# DESIGN DECISIONS FOR A BUILDABLE PREFABRICATED MODULAR HIGH-RISE STRUCTURE WITH CUSTOMIZED GEOMETRY: A CASE FOR HONOLULU, HI

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# ABSTRACT

The current status of high-rise buildings is dependent on generating the maximum profit for developers. This is limiting design freedom in high-rise structures and creating cities of extruded boxes as a result. Therefore, high-rise buildings are conforming to economic feasibility which excludes customizations. While prefabricated modules are typically used in low quality low rise structures with rigid orthogonal geometries, they have the ability to produce high quality high-rise structures that have customized forms enabled by mass customization strategies that also produce more economically feasible solutions compared to conventional construction. Designers and developers need a system that can assist them in the important decisions that must be made to construct a prefabricated modular high-rise building with customized geometrical forms that retains economic feasibility. This research develops a procedure of important decisions that can be followed from start to finish that enable a prefabricated modular building to be constructed as a high rise with a customized geometry. This is then implemented to a case in Honolulu,HI to generate a prefabricated modular high-rise building with a customized geometry that allows an ‘apples-to-apples’ comparison to be made with a conventionally constructed high-rise building with a customized geometry. Furthermore, the economic feasibility is accessed by demonstrating the financial implications that contribute to the overall cost savings.

# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# CHAPTER 1. INTRODUCTION

The ability to have design freedom in high-rise buildings is a current problem faced in the construction industry. Developers are trying to squeeze the most profit possible out of every structure and that in return is creating cities composed of extruded boxes. This is because developers want to maximize square footage for highest return value, as well as sacrificing design aesthetics in favor of greater profits. The current status of high-rise buildings is therefore dependent on generating the most revenue.

This is the case with current conventionally constructed high-rise structures though, and there have been many innovations that can help this situation. While prefabricated modular construction is relatively new in the high-rise development industry, it has the ability to address the financial feasibility issue due to the speed of the construction schedule. Modular construction is basically a construction method where individual modules are fabricated at an off-site facility, transported to the site, and then assembled to compose a larger structure. Modules can be almost fully completed off site with rooms, kitchens, and bathrooms, so there is minimal site work to be completed. This time savings translates directly into financial savings.

Prefabricated modules are thought by most to be made low quality for low rise buildings, but recent developments in technology afford them the ability to be of high-quality for high rise buildings. Prefabricated modules are also restricted to rigid orthogonal boxes, but with the help of recent technological developments of CAD/CAM software’s, mass customization techniques can aid in transforming prefabricated modules into customized geometrical forms that retain economic feasibility. Adding to this, modularity is one of the key enablers of mass customization. Mass customization is essentially achieving product variety at the same cost as mass production in the past, balancing cost and customization. This can be achieved in a variety of different ways and has many degrees to choose from to produce variable levels of cost and customization.

Designers and developers are in need of a method of design decisions or a process that demonstrates the important decisions that must be made in order to construct a prefabricated modular high-rise with a customized geometry while also showing the financial implications that prove the economic feasibility of this system. This research aims to show this process in a way that is usable for future designers and developers. It will be established further by providing an example of how this can be done for a case in Honolulu, Hawaiʻi. The purpose of this is to equip designers and developers with a decision making methodology that can offer designers more freedom and developers more profit. This will in return help transform the skylines of the future from extruded boxes into more dynamic geometry's.

# CHAPTER 2. PROBLEM DISCOVERY

By looking around and examining cities around the world there is a commonality that is present among almost of them. It is that most of the structures are boxes extruded from the ground, especially in high rise buildings. This is the starting point in identifying the problem for this research. Current practice to offset economic feasibility is to sacrifice design and extrude a box. One of the main reasons that there are so many box shaped high-rises is therefore, due to the economic constraints placed on them. This ties into the next aspect of the problem that buildings with customized geometrical forms are more expensive to build. The reason they are more expensive to build is because it is cheaper to produce many of the same part rather than many different parts. Thus, high-rise buildings are seen around the world as extruded boxes because they conform to economic feasibility which usually excludes customizations.

So, if economic feasibility is the limiting factor then a system proven to offset the economic feasibility of buildings should be examined. In this case that is a prefabricated modular system. Now that the economic feasibility has been taken into consideration with a prefabricated modular system, a new problem arises, and it is that prefabricated modules are restricted mostly to rigid box forms by many various factors. Therefore if a high-rise were constructed with prefabricated modules, while it may save costs, the same problem as in conventional construction of having the end product be an extruded box is present. Another problem is how to create a high-rise out of prefabricated modules that are mainly used in low rise construction. When people think of prefabricated modules the stigma of a low quality structure is also present, so a problem is how to show that they can achieve a high-quality. This is an important part of the problem discovery because it starts identifying problems that can be examined further to create solutions.

