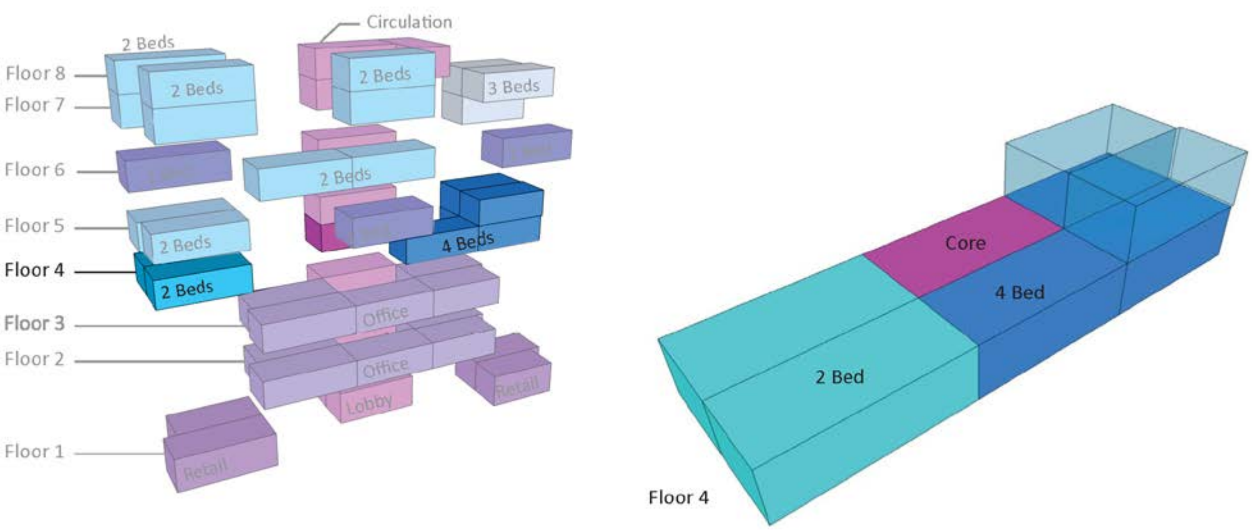


Figure 7.12.7.1 - Floor four spatial configuration

The fifth floor (Figure 7.12.8), the south center module is the only area that requires more finishes onsite because it takes advantage of the open circulation space, by giving more space to the unit that would have been unused otherwise.

Floor 5

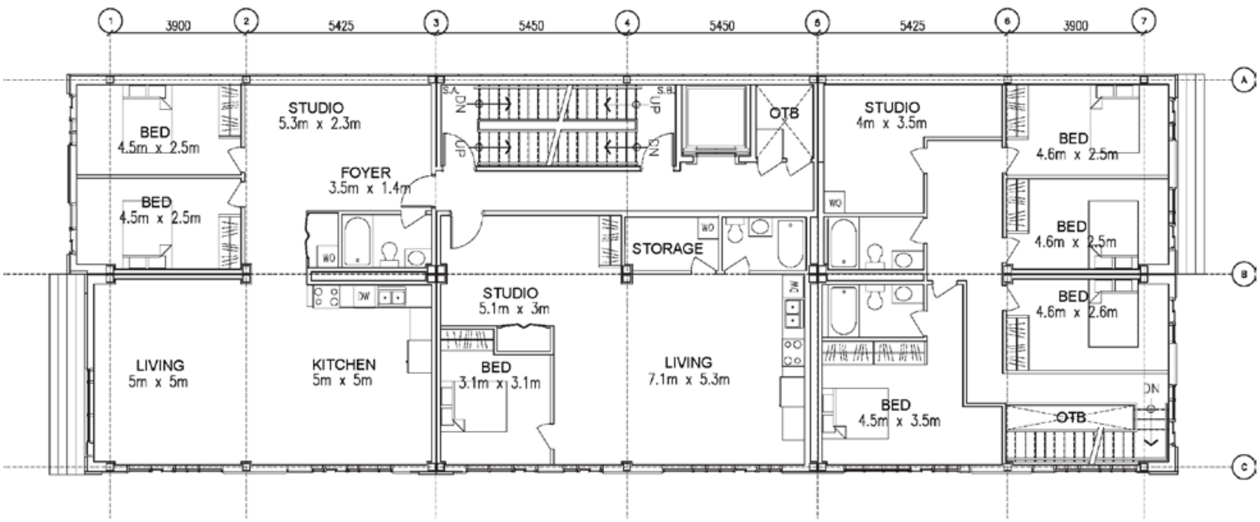


Figure 7.12.8 - Fifth Floor Plan, residential

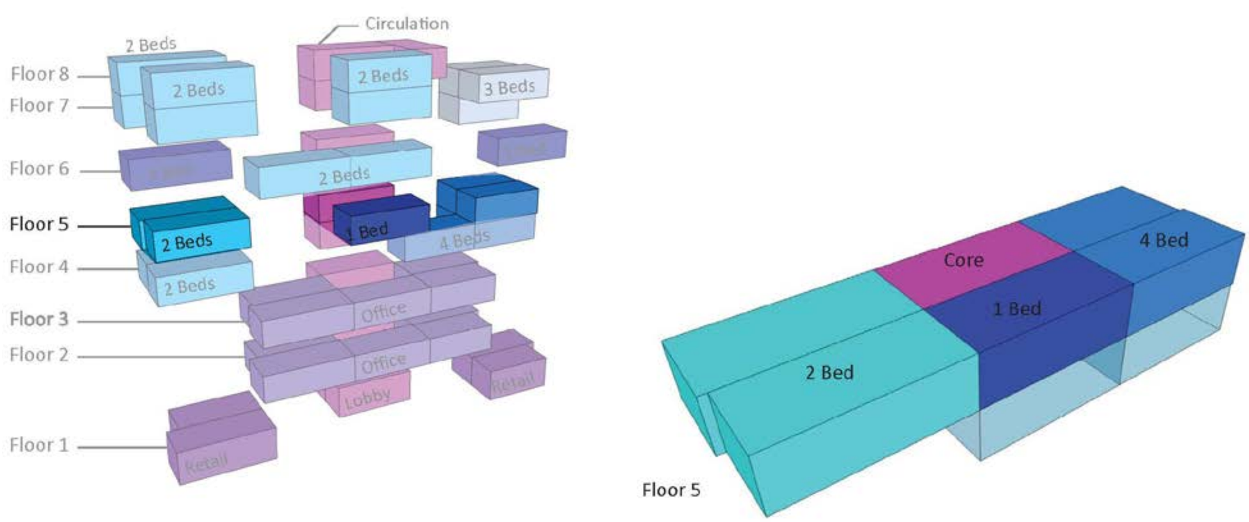


Figure 7.12.8.1 - Floor five spatial configuration

The sixth floor (Figure 7.12.9), displays the tightest one bedroom situation in the building, located in the north-west corner and south-east corner, which still provides comfort and meets all the desirable necessities. The objective is to explore as many scenarios to the layout as possible. The protruding units highlight modular design as well as provide southern sun exposure to the north-west corner. Situations such as the north-east corner will be designed to have a connecting unit and views into the city, in this case, a two story unit is designed that connects the north and south on the floor above.

Floor 6

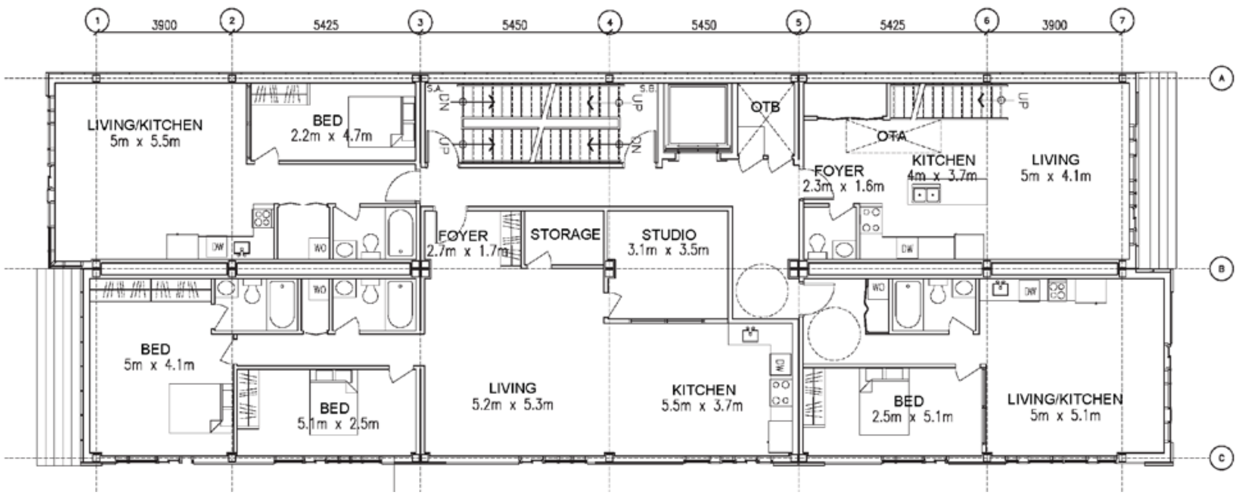
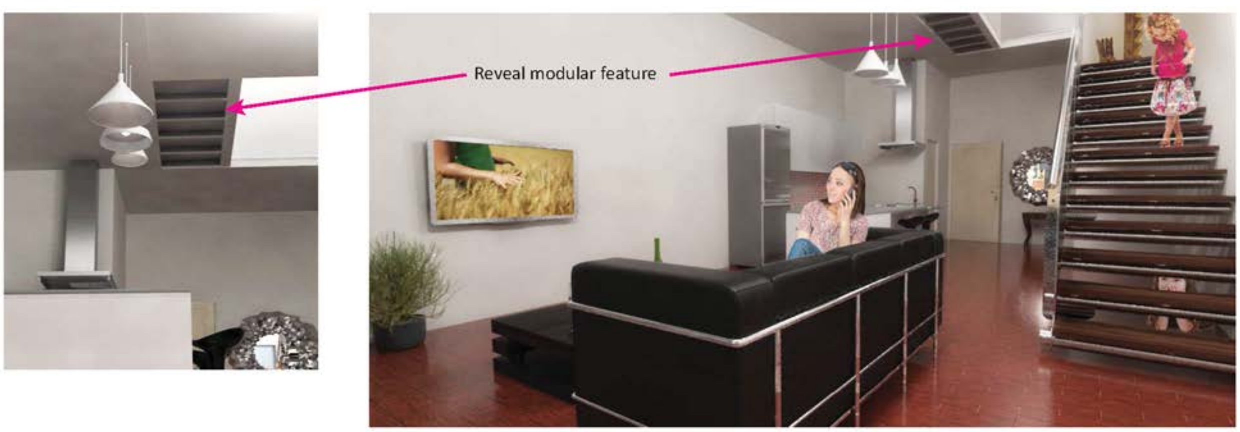


Figure 7.12.9 - Sixth Floor Plan, residential



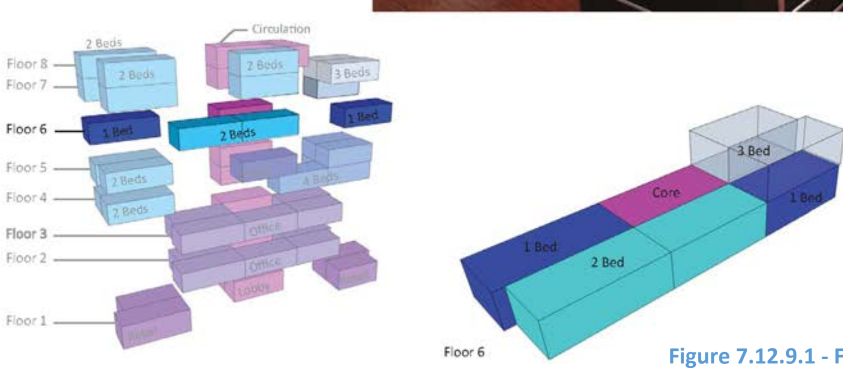


Figure 7.12.9.1 - Floor six spatial configuration

The seventh floor (Figure 7.12.10), contains two floor units that showcase double story heights.