Now, the problem arises in how to break away from the rigid box form of prefabricated modules and create customized geometrical forms while retaining their cost saving abilities. The first problem is to find out how customized geometrical forms can be created with a prefabricated modular system. The second problem is finding out what degree of customization can be created while remaining economical. These points both tie into the family of mass customization. Mass customization is a concept of producing these customized forms for a low price, but the problem is finding the amount of customization that can achieved and how many different parts can be produced.

Thus, the problem started by recognizing that high-rise buildings in cities across the world are mainly extruded box forms. That then translated into finding the next problem of economic feasibility as a limiting factor. While prefabricated modules can help the economic feasibility, the problem is that they are limited to rigid box forms as well. They also are usually used for low rise low quality structures. This moves into the problem of how prefabricated modules can create customized geometrical forms . The problem with the customized forms though is that they can compromise the ability of prefabricated modules to produce economic feasibility. The problem from here is find out how much customization can occur while keeping economic feasibility.

# CHAPTER 3. ADVANTAGES AND DISADVANTAGES

This research study has three main topics:

- Prefabrication
- Modularization
- Mass Customization

These topics will be examined here in order to gain a broader perspective on the current situations involving each of them. The purpose of this chapter is first to identify the barriers that create constraints, problems, limitations, disadvantages, and challenges of each of the main topics. The reason for doing this is to find out areas that this project can improve upon, why these limitations occur, and how these barriers can be avoided, eliminated or innovated. Then, the opportunities of the main topics will be examined that can be pursued further by demonstrating the freedoms, strengths, benefits, advantages, and solutions that these topics have to offer. The reason for this is to find out how the favorable qualities of the topics that can be used in this projects favor to help prove the point of this research study. By finding and identifying the advantages and disadvantages of each of the topics, it will further direct this research by aiding in developing this projects problem statement, research questions and objectives, and hypothesis which leads into the experimentation. It is not the objective of this research to give an in depth analysis of the opportunities and constraints of prefabrication, modularization or mass customization, but rather give a brief overview of these aspects to build upon because there is a plethora of literature already reviewing this.

The format of this chapter will be as follows. First, a question will be proposed. Then, an answer to the question will be given followed by the definition of the main topic. From here the disadvantages will be discussed followed by the advantages.

# PREFABRICATION

### What is the Problem?

Prefabrication methods are currently limited in their form and spatial layout to rectilinear orthogonal boxes.

### Prefabrication

Built from parts that have been made in a factory and can be put together quickly.[1]

### Why use prefabrication for high-rise buildings?

High-rise buildings using prefabricated construction systems can be used to achieve greater design flexibility in this type of structure while also reducing the overall construction costs for greater economic feasibility.

### High-Rise

A building with an occupied floor located more than 75 feet (22860 mm) above the lowest level of fire department vehicle access.[2]

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[1] Cambridge Dictionary, “Prefabricated definition,” Accessed October 11,2017. http://www.chicagomanualofstyle.org/tools_citationguide/citation-guide-2.html#cg-website.

[2] International Building Code, “Chapter 2 Definitions,” UpCodes, 2015, https://up.codes/viewer/colorado/int_building_code_2015/chapter/2/definitions#2.

## Disadvantages (barriers, constraints, problems, limitations, challenges)

Lack of prefabricated construction starts with economy of scale according to Hong. For the manufacturing to succeed, he states that there needs to be a steady demand for the product.[3] This makes sense logically because if there isn't a constant demand, then the factory will be dormant and someone will have to paying for many various factors such as rent. Time equals money. Economy of scale means that there will be economic benefits from the large scale of production. Therefore, if the factory isn't constantly producing, then economy is lost, and the main reason for prefabrication usually is for economic reasons. Another challenge is the large start up capitol needed for the facility, tools, equipment, hardware and training.[3] Sato states also states that prefabrication hasn't reached its full potential of economy and scale in North America compared to the electronics and auto industries.[4] These industries have a steady demand and therefore, benefit from prefabrication where factories may be running twenty-four hours a day. Currently, only ten percent of homes in North America are built entirely in a factory. This is a disadvantage because it minimizes the economy of scale. The reason they haven't gained an advantage over conventional construction is because aesthetics, comfort, and quality have been sacrificed. Many of them are built with the cheapest available technology, destined for early demise.[4] Hong brings up a valid point about stigma. He said that when people think of prefabricated, the stigma that it carries is of low quality construction that is limited and boxy. This means that the public perception is of a cheap unoriginal manufactured home.[3] Typically in prefabrication, manufacturers focus too narrowly on specific structural approaches which are not adapted to the issues of production and marketing.[5] This is the underlying reason that the

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[3] Fredrick Hong. 2008. "Modern Housing Solutions for Hawaii: Utilizing prefabrication technologies to develop high quality urban housing in Hawaii." Dissertation, University of Hawaii at Mānoa.

[4] Hisako Sato. 2008. "Home within Reach: Designing a New Prefabricated House." Dissertation, University of Hawaii at Mānoa.

[5] Mark Anderson and Peter Anderson. 2007. *Prefab Prototypes: Site-Specific Design for Offsite Construction*. New York: Princeton Architectural Press.

negative stigma is carried with the word prefabrication. Rather than thinking of ways to better market prefabricated items, manufacturers are worried to much about economic structures.

**Advantages (freedoms, strengths, benefits, solutions)**

In terms of the literature collected upon prefabrication, there is a plethora of advantages to using prefabrication compared to the disadvantages. First, all components are able to be incorporated in modules which enables minimal on-site work and it reduces construction time on site. Mass production and mass customization are also a strategy's that can be used depending on the scale.[6] Another benefit is that time can be saved because the construction of the components is done in a factory and multiple construction trades working under the same roof saves time. With weather no longer being an issue, delays are minimized as another time saving factor. Due to the factory being set up for maximum efficiency, less waste is produced and that equates out to saving even more money. This provides a more sustainable solution compared to conventional construction. Looking at the manufacturing process, less skilled labor is needed because each worker is trained to do a specific thing. This means that money can be saved from the cheaper labor costs. On the topic of quality, the factory setting provides a controlled environment where fewer mistakes are made, tolerances are improved, and quality control is more stringent. Quality and structural integrity are increased from this. On the topic of marketing and sales, the ability to know and see what the client is getting in advance, and how much it will cost, is very beneficial because it can help persuade clients to use this method of building.[7] The constant quality level that can be achieved partially comes from the help of CNC machines. The continuing increased demand for quality and shortened construction process is encouraging the use of prefabricated

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[6] Tharaka Gunawardena, Tuan Duc Ngo, Priyan Mendis, and Lu Aye. "Sustainable prefabricated modular buildings." Paper presented at the 5th International Conference on Sustainable Built Environment, Kandy, Sri Lanka, December 2014.

[7] Fredrick Hong. 2008. "Modern Housing Solutions for Hawaii: Utilizing prefabrication technologies to develop high quality urban housing in Hawaii." Dissertation, University of Hawaii at Mānoa.

elements, and today, society is demanding quick economic housing solutions.[8] Today there is a shortage of skilled labor and rising construction costs to go along with it. Prefabrication will provide a possibility for architects to design affordable, flexible, high quality housing.[9] According to Anderson Anderson, producing building components in an efficient work environment with access to special skills and equipment will reduce costs and time expenditures on the site while enhancing quality and consistency. This is an argument similar to Hong's where both state that the work environment is an important factor. Anderson and Anderson further state that prefabrication methods have the ability to enhance efficiency, reduce costs, and also enhance design and construction quality as prime benefits. More strengths include a more stable construction industry, improved safety and working conditions, more investment in research, greater creativity, reduced consumption of energy and materials, and the increased availability of better designed, higher quality environments. Prefabrication also give the opportunity to invest in research, prototype, and test prior to construction because many of these will most likely be produced. Obtaining permits and financing for new construction projects has become so complex, that some form of standardization is essential to reducing costs. Finance, accounting, administrative overhead could be reduced; permitting and code compliance could be streamlined; and increased predictability would lead to lower insurance and contingency costs as well.[10]

## MODULARIZATION

### Why is modular construction used in prefabricated high-rise buildings?

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[8] Gerald Staib, Andreas Dörrhöfer, and Markus Rosenthal. 2008. *Components and Systems: Modular Construction: Design, Structure, New Technologies*. Basel, Switzerland: Birkhauser.

[9] Hisako Sato. 2008. "Home within Reach: Designing a New Prefabricated House." Dissertation, University of Hawaii at Mānoa.

[10] Mark Anderson and Peter Anderson. 2007. *Prefab Prototypes: Site-Specific Design for Offsite Construction*. New York: Princeton Architectural Press.

Modular construction is used when a number of related tasks are to be solved. It compliments prefabrication, giving it the ability to have customizations and create a variety of forms, while retaining all of its positive attributes.

### Modular

Made from a set of separate parts that can be joined together to form a larger object.[11]

### Disadvantages (barriers, constraints, problems, limitations, challenges)

One of the primary constraints limiting modular buildings is the lack of knowledge by architects and the time that needs to be spent upfront in creating the details and drawings.[12] Before modular construction even starts, a disadvantage is that the perception of this type of construction is poor, there are a number of limited factories to meet a demand if needed, and there is a limited amount of success stories that would help promote modular design.[13] According to Knaack et al., the greatest disadvantage is the transportation because the weight and size are limited. If the transportation used is considered oversized, then special permissions are required which increase costs.[18] The module length is typically six to ten meters and the width is limited to four meters generally. The maximum height of a building using this is thus limited by compression resistance and wall bracing.[14] Issues of a module deal with height and width limitations that make high ceilings difficult and expensive.[15] The heavier the module, the more it will cost to transport

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[11] Cambridge Dictionary, “Modular definition,” Accessed October 11,2017. http://dictionary.cambridge.org/us/dictionary/english/modular.