Floor 7

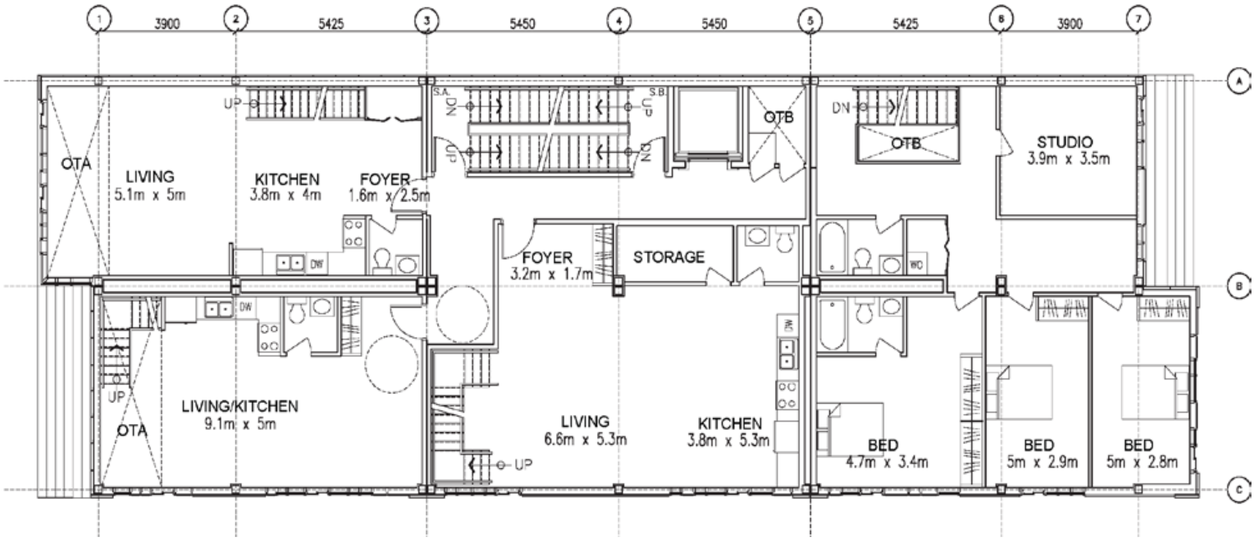


Figure 7.12.10 - Seventh Floor Plan, residential

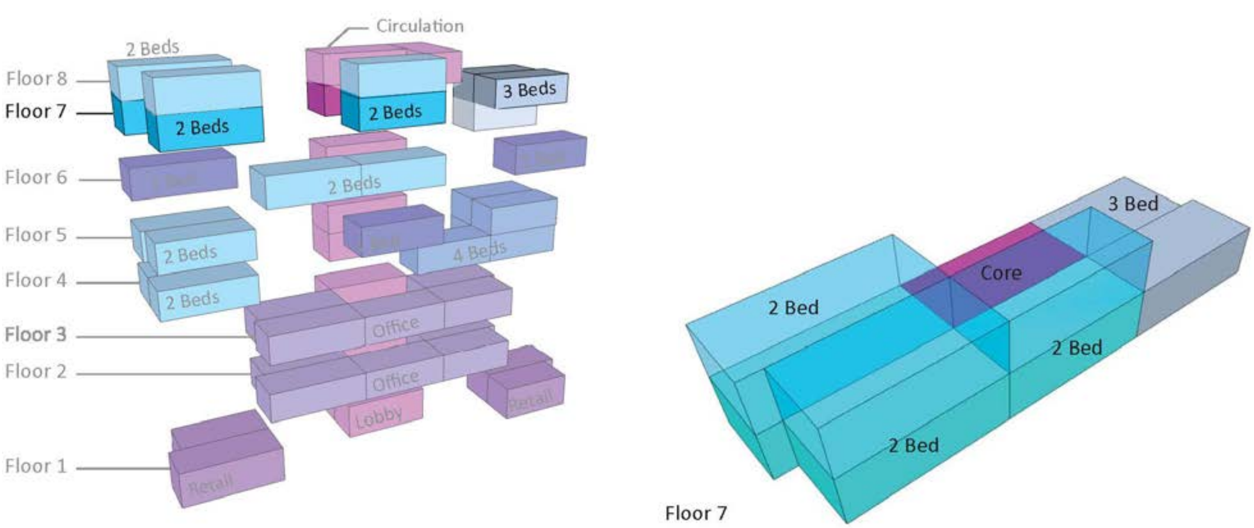


Figure 7.12.10.1 - Floor seven spatial configuration

The eighth floor (Figure 7.12.11), is dedicated to bedrooms so there is no access to residents units, which in turn allows for a communal space for the building.

Floor 8

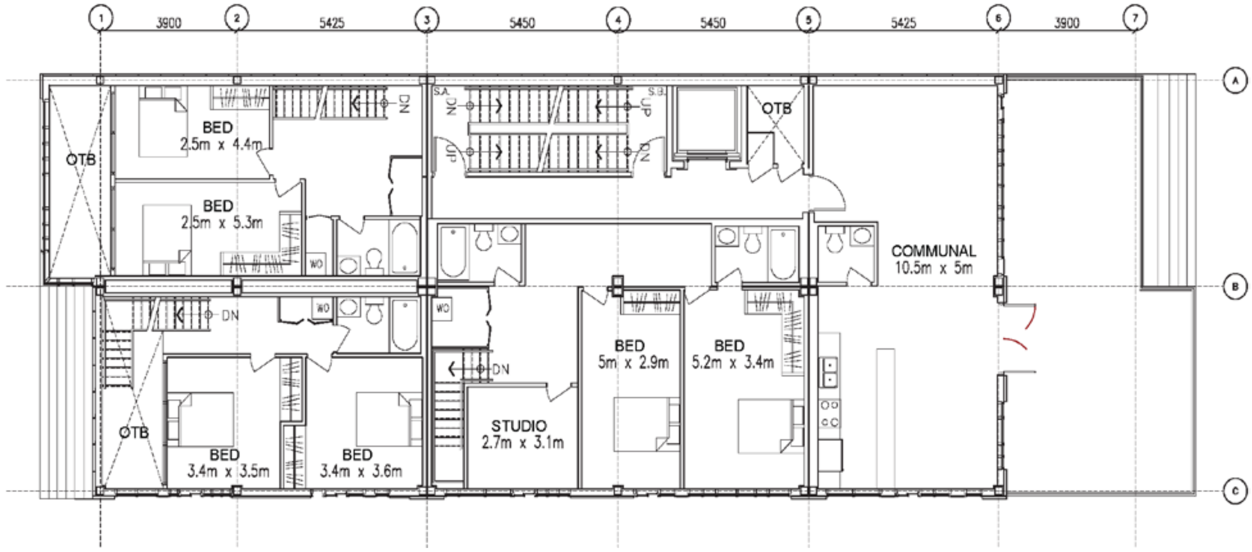


Figure 7.12.11 - The Eighth Floor Plan, residential and common space

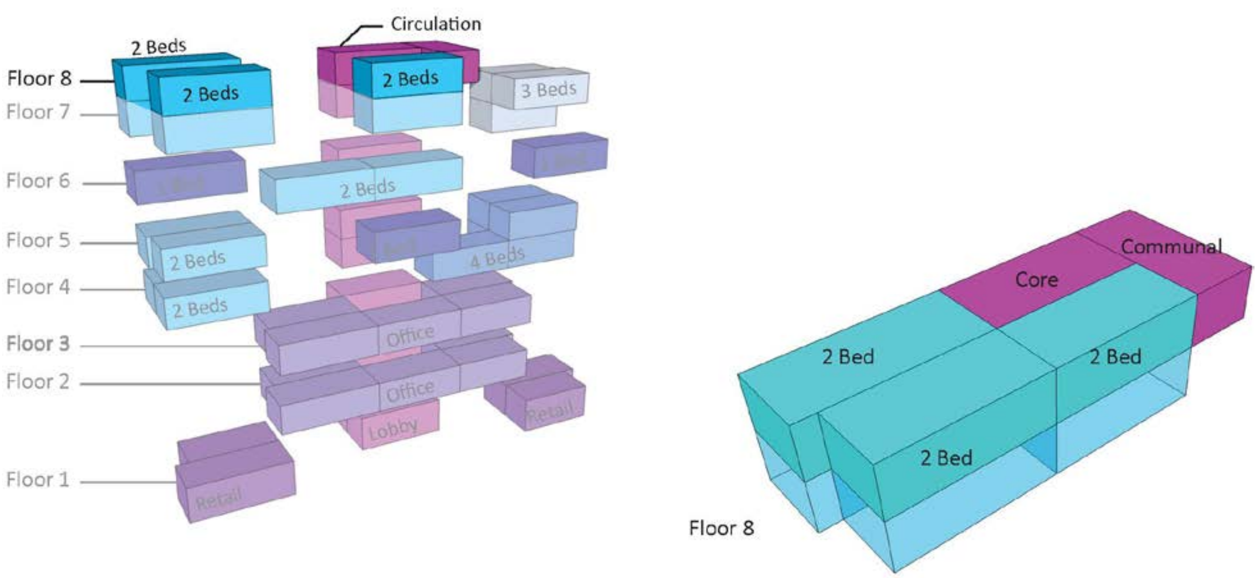


Figure 7.12.11.1 - Floor eight spatial configuration

The roof (Figure 7.12.12), is dedicated to the heating equipment, cooling towers, chilling modules, generators, boilers, and control rooms are placed strategically to maximize space in one module. The robust structure of modular design can potentially support future development if desired. The roof area can be turned into another floor and modules can be predesigned to stack on top of the existing. The remaining void spaces in between the roof and the next set of proposed modules stacked on top will become a common area.