[12] Joseph Schoenborn. 2012. “A case study approach to identifying the constraints and barriers to design innovation for modular construction.” Thesis, Virginia Polytechnic Institute.

[13] Sri Velamati. 2012. “Feasibility, benefits and challenges of modular construction in high rise development in the United States: A developer’s perspective.” Thesis, Massachusetts Institute of Technology.

[14] Robert Lawson. 2007. “Building Design Using Modules.” *The Steel Construction Institute* 348, (September): 1-16.

[15] Peter Cameron and Nadia DiCarlo. 2007. “Piecing together modular: Understanding the benefits and limitations of modular construction methods for multifamily development.” Thesis, Massachusetts Institute of Technology.

and erect as well.[16] This all leads to an increased requirement of transportation logistics, putting stress on an early commitment for engineering and design work.[17] Another major constraint is that there needs to be a modular grid for this to be efficient, therefore restricting architectural considerations.[18] The design of high-rise modular buildings is restricted by structure, fire, and service requirements also.[19] Disadvantages can be seen in over engineering due to lifting requirements and standardization.[16] This includes the temporary bracing that is often needed.[20] Concerns are raised in high rise construction about load bearing capacities and structural integrity. This often leads to extra permanent bracing.[21] Modularization attempts in the past have failed because of lack of variability. This is one constraint imposed by the rigid grid and prefabrication methods.[22] There are limited options to customize due to theses structural and demising elements.[23] The lack of variability also comes from the fact that there is little room for correction after off-site prefabricated pieces arrive, so everything has to fit perfectly. A major disadvantage that occurs before they are stacked on site is that modules can be damaged in transportation and installation, a very large staging ground is required, and there is assembly time required to position and erect the modules.[21]

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[16] R. Lawson, P. Grubb, J. Prewer and P. Trebilcock. 1999. *Modular Construction using Light Steel Framing: An Architect's Guide*. Silwood Park, Ascot: The Steel Construction Institute.

[17] Harvey Bernstein, John Gudel, and Donna Laquidera-Carr. 2011. "Prefabrication and Modularization: Increasing Productivity in the Construction Industry." *Smart Market Report*.

[18] Ulrich Knaack, Sharon Chung-Klatte, and Reinhard Hasselbach. 2012. *Prefabricated Systems: Principles of Construction*. Basel, Switzerland: Birkhauser.

[19] Mark Lawson, Ray Ogden, and Rory Bergin. 2012. "Application of modular construction in high-rise buildings." *Journal of Architectural Engineering* 18, no.2 (June): 148-154.

[20] M. Gorgolewski, P. Grubb, and R. Lawson. 2001. *Modular Construction using Light Steel Framing: Design of Residential Buildings*. Silwood Park, Ascot: The Steel Construction Institute.

[21] Koorosh Gharehbaghi. 2017. "Modular high-rise construction: An alternative building system." *The international journal of the constructed environment* 8, no. 3: 15-23.

[22] Stephen Kieran and James Timberlake. 2004. *Refabricating Architecture: How manufacturing methodologies are poised to transform building construction*. New York: McGraw-Hill.

[23] Sri Velamati. 2012. "Feasibility, benefits and challenges of modular construction in high rise development in the United States: A developer's perspective." Thesis, Massachusetts Institute of Technology.

### Advantages (freedoms, strengths, benefits, solutions)

The general advantages include economy of scale due to the repetition of units, the speed of installation, and improved quality relating to the increased quality control in the factory setting.[24] According to Bernstein et al., advantages to modular prefabrication include: project schedules decreasing, project budgets decreasing, reduced construction waste, a competitive advantage, greater ROI (return on investment) generated, owner/client demand, greener projects, saving money, saving time, competitive market advantage, better quality control, firm demand, safer construction sites, and effective use of labor.[25] Modularization handles three conflicting demands: the customer and variety, competition and efficiency, and technology and complexities. It also has three basic drivers of creation of variety, utilization of similarities, and reduction of complexities.[26] Starting with sustainability benefits, this includes: decreasing construction waste by five to ten percent, delivery vehicles reduced by seventy percent, noise reduced thirty to fifty percent, there's an increased air tightness, a lower embodied energy overall, better acoustical insulation, and a safer work environment with eighty percent less injuries.[24] Gunawardena though, states that construction waste can be reduced by up to fifty two percent.[27] Modular prefab construction is immediately usable after utilities are hooked up. There is also speed, ease of construction, and an un cluttered site.[28] The fact that units can be occupied sooner is what gives this method of construction the ability to generate revenue sooner than in standard construction.[29] In the construction, benefits can be found where there are noise limitations, weather barriers, lack of

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[24] Mark Lawson, Ray Ogden, and Rory Bergin. 2012. "Application of modular construction in high-rise buildings." *Journal of Architectural Engineering* 18, no.2 (June): 148-154.

[25] Harvey Bernstein, John Gudel, and Donna Laquidera-Carr. 2011. "Prefabrication and Modularization: Increasing Productivity in the Construction Industry." *Smart Market Report*.

[26] Thomas Miller and Per Elgard. 1998. *Defining Modules, Modularity, and Modularization: Evolution of the Concept in a Historical Perspective*. Lyngby: IKS.

[27] Tharaka Gunawardena, Tuan Duc Ngo, Priyan Mendis, and Jose Alfano. 2016. "Innovative flexible structural system using prefabricated modules." *Journal of Architectural Engineering* 22, no.4 (May): 1-7.

[28] Ulrich Knaack, Sharon Chung-Klatte, and Reinhard Hasselbach. 2012. *Prefabricated Systems: Principles of Construction*. Basel, Switzerland: Birkhauser.

[29] Ryan Smith and James Timberlake. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

trades at a location, and lack of working space for elements like storage.[30] While modules are thought of as boxes, they can actually be customized for more permanent installations and the façade can be independent, giving it freedom of design as well.[31] Independent self-contained pieces are able to be combined with others to achieve an overall function. Components can be changed to change the functionality. This allows a designer to control the degree of changes by promoting interchangeability, creating flexibility.[32] Advantages of customizations include allowing multiple modules to be placed together for larger spaces and the ability for balconies or other components to be attached. There is also adaptability for future extensions.[33] The ability to create variety by combination and interchange of different modules is a major benefit of the quality of space, but requires some degree of standardization of interfaces. They also contain essential and self-contained functionality making them independent.[34] Modular strategies can be used to increase architectural aspects of design by using alternating setbacks, stepping back and cantilevering, stacking into a pyramid by excluding modules, radially orienting, and separating to provide an atrium.[35] Modular systems offer the most integrated form of construction. Instead of having hundreds of parts put together on site, parts are better fitted in a factory.[36] From this, structural benefits found include better insulation, soundproofing, lower mold issues, and superior structural integrity.[37]

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[30] R. Lawson, P. Grubb, J. Prewer and P. Trebilcock. 1999. *Modular Construction using Light Steel Framing: An Architect's Guide*. Silwood Park, Ascot: The Steel Construction Institute.

[31] Ulrich Knaack, Sharon Chung-Klatte, and Reinhard Hasselbach. 2012. *Prefabricated Systems: Principles of Construction*. Basel, Switzerland: Birkhauser.

[32] J. Gershenson, G. Prasad, and Y. Zhang. 2003. "Product modularity: definitions and benefits." *Journal of Engineering Design* 14, no.3: 295-313.

[33] Robert Lawson. 2007. "Building Design Using Modules." *The Steel Construction Institute* 348, (September): 1-16.

[34] Thomas Miller and Per Elgard. 1998. *Defining Modules, Modularity, and Modularization: Evolution of the Concept in a Historical Perspective*. Lyngby: IKS.

[35] Gorgolewski, M, Grubb, P, and Lawson, R. 2001. *Modular Construction using Light Steel Framing: Design of Residential Buildings.* Silwood Park, Ascot: The Steel Construction Institute.

[36] Hisako Sato. 2008. "Home within Reach: Designing a New Prefabricated House." Dissertation, University of Hawaii at Mānoa.

[37] Peter Cameron and Nadia DiCarlo. 2007. "Piecing together modular: Understanding the benefits and limitations of modular construction methods for multifamily development." Thesis, Massachusetts Institute of Technology.

## MASS CUSTOMIZATION

### Why is mass customization applied to modular prefabricated systems?

Mass customization has the ability to offer a multitude of options at a cost similar to mass production, thus making variety economically feasible and expanding design freedom.

### Mass Customization

Meeting the demands of each individual customer, while still being produced with mass production efficiency.[38]

### Disadvantages (barriers, constraints, problems, limitations, challenges)

The biggest issue is balancing standardization and freedom of choice offered. A disadvantage to this strategy can occur when a customer is presented with too many options, where the cost of evaluation can outweigh the increased utility.[39] Too much variety will actually create frustration and backfire and has been documented in cases such as when Nissan offered eighty seven variations of steering wheels. Mikkola points out some main barriers occurred in the categories of management paradigms, operational changes, supply chain management, dealers' roles, labor and organizational changes, and information technology.[40] Providing differentiating products, while maintaining cost and time requirements is therefore one of the biggest struggles with mass customization. There is also the aspect that country-specific regulations are mandating

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[38] Poorang Piroozfar and Frank Piller. 2013. *Mass Customisation and Personalisation in Architecture and Construction*. New York: Routledge.

[39] Tim Crayton. 2004. "The Design Implications of Mass Customisation." *Architectural Design* 71, no. 2: 74-81.