— Roof Floor Plan

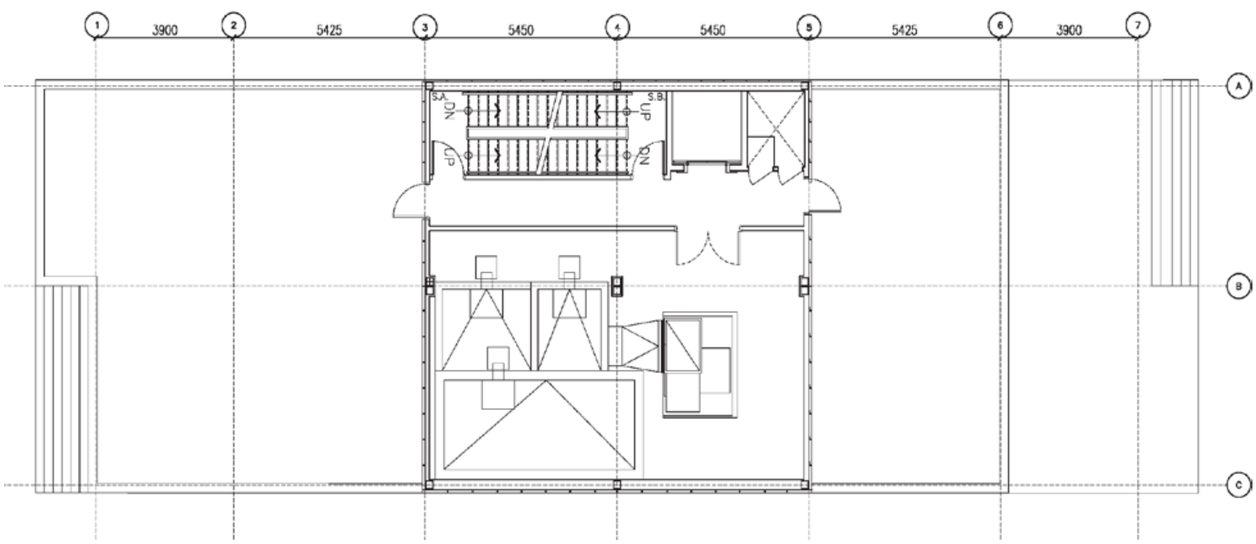
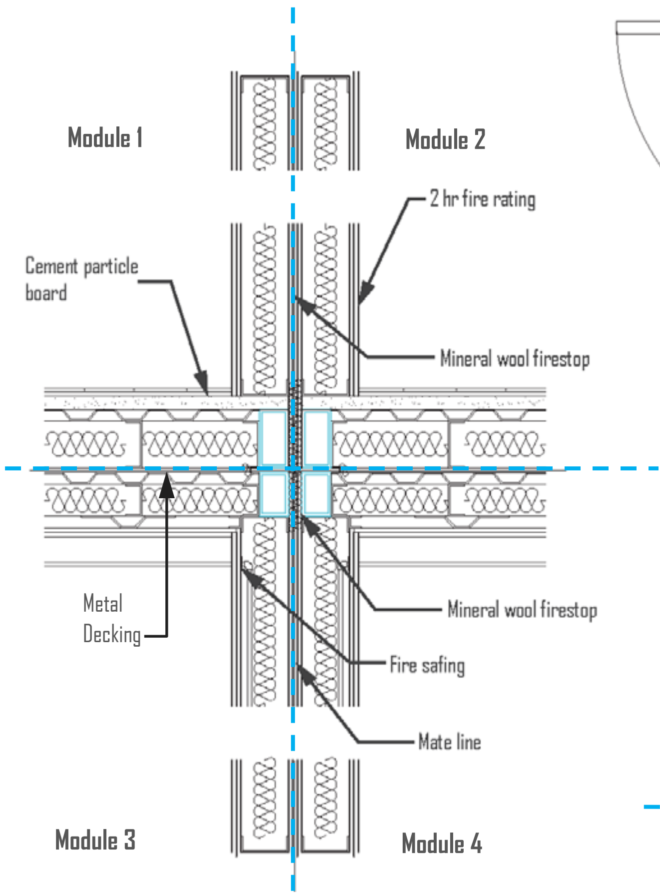


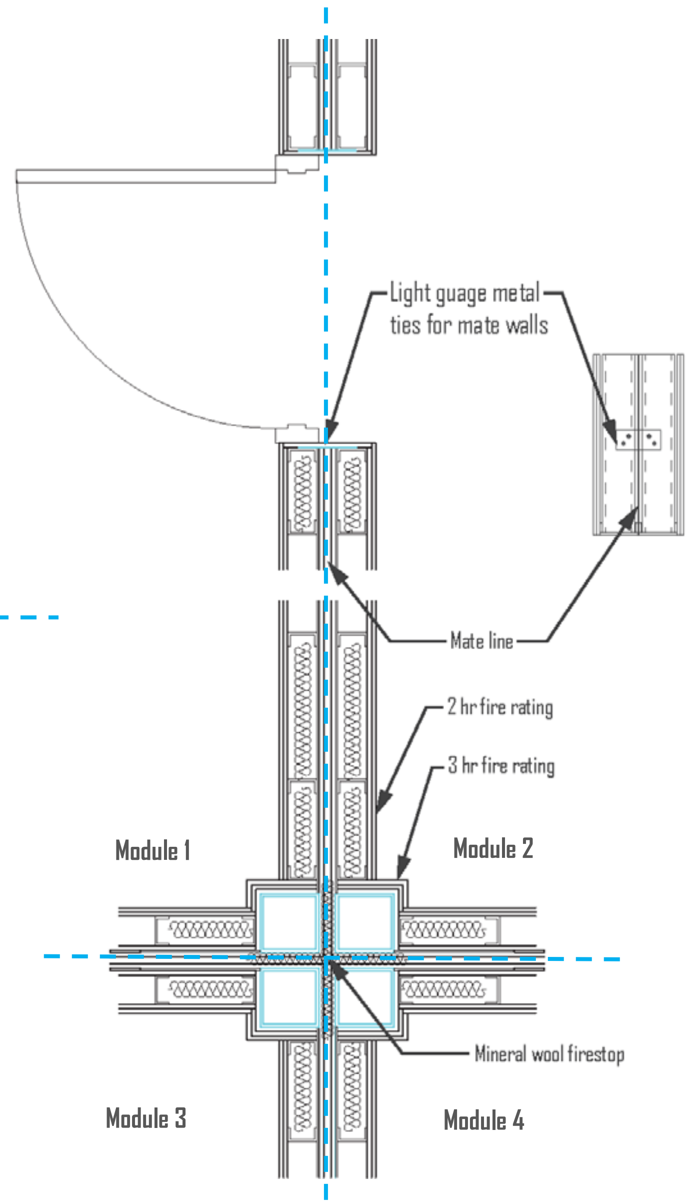
Figure 7.12.12– Roof Floor Plan, mechanical

7.13 Interior Mate Line Assembly

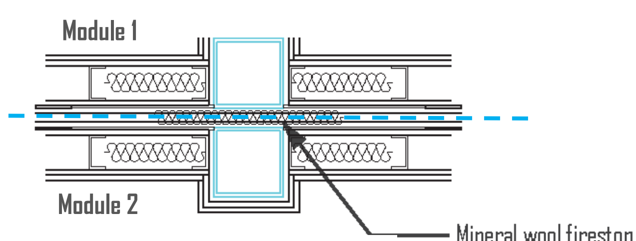
Typical materials will be used for the interior as labeled in the wall assembly in Figure 7.7.2. Fire separation between two modules requires a two hour rating which is achieved using gypsum (Figure 7.7.1 and Figure 7.13.1). As a precaution, the cavity space in between the modules are also lined with one layer of gypsum in the factory in case smoke or fire leaks into the cavity spaces from the building. A major benefit when buying a modular condo space is the thermal properties and noise reduction of the double wall and floor between each unit (Figure 7.13.1) these details show a number of scenarios that will be applied in the design of each module.



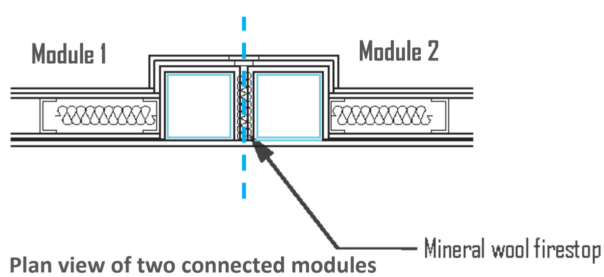
Section view of four modules



Plan view of four modules interior corner



Plan view of two modules interior



Plan view of two connected modules

Figure 7.13.1 - Interior section, material and fireproofing

The mate-lines can be concealed or revealed as part of the tectonic of the building.

For walls and ceilings, GWB is the most common material requiring mate-line finishing. These joints can be field-finished using standard GWB finishing techniques.

Flooring can be applied on site, in the factory, or a combination of the two:

• Ceramic tile - Tile can be set in the factory, allowing one tile to be set on-site over the mate-line.

• Vinyl Composition Tile and Engineered Hardwood is set in the factory such that the tile which will cover the mate-line will be cut to allow a precise fit to be made on site.

• Concrete can be placed in the mate-line joint on

7.14 Interior Design

The modules are designed to be as wide as possible in order to take advantage of the maximum lot size available. The extra fees incurred with shipping are recovered from lean and efficient structural design, attaining the maximum floor space, and designing fully finished units which also reduces the chance for error in connecting, sealing, and overall construction. Therefore, orienting the modules onsite, designing the floor layout, and scheduling the project efficiently, will establish a greater return on investment overall.

The open design of the volumetric modular units give the interior unit the ability to create an open concept design, giving flexibility in the final interior layout, and with high ceilings the units feel larger. A 70 square meter (750-sf) unit is either too small or too big, too small to have six people for dinner and too big of a kitchen for one person. It is easier to live in a smaller room that has been designed efficiently.

The modules are providing a shell like structure, giving the interior an open concept, however, if the homeowner would like to change the layout or add walls, the design has the flexibility to do so. When working with a manufacturer, one advantage is custom detailing how any installation can be made. Any wall that does not have services running through it is flexible to move if need be. The design involves a system that is customized, and could potentially be used anywhere. The idea is simple, similar to an IKEA cam lock and screw installation, the existing walls that are allowed to move will include manual key locks located at the top and bottom edge of the wall and at every 800 mm on center (Figure 7.14.1). Any corner or extension wall is connected by a lap joint that also contains the locks to keep it in place (Figure 7.14.2); these small turnkey locks are embedded into the floor and ceiling by the homeowner, and fastened with a hex key, so that they can be capped and flush. Therefore, if the homeowner decides to change the space multiple times, they can do so without leaving marks behind, they are considered permanent modular wall components. If the homeowner does go back to the original design, the extra wall will be attached to an existing wall or returned back to the manufacturer. The manufacturer or architect would need to be contacted to provide the wall type. This idea was derived from another problem from previous flexible spaces that have pre-

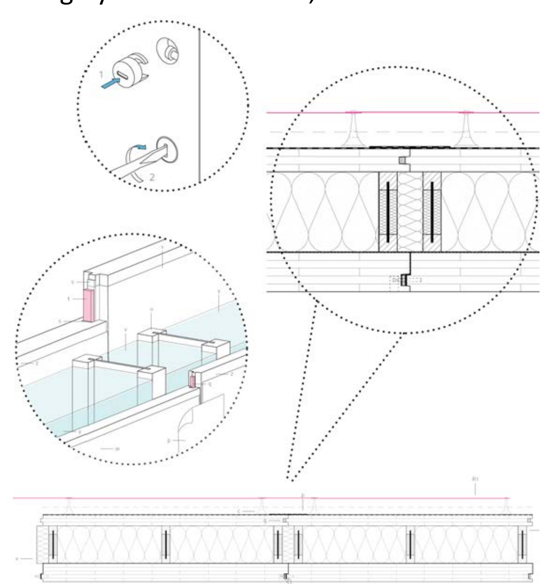


Figure 7.14.1 - Interior wall turnkey lock and joint

installed tracks along the floor and ceiling, but these are still limiting, not soundproofed, and visually unappealing.

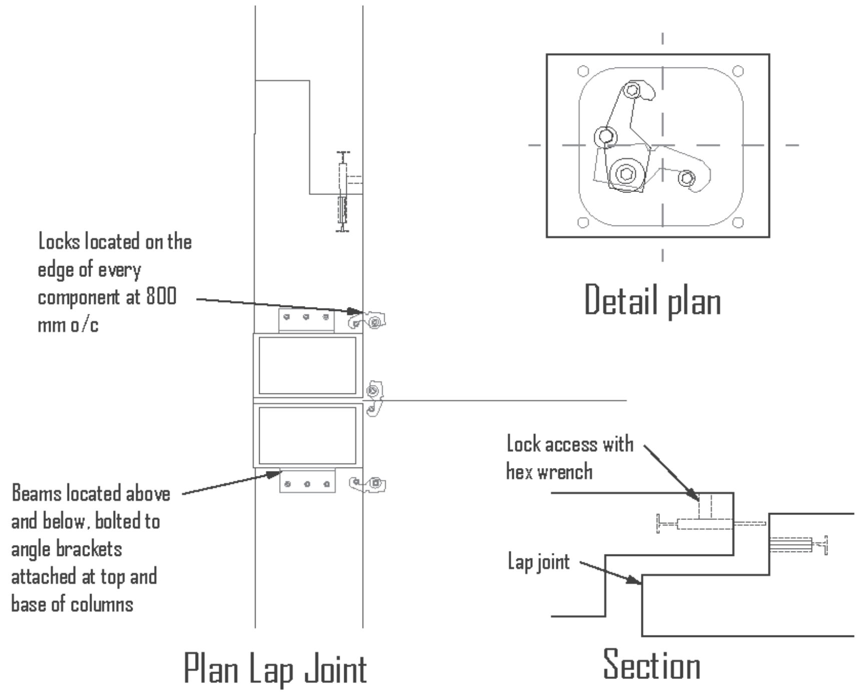


Figure 7.14.2 - Lap joint connection details

Design for small housing/living, initiated design solutions for various spatial planning options such as, strategically designing for double height spaces, flexibility of interior walls and movable furniture, as well as joining modules side to side, and top to bottom. Strategically choosing materials and fixtures that are clean and minimal also create the perception of a larger space and open feel. A design expression within the units include an area of the ceiling that is exposed to highlight modular design in the kitchen space, a design feature that reveal steel purlins and corrugated steel in the ceiling (Figure 7.14.3 and Figure 7.14.4).

Figure 7.14.3 - Interior render, ceiling revealed

Figure 7.14.4 - Interior render, showcase modular design of purlin and corrugated steel reveal in ceiling

The metal reveal is complemented with warm wood tones and textures that provide comfort to the resident on the interior to complete the industrial loft expression and still achieve comfort. The design of the access panel that closes the gasket and seals between two modules will be disguised with a wood panel feature wall that allows easy access after the modules are in position to seal the modules together in the building, and is visually pleasing for the homeowner (Figure 7.14.5).

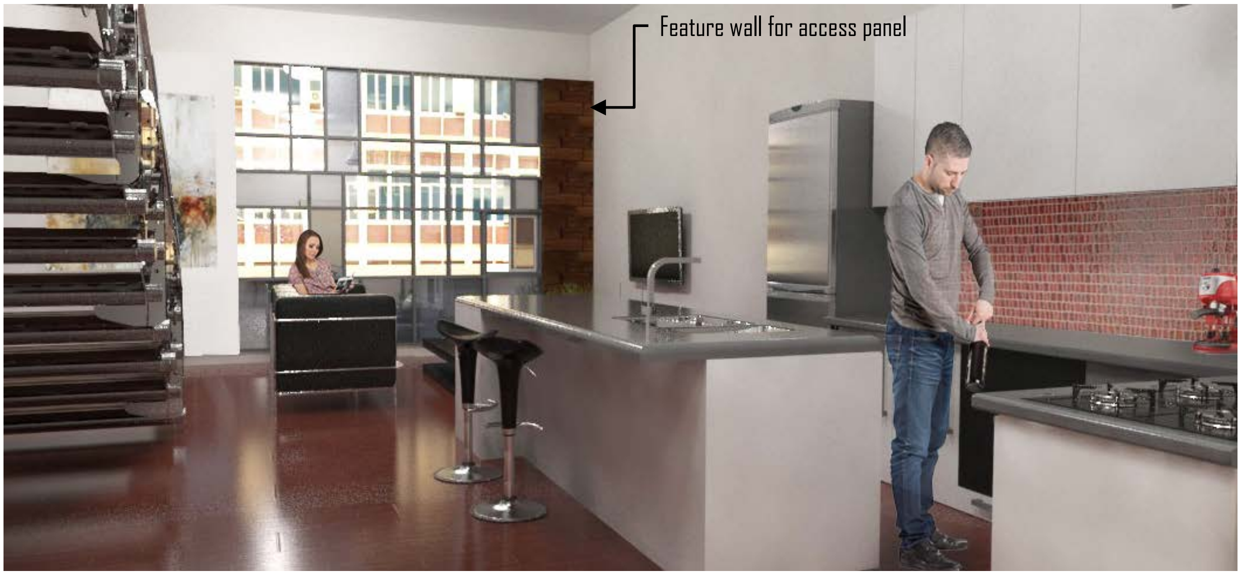


Figure 7.14.5 - Interior render, view looking south outside with feature wall to disguise access panel for sealing modules

8. Multifamily Housing Concept

Apart from describing the process and details of the project, this section wishes to imaginatively engage architectures existing modes of construction to speculate about the possibilities with a conceptual lens. Rethinking design and processes in this thesis to look at the forces leading towards prefabrication and modular design techniques of custom multifamily homes. This section explores how to create a design context that can change the standardization of multifamily home configurations, primarily through the collection of design combinations that allow for flexibility of spaces for the homeowners during the design phase. The typical multifamily building today is built first, then the user moves into building with no choice on how they want to live besides the typical choice of buying a one, two, or three bedroom unit and possibly some choice of material. I would like to propose an argument with the aim to encourage a continuing dialogue and debate to change that process, altering the traditional concept of multifamily development.

By having multifamily modular built homes, the homeowner can participate in the design process by choosing how they would like to configure their unit. Therefore, the participation will influence the architect at a conscious level during the design development phase of the building within the areas of, spatial relationships, program, and finishes. This integration and participation will improve the consumers understanding of space and how they exist within it; this will allow the homeowner to respect/appreciate the design environment in which they live, and where the homeowner will create a deeper connection to the building when they become part of the design. Kevin Lynch claims ‘users obtain immeasurable benefits from a greater understanding of their environment’ (Lynch, 111). My work up to this point had been similar to the vision of Nicholas Negroponte. Negroponte’s love for technical advancement had resulted in him becoming the founder of MIT’s Architecture Machine Group in 1967, with the philosophy that computers would make life better for everyone, this group was a combination of a lab and a think tank to research and develop new approaches for human and computer interaction (Hirst & Harrison, 2007). However, Yona Friedman, who was famous around the 1950’s and 1960’s during the age of the megastructure, has a more direct relationship to this concept of homeowner participation. The architect, urban planner and designer, published a manifesto on “mobile architecture.” Mobile architecture is considered as the ‘dwelling decided on by the occupant’ (Vardouli, 2011). Friedman advocated for an architecture where ‘the habitat can be altered according to the desire of each inhabitant;’ ‘the habitat is decided by the user within the framework of an infrastructure which is neither determined nor determinant’ (Vardouli, 2011) and where the buildings make as little impact on the ground as possible.

Friedman outlines the fundamental principles on the model of the “Spatial City” (Figure 8.1) large structures that are raised up on piles which contain habitable and inhabitable spaces. According to Friedman, the teaching of Architecture had led architects to invent the “Average Man,” to estimate the needs of a fictional idea and not the needs of the real user.

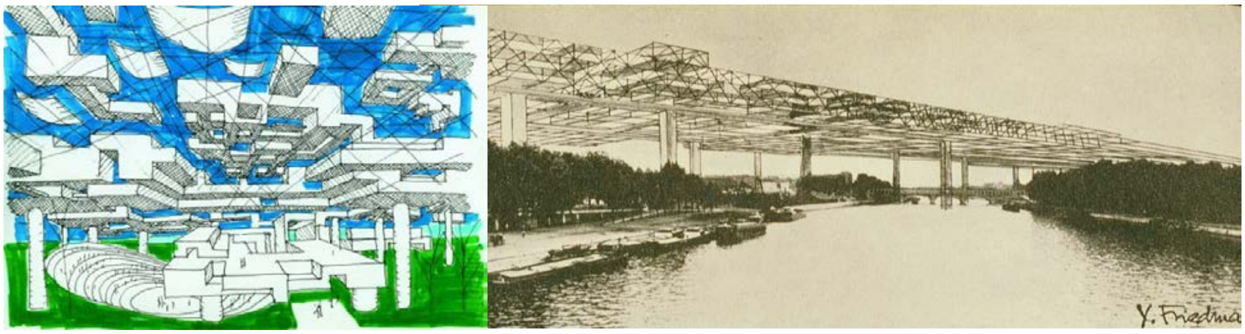


Figure 8.1 - Spatial City concept by Yona Friedman

‘Building is not an object, it’s a process’ this quote by Friedman caught the eye of Cedric Price, who is an architect and theorist of the same time, and has conceived the same idea as a way to drive economic redevelopment. Price stressed the need for flexibility in architectural design for potential future uses. Form was of little consequence to him, Price persistently explored the fusion of information technology and advocated for users to be considered as co-designers (Fentener, 2013).

Integrating construction methods, and the knowledge gained from the benefits of modular design has revealed opportunities into the design and development of multifamily building design, as well as opening the idea of reforming traditional conceived methods of multifamily development with the participation of the homeowner. Designing with the homeowner’s participation to create a custom unit is achievable when all design variables have been considered and the construction process has been planned in advance (i.e. Applying a number of floor layout scenarios that fit within the set criteria of the design, but still maintain efficiency and consistency to conform to the overall project).

This eventually led to an experiment of varying types of unit configurations in the design. The buildings units resulted into three, one-bedrooms, five, two-bedrooms, one, three-bedroom, and one, four-bedroom unit. These floor plan design iterations in Figure 7.12.4 to Figure 7.12.11 are the prime examples which can offer a number of different unit configurations. These experiments were guided by previous knowledge of modular design with the consideration of services through the building, natural light and unprotected openings for each bedroom, and other site constraints. With the variation in units, the exploration process had influenced another dialogue for a closer relationship with the homeowner. It laid out possible spatial scenarios that can be implemented into the design, so that the architect is well equipped and knowledgeable of different unit scenarios and their capabilities before working with homeowners to discuss what custom living arrangements will work for them.

In this thesis project, the shape of the building was formed by my decision to highlight modular systems of design and construction to showcase the building as my interpretation of a future example on what the industry may look toward for change (Figure 8.2, Figure 8.3, and Figure 8.4). Therefore, in a real life application with actual clients, the buildings overall form may take on any shape when the homeowners begin to choose more options of custom living arrangements, each building will have an impact on its surroundings because of its influence from the community and culture (Figure 8.5).