[40] Juliana Mikkola. 2007. "Management of Product Architecture Modularity for Mass Customization: Modeling and Theoretical Considerations." *IEEE Transactions on Engineering Management* 54, no.1: 57-69.

compliance, impeding the ability to offer a product in multiple markets.[41] User satisfaction and have been insufficient so far because it's difficult to configure, manage, and produce a lot of design alternatives for different users.[42] It has also been found that a build to order technique has moved rather slowly. Before embarking on this construction method, one must need to understand the trade-off considerations between levels of customization, lead time, and cost.[43] As a designer, deciding what will be mass customized and what is the desired level of customization allowed is another important factor that determines the aesthetics and price.[41] Looking at the actual customization, the number of varying interfaces is a key issue when designing modules for mass customization because it determines the product variants and the final cost.[44] A challenge to customized apartments is managing the trade-off between increased product variety and efficiency loss due to customization. A challenge to high-rise customized apartments is that a wide range of products contradicts typical developments, challenging the developer. A separate challenge is to make mass customization efficient and harmonious. This ties into the fact that there are technical problems in housing personalization that occur in the entanglement between the design and construction. If the contractors do not usually work on modular buildings, then it may not produce harmonious aesthetics. Market standards have also never been established and the construction industry is not receptive to new ideas.[45] In the actual customizations, geometric customization is rare. There is mostly material and surfaces customizations. A reason for this besides economic feasibility is because most customers don't want to assume design responsibility of their home.[46] This is also partly due to the learning curve of the hardware and

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[41] Fabrizio Salvador, Cipriano Forza, and Manus Rungtusanatham. 2002. "How to mass customize: Product architectures, sourcing configurations." *Business Horizons* 45, no.4: 61-69.

[42] Ahmet Dincer, Gulen Cagdas, and Haken Tong. 2014. "A computational model for mass housing design as a decision support tool." *Procedia Environmental Sciences* 22: 270-279.

[43] James Barlow, Paul Childerhouse, David Gann, Severine Hong-Minh, Moh Naim, and Ritsuko Ozaki. 2003. "Choice and delivery in housebuilding: Lessons from Japan for UK housebuilders." *Building Research & Information* 31, no. 2: 134-145.

[44] Cecilia Rocha, Carlos Formoso and Patricia Tzortzopoulos. 2015. "Adopting Product Modularity in House Building to Support Mass Customisation." *Sustainability* 7, no.5: 4919-4937.

[45] Poorang Piroozfar and Frank Piller. 2013. *Mass Customisation and Personalisation in Architecture and Construction*. New York: Routledge.

[46] Branko Kolarevic. 2015. "From Mass Customisation to Design 'Democratisation'." *Architectural Design* 85, no.6: 48-53.

software, which not all may know.[47] Another problem is that financial risks have roots in the technical abilities. Lenders still prefer to invest in buildings with familiar building methods that have less risk and innovation. On the financial side also, if there aren't enough sub-contractors, they can take advantage of the situation. Lack of competition puts developers in an inferior position when negotiating.[48] A challenge for companies is that in order for firms to sustain in this industry, they would have to keep introducing innovation in the form of unique components because standardized interfaces make imitation easy.[49] A challenge seen for architects is to make politicians feel more comfortable about making long term decisions because of the large upfront costs.[50]

### Advantages (freedoms, strengths, benefits, solutions)

An important benefit of mass customization is that previous barriers including factories, custom machinery, equipment, materiality, lifting devices, and transportation have all been figured out. Building codes have been developed and modified, officials have been taught, and labor forces have been attained and trained. One of the significant technological enablers of the concept of mass customization is the advent of digital design and manufacturing. Now flexible production methods allow for customization on a large scale. Repetitive appearance is not a prerequisite of off-site fabrication anymore either. We can use the multiplicity of form that new methods of fabrication have given rise to in a way to make more for less. Because each module comes to the assembly line ready to be attached, there is higher quality, a reduced number of joints, more scope and features, less time spent, and has a lower cost. The purpose is to achieve higher quality, better features, less time to fabricate, and lower cost. Mass customization can be thought

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[47] Wanda Dye. "Mass Customization in Architecture: Heterogeneity in the Making." Presentation at the 92nd ACSA Annual Meeting, Miami, Florida, March 18-21, 2004.

[48] Shaul Goldklang. 2013. "Mass-Customization in Commercial Real Estate: How the aviation industry can help us create beautiful buildings that add value." Masters thesis, Massachusetts Institute of Technology.

[49] Juliana Mikkola. 2007. "Management of Product Architecture Modularity for Mass Customization: Modeling and Theoretical Considerations." *IEEE Transactions on Engineering Management* 54, no.1: 57-69.