The process begins with a shift in the organization of multifamily establishments, where the homeowner would buy volume of a space; much like someone would purchase land property, except in this case they are purchasing vertical property. The homeowner will be given a choice on how many modules they want and in which configuration they prefer, for instance, a one module unit, a two module unit north to south on the same level, another two module unit east to west on the same level, a two module unit stacked one on top of the other for two levels, or a combination of them all. This opens up a wide range of scenarios, but since the architect has already analyzed the potentials and constraints to work under specific guidelines, in order to keep the building functional and operable. These design guidelines include having the water closet and the kitchen stacked in one area of the building to have mass production packages in some areas, and customized spaces in the other areas to fit accordingly. If the time is spent during the design development phase, the production workflow will be easier to comprehend in a manufacturing setting, meaning, there are repeated patterns in most of the configurations if the design of the modules is strategic and the factory floor is designed for the specific job. All the units are staged on the same chassis, and with the proper jigs installed, the production will be effective.

The building is configured with the knowledge that all the services are passing through the core of the building and leading out the main corridor to attach to each unit, allowing for multiple living arrangements. This scenario makes each module independent and will not disturb or put any existing homeowner out of place if maintenance is needed in one unit or if future development to the building is desired. The modular structural system is designed and robust enough to accept future modules as described by Lawson, Grubb, Pewer, Trebilcock, 1999, therefore, the design can provoke expansion to the existing building with the designed connection system implemented.

All of the mechanical equipment and electrical services are on the top of the building instead of the basement. Heating equipment, cooling towers, chilling modules, generators, boilers, and control rooms are placed strategically to maximize space in one module. The predesigned roof area will be turned into a floor if future modules are stacked on top. The remaining void space in between the roof and the next set of proposed modules stacked on top will become a common area.

The public demand in today's market is wanting more customization than standardization, you can choose the design of your phone, your computer, and your car, so why not your condominium? A typical person would not trust the quality of a car made in someone's backyard, so why should they for their home? It would take a little more time to work with individual homeowners to discuss design options but it is not unlike traditional market condos in a sense that most people buy the condo before construction has even begun, except they do not have a choice in the design of their new home. The dedicated time scheduled for short design and long construction will be reversed, meaning, more time will be spent on the design phase to detail the entire projects design and construction phases, with the goal that the construction time will be significantly reduced.

"Good design is thorough down to the last detail" says Dieter Rams, a German industrial designer who wrote ten principles of good design (Rams, 2012). From my studies, going through the processes and workflows, understanding the productions and assembly, realizing all the organization and planning, along with the many design iterations, has helped this paper devise a design proposal where I could begin to conceive and transform how I perceive things in the industry and where I see potentials leading.

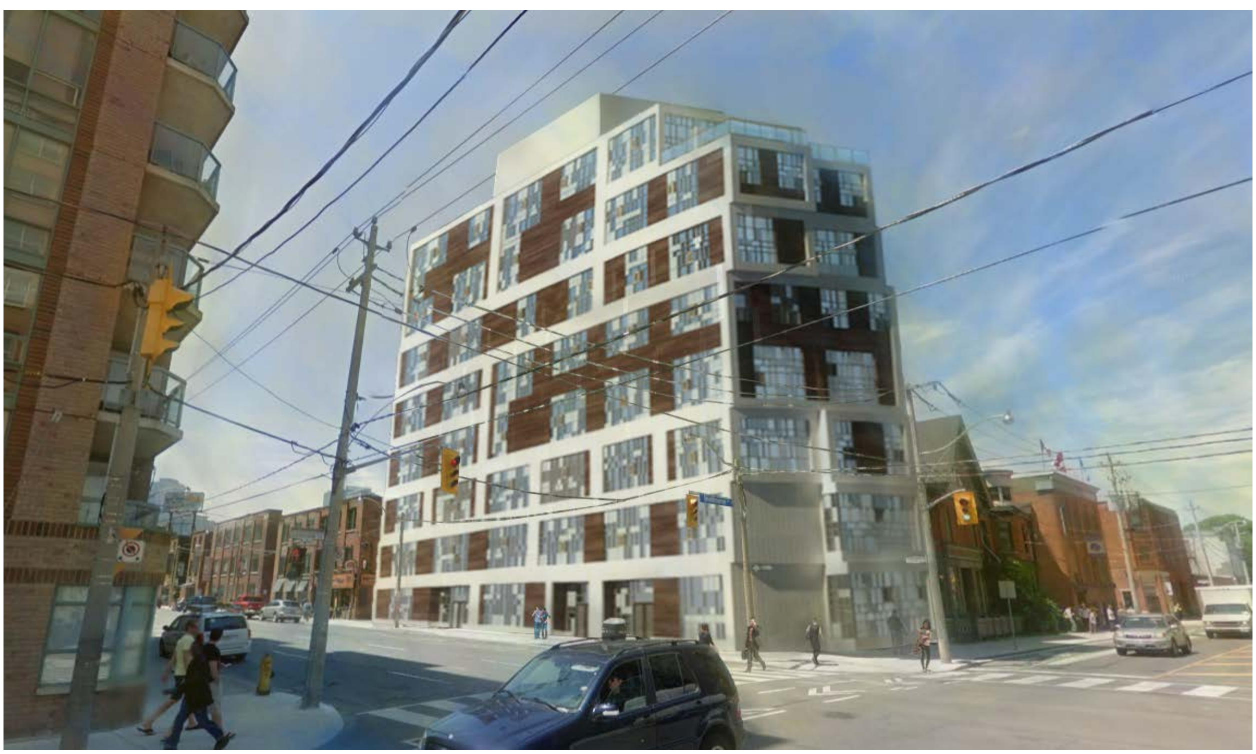


Figure 8.2 - Exterior render, intersection of Sherbourne Street and Richmond Street view looking north-west

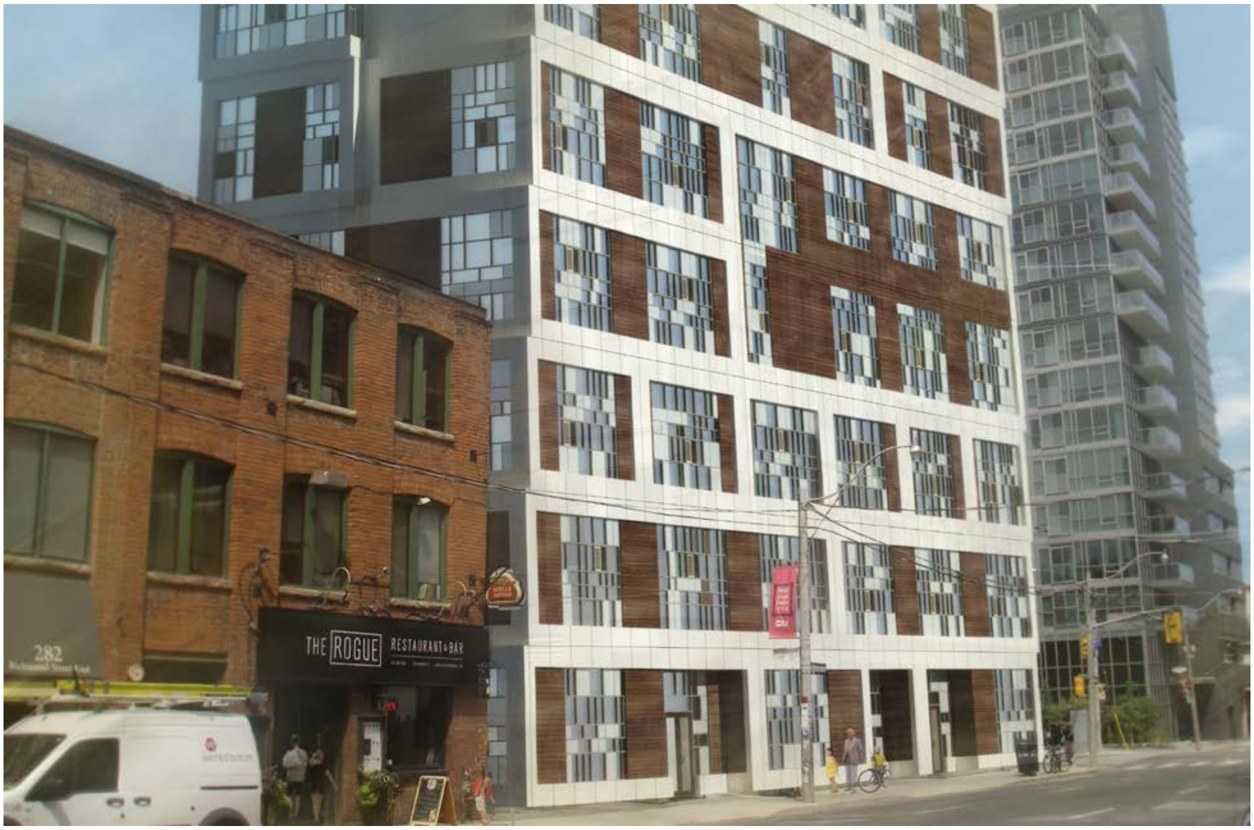


Figure 8.3 - Exterior render, Richmond street view looking north-east

Figure 8.4 - Exterior render, lobby entrance

9. Conclusion

Many contributions have been made to the field of prefabrication and modularization, without making a significant impact on the industry. In the past, issues of accuracy were effecting the probability of a successful project because the technology at the time was not fully optimal to coordinate with other relating variables to achieve cohesiveness, and the technology was not fully implemented to complete most of the elements offsite; elements of construction had to match high precision offsite fabrication with uncontrolled onsite builds. Therefore, prefab and modular technology was never fully adopted by the masses largely because the technology was not quite advanced at the time and also because modular design was seen as a commodity. These issues are still relevant today but can be dealt with through recent technologies and platforms such as BIM that can collaborate, detail, analyze, and monitor a process to survey accuracy of the digital to physical build. The latest fabrication technology has changed the image of modular design being labeled as a commodity through custom fabrication techniques that can be just as cost effective as mass produced techniques. With the continuous advancement in technologies there will never be an overhaul of one system, but more modular design contributions and solutions will present themselves as future complications arise within development and construction, as shown through the Leadenhall case study in section 6.8.1, on the issues of restricted accessibility and limited space onsite, and as discussed under the future design considerations of section 6.2 which include development on small urban infill's, small living demands, limited skilled craftsman available, and other sustainable and environmental aspects that further escalate the importance and application of modularization.

This thesis has attempted to change the perception of modularization as a commodity through the extended use of bespoke design and techniques. The thesis contributions have achieved a closer relationship between architecture and construction through informed design by integrating design, manufacturing, and assembly through the concepts of modularization. This resulted in a project that has mapped and detailed the design and construction phases so that the building is built as designed, meaning the physical build will perform exactly like the digital simulation. This has led to opportunities within architectural design by considering design potentials through the lens of the small scale details from joining connections, services, structure, and wall components to create modules. By understanding the integral parts of how the module can perform, it allows for a number of design variations in connecting modules together. This can establish different apartment units and their configurations. From this, the building will begin to take form and establish sub-floors, floor layouts, and other spatial arrangements, this in turn will affect the processes required for the sequence of construction.

In an architect's perspective, applying manufacturing and assembly into design will help create a more accurate transition between digital to physical when applied at the beginning of the project so that every detail can be accounted for in the digital model before it is fabricated and built. The project in this thesis has went over the details of the module so that the module can be adapted when adjusting the size of the module to suite specific sites. This also helps understand how the modules could potentially be combined to create different units to eventually generate the form of the building. Hence the digital model needed to cover critical details that include the connection details within the module ie. structure, services, and wall components, and outside the module ie. gaskets and mate-line connections on how the modules are stacked and connected on each side. After outlining the limitations and variations of the module, the project researched details on how the modules will be fabricated, this was adopted from Atlantic Yards B2K because I do not have the resources or time in this thesis to go into detail with this section, therefore it was used as a placeholder for the project. Once the modules are completed the project called for details on how the modules will be stacked. The site analysis determined the sequential order of the modules during construction for an optimal position for the most access for the workers to assemble the connections and reduce any obstructions for the crane operator to speed the construction schedule. The overall project was a test to explore the number of different unit/apartment variations of the modules within the specific site constraints, this began the floor layout exploration to demonstrate the tightest possible living condition only if it was required within the design, and the other spaces included a unit with two storeys, and units that connected in either North to South, West to East, or a combination of both, leading to units that range from one module to 5 modules. Details in material choices were chosen to highlight modular design and construction to provide the homeowner with a sense of the project and give them an industrial yet comfortable living environment when working with limited module sizes determined by site and shipping arrangements.

This project has influenced new opportunities in design to detail the processes to become more sophisticated and match the advanced level of digital technology in a project such as BIM in order to ease the construction and assembly methods to achieve the intended outcome. The design information will become construction information in order to conceive of a more efficient and possibly future oriented building process where design development is given more emphasis but eventually produces in a much shorter time. As well as to benefit society, showcasing the communities and cultures through these custom buildings and highlighting new opportunities in the way multifamily buildings are designed and constructed.

Architectural design has become a complex workflow where spatial and geometric information is absorbed through analysis and simulation processes for optimal performance. The aim is to relay the information into an integrated model that can generate ranging variables such as manufacturing instructions to help set up for files and instructions for production and assembly purposes. People are beginning to attempt similar scenarios through open source networking and scripting. This technology has impacted the way design teams are thinking about integration and work by engaging with the broader culture. At its very core, custom scripting opens up limitless design potential in a way that was not possible before. The open source network can create a script loaded with information and design parameters to control and manipulate the resulting form of a design as desired to the users intended outcome. Sharing this work in an online community means someone can pick up where the last person left off, and that person can input XYZ variables needed to produce a final outcome or they can adjust the script to make it suit their own needs, continually updating and progressing the file as they go, but in its current early stages this is more of a representational model than anything else. Once the industry becomes more familiar with the technology, we will begin to see the methods taken in this thesis project into a script to adjust for the appropriate module and size of unit with the desired preferences of each homeowner to produce mass-customized homes.

Productivity is one of the top drivers for modular design and construction, and if I were to speculate, the demand to integrate modular design and construction into scripting will become a major driver to further enhance the integrated information of BIM within parametric tools and algorithmic processes. When more time and experience has passed, we will begin to see BIM become integrated with machine dynamics that are generated from parametric algorithms. For instance, the BIM model will highlight details of the 3D model to display the material information for fabricators to interpret items like tolerances for accuracy and assembly procedures. Each element in the model could potentially be controlled and parametrically linked as part of an integrated workflow, for instance, each element can be numbered in sequential order for detailed instructions of production and assembly. Detailed designs are beginning to include assembly logic which consist of parametric defined relationships of their component parts. ‘The logic is placed between creative thinking and a calculated output’ (Marble, 2012). This should not be seen as limiting creativity, I believe that its purpose is to translate the idea into form in the most efficient way possible. The most ideal solution is have the design team learn as much about the machines as possible so that they are not considered as a constraint but more like another tool in the tool belt; utilizing machines instead of hands to achieve consistent results. This eliminates uncertainty and enables clients to be more involved/engaged with the project by giving the client one principle company of design and build. This will help make sure every variable is accounted for to achieve the best solutions out of modular design and construction, which in turn provides a more refined relationship between architectural design and construction.

Today, integrating manufacturing and assembly into digital design and delivery can transform the working relationships in the making of architecture, and can place the design team in the center of this creative process as proposed by Kieran and Timberlake in their book "Refabricating Architecture." There is in essence a convergence whereby crafts people can become an industry of one (Campbell, 2006), and the architect, once a remote fabricator, can directly control the manufacturing process. The roles of crafts people and architects are interconnected with the aid of manufacturing technologies available that engage design with the construction and production by using precise components detailed in a 3D model. With the focus of a stronger and closer relationship between digital to physical in architecture and construction, a dialogue was needed within the design of the connection and assembly for this to be successful. Meaning you have to visualize the design object by the sum of its connecting parts and how those parts are assembled to create a whole, and the best platform to visualize this is through a detailed 3D model. In addition to Kieran and Timberlake's position, the thesis has detailed assembly into the design as an essential piece of the project to use precise illustrations for instructions during production and construction. Informed design and knowing how everything is assembled will provide great benefits that include but not limited to the use of lean construction, by easing the fabrication and assembly process of complex forms through design which will reduce the amount of time, labour, energy, and material used in the overall form, and other benefits that are indirect may arise when there is a shortage of skilled labor. When complex components and there connections are derived by a digital design the architect will be able to realize the process or sequence required when assembling so that the object is built as designed. This has opened a new window for fresh context where architects may re-engage within the digital and physical transition, which will fuel more transformation and progression to occur. The theories and arguments are potentials for architects to rationalize this complexity and reposition themselves in a larger market by taking a more influential role within the current restructuring of industry and create new organizational models to enhance the capabilities of a design team to design and manage all aspects of production and build in a project. Therefore, if the strategies proposed in this thesis can be followed, it will contribute to a stronger relationship between architecture and construction through informed design and efficient workflow processes; encouraging new tools within design and industry to engage with the broader culture.

APPENDIX A1

A1 Zoning and Unprotected Openings

A1 Zoning and Unprotected Openings

Zoning limitations for the site show the setback can range from zero to three meters, the first floor must be a minimum four and a half meters high, a maximum 30 meter height limit, and overall site dimension (Figure A1). The unprotected opening for the lot is shown at the maximum lot coverage to be:

North Elevation, 0%	= 0m2 abutting next to the other property.
South Elevation, 100%	= 330m2 of unprotected opening, sprinklered, nine meters from center of Richmond St. E.
West Elevation, 33%	= 108.9m2 of unprotected opening, sprinklered, four meters from the center of Stonecutters Laneway.
East Elevation, 68%	= 224.4m2 of unprotected opening, sprinklered, seven meters from center of Sherbourne St.