[50] Donald Bates. 2015. "Permanence and Change." *Architectural Design* 85, no.6: 80-85.

of as a way to make more for less. This century, people value choice, individuality, expression, and commercial industries are reacting. Mass customization enables the customer to determine what the options will be by participating in the design process if wanted.[51] Looking at the freedoms afforded by mass customization, the flexible manufacturing technologies reduce the tradeoff between individuality and efficiency. This is enabling economic variety to occur in buildings, enhancing design flexibility, economy of scale, and economy of scope.[52] According to Miller, mass customization is a way for modularity to balance standardization and rationalization with customization and flexibility.[53] Pre-assembly can benefit because it provides clearer lines of responsibility and better control over quality and cost. It has also given the ability to exploit technical processes to create new capital equipment in order to improve quality and productivity. Because of this, management control can tighten creating better coordination of processes.[54] The technology to deliver economically mass customized houses is seen now through parametric design and digital fabrication.[55] Cad-Cam is a method of fabrication that allows complexity to happen within a repetitive process and the affordability of this technology is increasing.[56] Product customization can take place on a common platform, which has different options, or can be based on mixing and matching modules to achieve different product characteristics.[57] Cost savings can then occur through postponement strategies because the customization company can delay final assembly until the demand is placed. Therefore, the main improvement is in product

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[51] Stephen Kieran and James Timberlake. 2004. *Refabricating Architecture: How manufacturing methodologies are poised to transform building construction*. New York: McGraw-Hill.

[52] Poorang Piroozfar and Frank Piller. 2013. *Mass Customisation and Personalisation in Architecture and Construction*. New York: Routledge.

[53] Thomas Miller and Per Elgard. 1998. *Defining Modules, Modularity, and Modularization: Evolution of the Concept in a Historical Perspective*. Lyngby: IKS.

[54] James Barlow, Paul Childerhouse, David Gann, Severine Hong-Minh, Moh Naim, and Ritsuko Ozaki. 2003. “Choice and delivery in housebuilding: Lessons from Japan for UK housebuilders.” *Building Research & Information* 31, no.2: 134-145.

[55] Branko Kolarevic. 2015. “From Mass Customisation to Design ‘Democratisation’.” *Architectural Design* 85, no.6: 48-53.

[56] Wanda Dye. “Mass Customization in Architecture: Heterogeneity in the Making.” Presentation at the 92nd ACSA Annual Meeting, Miami, Florida, March 18-21, 2004.

[57] Juliana Mikkola and Tage Skjott-Larsen. 2004. “Supply-chain integration: implications for mass customization, modularization and postponement strategies.” *Production Planning & Control* 15, no.4: 352-361.

differentiation, but it also has price, quality, flexibility, delivery and service advantages.[58] Finally, in terms of the market, strict regulations are rapidly deregulating though, giving firms an opportunity to compete in a once dominated market.[59]

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[58] Ashok Kumar. 2005. “Mass Customization: Metrics and Modularity.” *The International Journal of Flexible Manufacturing Systems* 16, no.4: 287-311.

[59] Fabrizio Salvador, Cipriano Forza, and Manus Rungtusanatham. 2002. “How to mass customize: Product architectures, sourcing configurations.” *Business Horizons* 45, no.4: 61-69.

# CHAPTER 4. PROBLEM STATEMENT

## Statement

Modular prefabricated designs are restricted spatially and formally to rigid boxes in high-rise buildings, and buildings with customized forms lead to structures that are more complex and expensive. This project will challenge these facts and demonstrate that by following a prefabricated modular design methodology, a customized geometrical form can be created while becoming more economically feasible.

## Explanation

There are two problems that this research is looking at that are interrelated. The first is that modular prefabricated designs are restricted spatially and formally to rigid boxes in high-rise buildings. The second is that buildings with customized forms are more complex and expensive. Therefore, while a prefabricated modular system can save on the overall building cost, it is generally an orthogonal box structure, and when a customized geometry is desired, the overall building price increases.

This project aims to challenge these two points by showing that a prefabricated modular design can break away from the rigid box form with a customized geometrical form and that by using the advantages of a prefabricated modular system and mass customization it will reduce the buildings price and make customized forms buildable (economically and structurally feasible).

# CHAPTER 5. RESEARCH QUESTIONS

The research questions proposed here are demonstrating what this project will be investigating.

- Can a prefabricated modular construction system be used to construct high-rise structures?
- Can a prefabricated modular construction system break away from the rigid orthogonal rectangular form?
- Can a prefabricated module be used for high-quality structures?
- Is a prefabricated modular system feasible in Hawai‘i?
- Can customized geometrical forms become economically feasible?
- What is the extent of the customization that can occur that meets the developers desire for profit and the clients desire for variation?
- What are the important steps involved in constructing a prefabricated modular high-rise structure with customized geometry?
- If a prefabricated modular construction system was used in place of a conventional construction system for a high-rise building with a customized form, can the buildings properties and qualities be retained? How would it affect the overall cost?