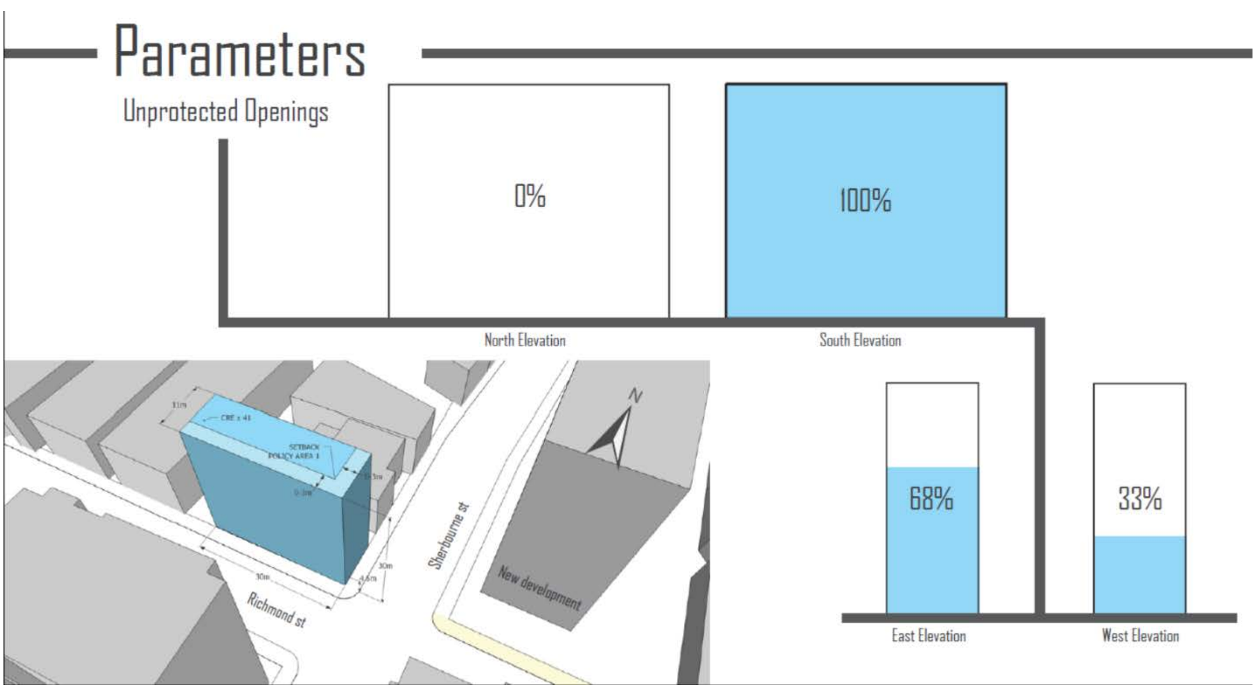


Figure A1 - Zoning and unprotected openings

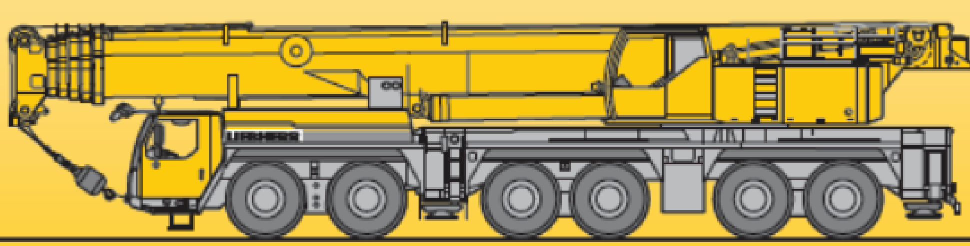
APPENDIX A2

A2 Crane Technical Data

Mobile Crane
Grue mobile

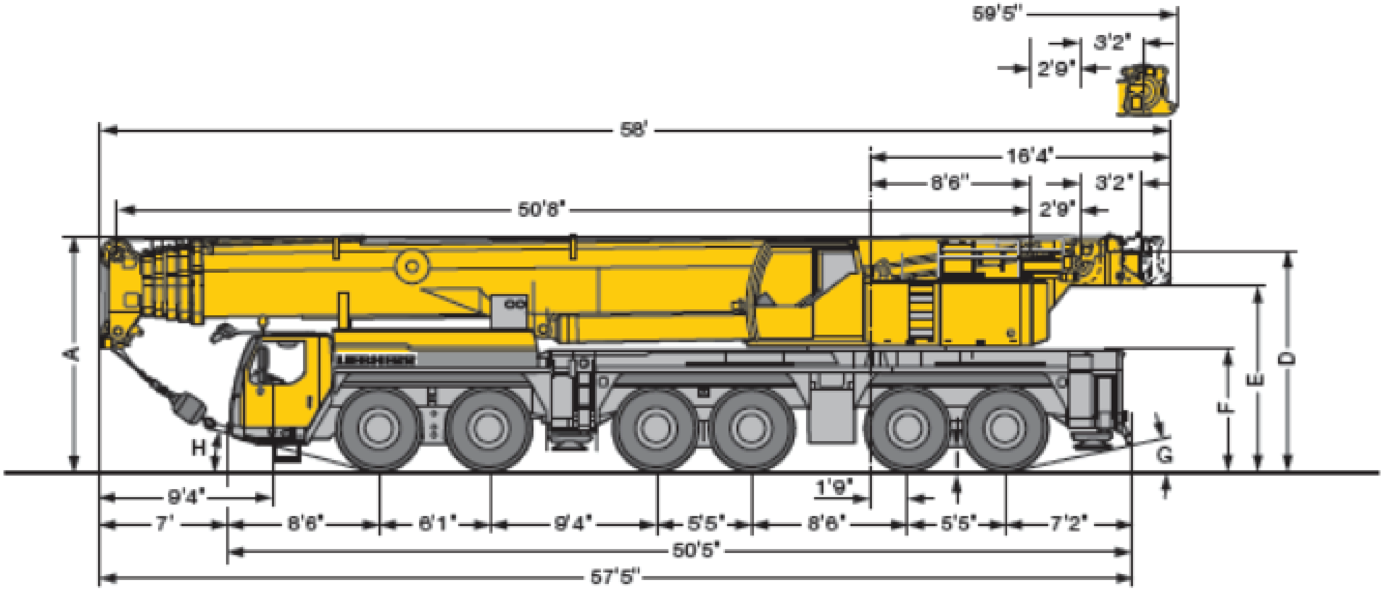
LTM 1250-6.1

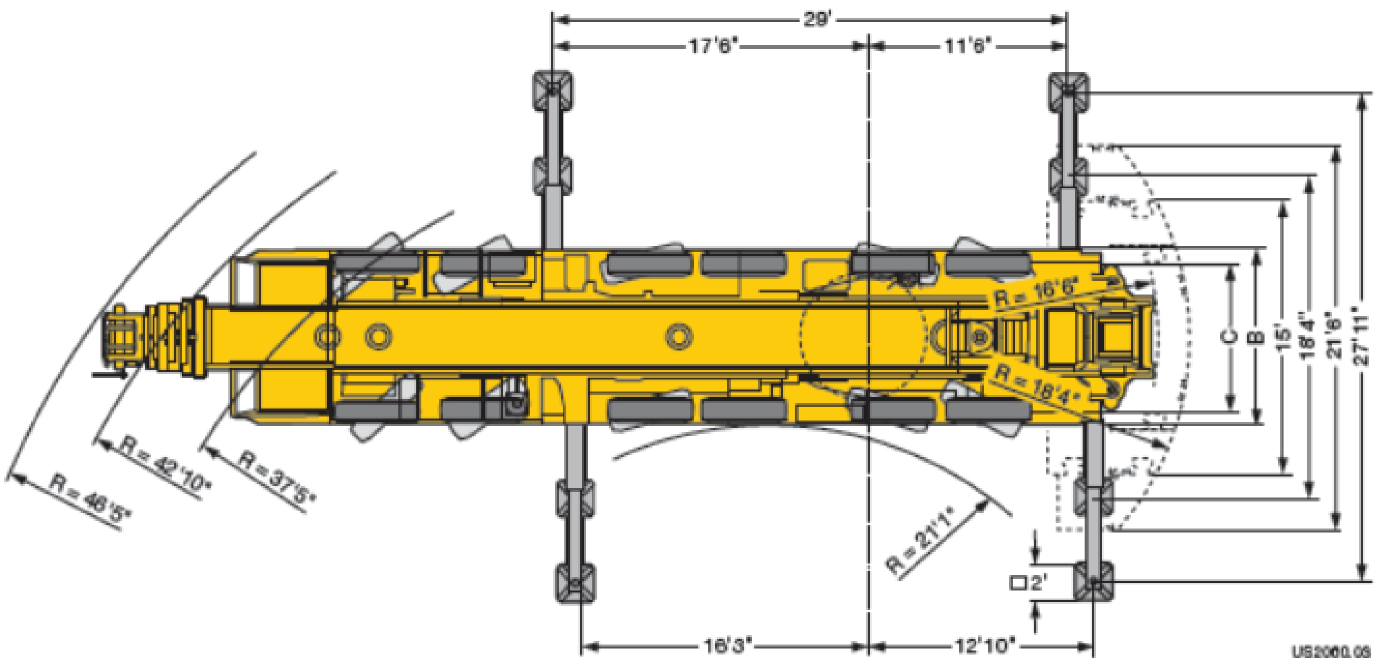
Technical Data
Caractéristiques techniques



LIEBHERR

Dimensions
Encombrement





	Dimensions / Encombrement									
	A	A 0'6"*	B	C	D	E	F	G	H	I
445/95 R 25 (16.00 R 25)	13'1"	12'8"	9'10''	8'4"	12'4"	10'4''	6'9''	12°	14°	1'3"
525/80 R 25 (20.5 R 25)	13'1"	12'8"	10'8''	8'10"	12'4"	10'4''	6'9''	12°	14°	1'3"

* lowered / abaissé

131

Weights
Poids

Axle Essieu	1	2	3	4	5	6	Total weight lbs Poids total lbs
lbs	26400	26400	26400	26400	26400	26400	158400

Load kips[1)] Forces de levage kips[1)]	No. of sheaves Poulies	No. of lines Brins	Weight lbs Poids lbs
388	9	19	5290
315	7	14	3750
238	5	10	3200
156	3	6	2290
69	1	3	1850
22	–	1	1100

[1)] The safety regulations of the respective country shall be applicable.
Les spécifications de sécurité du pays concerné seront en vigueur.

Working speeds
Vitesses

		1	2	3	4	5	6	7	8	9	10	11	12	R 1	R 2	
445/95 R 25 (16.00 R 25) 525/80 R 25 (20.5 R 25)	mph	3.5	4.5	5.8	7.5	9.5	12.8	16.1	20.6	26.7	34.2	43.4	50	3.8	4.9	47.9 %

Drive Mécanismes	infinitely variable en continu	Rope diameter / Rope length Diamètre du câble / Longueur du câble	Max. single line pull Effort au brin maxi.
1	0 – 427 ft/min single line ft/min au brin simple	0.9" / 1181'	23605 lbs
2	0 – 492 ft/min single line ft/min au brin simple	0.9" / 1378'	23605 lbs
360°	0 – 1.6 rpm		
	approx. 60 seconds to reach 82° boom angle env. 60 s jusqu'à 82°		
	approx. 600 seconds for boom extension from 51 ft – 236 ft env. 600 s pour passer de 51 ft – 236 ft		

Lifting capacities
Forces de levage

T

51 – 236 ft | T | 360° | 214900 lbs | 85%

ft	51 ft *	51 ft	68 ft	85 ft	102 ft	119 ft	136 ft	153 ft	170 ft	187 ft	204 ft	221 ft	236 ft	ft
9		389												9
10	585	388	297											10
12	370	370	297	258										12
14	331	331	297	258										14
16	305	305	284	258	197									16
18	286	286	268	250	197	157								18
21	261	261	246	232	197	157	134							21
24	239	239	226	214	195	157	134	104						24
27	220	220	209	198	188	157	134	104	81.5					27
30	201	201	195	184	175	157	132	102	81.5	63.5				30
33	183	183	182	172	164	156	130	97.5	81	63.5				33
36	163	163	170	162	154	150	129	93.5	79	63.5	46.3			36
39	142	142	158	153	145	141	124	89.5	76.5	63.5	46.3	41.3		39
45			137	136	130	127	113	82	71.5	60.5	46.3	41.1		45
51			116	121	117	115	104	74.5	66	57.4	46.3	40.8	34	51
57			77.5	107	105	104	96	68	60.5	53.6	46	39.8	33.8	57
63				93	94.5	95	89	63	55.7	49.9	44	38.5	33.2	63
69				79	84	86	82.5	59.2	51	46.4	41.3	36.9	32.3	69
75					75	78.5	76.5	56.1	46.9	43.2	38.8	35.1	31	75
81					67	72.5	71	53.2	43.7	40	36.4	33.2	29.4	81
87					59.1	67	65	50.5	40.9	37	34.2	31.4	27.9	87
93						61	59.4	48	38.4	34.5	32.1	29.8	26.4	93
99						53.8	54.3	45.6	36.1	32.1	30.1	28.2	25.1	99
105							49.9	44	33.8	30.3	28.3	26.6	23.7	105
111							45.9	42.4	32	28.6	26.5	25.1	22.5	111
117							40.7	40.9	30.7	27	25	23.8	21.3	117
123							36.7	39.5	29.5	25.4	23.6	22.4	20.1	123
129								36.9	28.4	24.1	22.4	21.1	19	129
135								33.6	27.4	22.9	21.2	19.8	17.9	135
141								23.9	26.3	21.8	20.1	18.6	16.9	141
147									25.4	20.8	19.3	17.4	15.9	147
153									24.4	19.8	18.4	16.3	14.9	153
159										19	17.7	15.4	14	159
165										18.3	16.9	14.6	13.3	165
171										17.7	16.2	13.7	12.6	171
177										14.7	15.5	12.9	11.9	177
183											14.8	12.2	11.2	183
189												11.4	10.5	189
195												10.7	9.8	195
201												10	9.2	201
207													8.5	207
213													7.9	213

* over rear - en arrière

TAB 131201 / 131351

51 – 236 ft T | 360° | 187400 lbs | 85%

ft	51 ft	68 ft	85 ft	102 ft	119 ft	136 ft	153 ft	170 ft	187 ft	204 ft	221 ft	236 ft	ft
9	389												9
10	388	297											10
12	370	297	258										12
14	331	297	258										14
16	305	284	258	197									16
18	286	268	250	197	157								18
21	261	246	232	197	157	134							21
24	239	226	214	195	157	134	104						24
27	220	209	198	188	157	134	104	81.5					27
30	201	195	184	175	157	132	102	81.5	63.5				30
33	183	182	172	164	156	130	97.5	81	63.5				33
36	163	170	162	154	150	129	93.5	79	63.5	46.3			36
39	142	158	153	145	141	124	89.5	76.5	63.5	46.3	41.3		39
45		137	136	130	127	113	82	71.5	60.5	46.3	41.1		45
51		116	119	116	115	104	74.5	66	57.4	46.3	40.8	34	51
57		77.5	103	102	103	96	68	60.5	53.6	46	39.8	33.8	57
63			90.5	89	91.5	89	63	55.7	49.9	44	38.5	33.2	63
69			78.5	78.5	83	82	59.2	51	46.4	41.3	36.9	32.3	69
75				70.5	76.5	74.5	56.1	46.9	43.2	38.8	35.1	31	75
81				64.5	69	67	53.2	43.7	40	36.4	33.2	29.4	81
87				59.1	63	61	50.5	40.9	37	34.2	31.4	27.9	87
93					57.3	55.2	48	38.4	34.5	32.1	29.8	26.4	93
99					52.4	50.2	45.6	36.1	32.1	30.1	28.2	25.1	99
105						45.8	44	33.8	30.3	28.3	26.6	23.7	105
111						42	42.4	32	28.6	26.5	25.1	22.5	111
117						38.6	40.3	30.7	27	25	23.8	21.3	117
123						36.2	37.4	29.5	25.4	23.6	22.4	20.1	123
129							34.6	28.4	24.1	22.4	21.1	19	129
135							32.2	27.4	22.9	21.2	19.8	17.9	135
141							23.3	26.3	21.8	20.1	18.6	16.9	141
147								25.4	20.8	19.3	17.4	15.9	147
153								24.4	19.8	18.4	16.3	14.9	153
159									19	17.7	15.4	14	159
165									18.3	16.9	14.6	13.3	165
171									17.7	16.2	13.7	12.6	171
177									14.7	15.5	12.9	11.9	177
183										14.8	12.2	11.2	183
189											11.4	10.5	189
195											10.7	9.8	195
201											10	9.2	201
207												8.5	207
213												7.9	213

TAB 131352

Lifting capacities
Forces de levage

T

51 – 236 ft | 360° | 159800 lbs | 85%

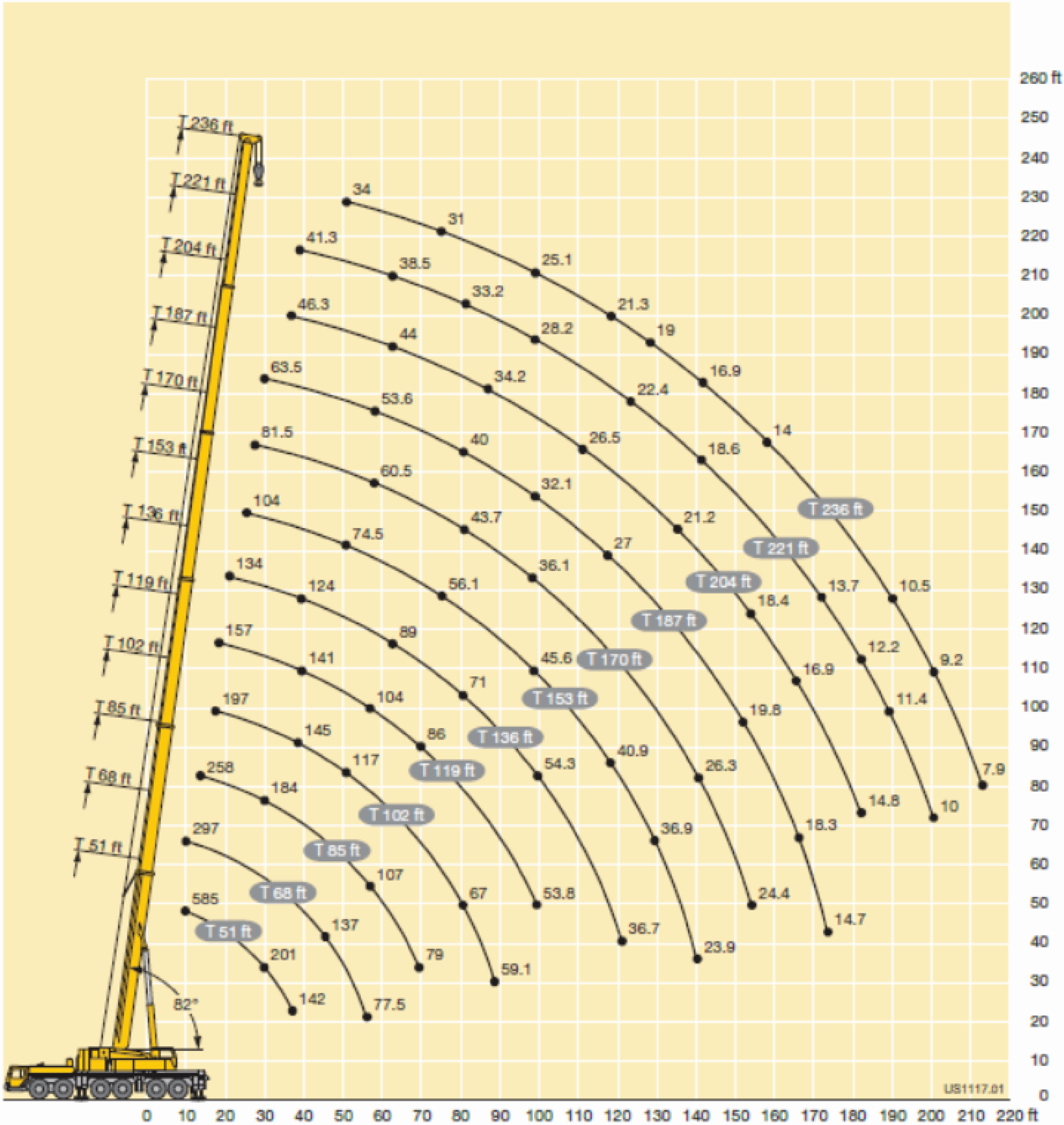
ft	51 ft	68 ft	85 ft	102 ft	119 ft	136 ft	153 ft	170 ft	187 ft	204 ft	221 ft	236 ft	ft
9	389												9
10	388	297											10
12	370	297	258										12
14	331	297	258										14
16	305	284	258	197									16
18	286	268	250	197	157								18
21	261	246	232	197	157	134							21
24	239	226	214	195	157	134	104						24
27	220	209	198	188	157	134	104	81.5					27
30	201	195	184	175	157	132	102	81.5	63.5				30
33	183	182	172	164	156	130	97.5	81	63.5				33
36	163	169	162	154	150	129	93.5	79	63.5	46.3			36
39	142	155	153	145	141	124	89.5	76.5	63.5	46.3	41.3		39
45		130	130	127	127	113	82	71.5	60.5	46.3	41.1		45
51		113	111	109	110	104	74.5	66	57.4	46.3	40.8	34	51
57		77	96	94.5	97.5	94.5	68	60.5	53.6	46	39.8	33.8	57
63			84	82.5	88	84	63	55.7	49.9	44	38.5	33.2	63
69			74	74.5	79	74.5	59.2	51	46.4	41.3	36.9	32.3	69
75				69	70.5	66.5	56.1	46.9	43.2	38.8	35.1	31	75
81				64	63	59.7	53.2	43.7	40	36.4	33.2	29.4	81
87				57.5	56.9	53.9	50.5	40.9	37	34.2	31.4	27.9	87
93					51.3	48.9	48	38.4	34.5	32.1	29.8	26.4	93
99					46.4	44.4	45.5	36.1	32.1	30.1	28.2	25.1	99
105						41.5	41.9	33.8	30.3	28.3	26.6	23.7	105
111						39.8	38.3	32	28.6	26.5	25.1	22.5	111
117						37	34.9	30.7	27	25	23.8	21.3	117
123						34	31.8	29.5	25.4	23.6	22.4	20.1	123
129							29.1	28.4	24.1	22.4	21.1	19	129
135							26.6	27.2	22.9	21.2	19.8	17.9	135
141							20.5	25.4	21.8	20.1	18.6	16.9	141
147								23.3	20.8	19.3	17.4	15.9	147
153								21.5	19.8	18.4	16.3	14.9	153
159									19	17.7	15.4	14	159
165									18.1	16.9	14.6	13.3	165
171									16.7	16.1	13.7	12.6	171
177									14.7	14.8	12.9	11.9	177
183										13.6	11.8	11.2	183
189											10.7	10.5	189
195											9.6	9.6	195
201											8.6	8.6	201
207												7.6	207
213												6.8	213

TAB 131353

51 – 236 ft T | 360° | 37500 lbs | 85%

ft	51 ft	68 ft	85 ft	102 ft	119 ft	136 ft	153 ft	170 ft	187 ft	204 ft	221 ft	236 ft	ft
9	389												9
10	388	297											10
12	370	297	258										12
14	331	297	258										14
16	305	284	258	197									16
18	277	256	234	192	157								18
21	231	212	191	171	149	133							21
24	185	169	153	139	131	126	103						24
27	149	142	131	128	117	107	99	80.5					27
30	123	121	116	109	101	94.5	89.5	79.5	63.5				30
33	104	104	100	94.5	87.5	86	78.5	72	63				33
36	89.5	90	87.5	83	78	76	71.5	67.5	62	46.3			36
39	78	79	77.5	74.5	69	68	65.5	61	56.4	46.3	41.3		39
45		63	62	62	55.8	57.4	54.3	51.7	48.1	44.4	40.6	33.9	45
51		50.8	51	51.6	49.3	48.6	45.9	43.8	40.4	37.8	34.2	32	51
57		41	42.5	43.4	42.1	41	38.8	36.8	33.7	31.4	28.1	27.3	57
63			35.8	36.7	35.7	34.8	32.9	31.1	28.3	26.2	23.2	22.5	63
69			29.8	31.3	30.4	29.8	28	26.4	23.8	21.9	19.1	18.6	69
75				26.9	26.1	25.6	24	22.5	20.1	18.4	15.7	15.3	75
81				23.1	22.5	22.1	20.6	19.3	17	15.3	12.8	12.4	81
87				19.6	19.5	19.2	17.7	16.5	14.3	12.8	10.3	10	87
93					16.8	16.7	15.2	14.1	12	10.5	8.1	7.8	93
99					14.3	14.5	13.1	12	9.9	8.5			99
105						12.5	11.2	10.2	8.2				105
111						10.6	9.6	8.6	6.6				111
117						9	8.1	7.1	5.2				117
123						7.6	6.7	5.9					123
129							5.3	4.8					129
135							4.2						135

TAB 131329


T 236 ft
T 221 ft
T 204 ft
T 187 ft
T 170 ft
T 153 ft
T 136 ft
T 119 ft
T 102 ft
T 85 ft
T 68 ft
T 51 ft
82°
260 ft
0
220 ft
US1117.01

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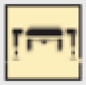
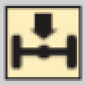
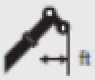
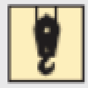
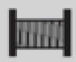
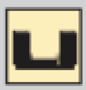
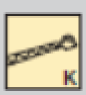
Description of symbols
Explication des symboles

General symbols
Symboles généraux

	Outriggers Calage		Driving speed Vitesse de translation
	Axle Essieu		Gear Vitesse
	Radius Portée		Hookblock / Capacity Moufle à crochet / Capacité de charge
	Boom length Longueur de la flèche		Hoist gear Treuil de levage
	Boom position Position de la flèche		Crane carrier Châssis porteur
	Counterweight Contrepoids		Crane superstructure Partie tournante de la grue
	Tyres Pneumatiques	85%	Standard Norme
	Slewing gear / Working area 360° Mécanisme d'orientation / Plage de travail 360°		Gradability Aptitude à gravir les pentes

Crane specific symbols
Symboles spécifiques à la grue

	Telescopic boom Flèche télescopique		Fixed lattice jib Fléchette fixe
	Swing away jib Fléchette pliante		Luffing lattice jib Fléchette à volée variable
	Hydraulic swing away jib Fléchette pliante hydraulique		

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