# CHAPTER 6. RESEARCH OBJECTIVES

The research objectives explained here are defining the intent of this research, state what the success would look like, and explain the solution. Here, the aims and objectives of this project are demonstrated to explain the research aspirations and what is hoped to be achieved along with the desired goals, outcomes, what is to be accomplished, and how it will be achieved.

## Aims

- To show that prefabricated modular structures can be used for high-rise buildings.
- To allow greater design freedom to occur in a prefabricated modular system.
- To create a method of design decisions that can be utilized for the development of a prefabricated modular high-rise building that has a customized geometry.
- To show that a customized geometrical from can be created with prefabricated modules reducing the price of the structure relative to conventional construction.

## Objectives

- This project will prove prefabricated modular systems can be used for high-rise structures through the use of case study examples.

- Greater design freedom will be achieved in a prefabricated modular system by decomposing a unit into components that can be mass produced and mass customized and attached to make large units that have customization.
- This project will prove prefabricated modules can achieve high-quality through the use of case studies at the projects location.

- This project will show that it is feasible to use a prefabricated modular system in Hawaiʻi by demonstrating the steps involved such as identifying the manufacturing location, shipping method, allowable dimensions, staging area, site, and constraints.

- Finding the customization sweet spot that balances the amount of customization and cost of customization so that the client receives satisfactory variation for a reasonable price and the developer receives profit.

- This project will demonstrate the important steps involved in constructing a prefabricated modular high-rise structure with customized geometry by developing a design methodology that can be followed by future designers and will be implemented into this project as an example.

- This project will show that a high-rise high-quality building with a customized geometry can be constructed more economically with a prefabricated modular system rather than a conventional system, by conducting an experiment that reconstructs an existing building using the proposed methodology enabling an ‘apples-to-apples’ comparison to prove that the overall properties and qualities can be retained while reducing the overall cost.

# CHAPTER 7. HYPOTHESIS

A hypothesis, otherwise known as a theory, is a proposed explanation made on the basis of the initial evidence gathered as a starting point for more investigation. The hypothesis is also seen as a testable solution to a problem found. Once the question to investigate is identified and current information about the topic is examined, an educated guess, prediction, or hypothesis is formulated that is tested and later determined to be correct or incorrect. The hypothesis is essentially a proposition for further investigation.

## Hypothesis

If a conventionally constructed high quality high-rise building with a customized form is reconstructed with a prefabricated modular system, then the overall qualities and properties can be retained while the reducing the buildings price.

## Explanation

Further explaining the hypothesis, conventional construction referred to is the typical site built concrete structures that are constructed using in situ (cast-in-place) methods. When high-quality is referred to, it means luxurious, and that not only are the highest quality materials used, but also that the construction grade is also with tight connections and high tolerances. It is meant that there will be high-standards all around. Customized forms mentioned in the hypothesis is referring to geometries that are modified or irregular and do not conform to standard rigid dimensions. When the hypothesis states that the overall qualities and properties will be retained it means that the program, spaces, dimensions, etc., will not change. This is to prove that the overall price reduction occurs as a result of using the prefabricated modular system alone and not because of modifications or compromises made elsewhere.

In testing the hypothesis, the independent variable is the variable changed, and in this case, it is the type of construction system used (prefabricated mass customized modules) and the form generated. The dependent variable is the change that happens due to the independent variable, so here that is the form achieved, the overall time schedule and final cost of the structure. The controlled variable is the Waiea tower and its program, spaces, dimensions, amenities, etc.

# CHAPTER 8. RESEARCH STRATEGY

This research study uses a mixed methods approach of both qualitative and quantitative strategies. It involves using methods best suited to the research problem and gives the researcher freedom to use any of the available methods, techniques, and procedures that are associated with either qualitative or quantitative research. The reason that this method of research was chosen is because every method has its limitations, and different methods can be complimentary. For example, a researcher may look at literature and analyze the pros and cons of certain aspects that their research deals with and then transition into looking at metrics, formulas, and statistics to help carry out an analysis. A distinct advantage of this type of approach is that the researcher can triangulate data. Triangulation of data is common in mixed methods of study that involves using a variety of data, different researchers, multiple perspectives, and multiple methods to investigate a research problem. These methods can occur simultaneously or consecutively.

In this study, qualitative research is used to gain an understanding of underlying reasons and motives. It is meant to uncover common trends related to the major topics. This provides insight into current situations and aids in the setting of the problem, which is used to generate the hypothesis for later quantitative research. In this research, qualitative research is used for these purposes, such as identifying the advantages and disadvantages of major topics, gaining an understanding of the current trends in the main fields of research, and identifying a problem that can be explored in more depth. This then translates into a hypothesis that can be evaluated through quantitative research strategies. Quantitative research is used to collect data, quantify data, measure results, and draw conclusions. After the hypothesis is made, questions and predictions are made that can be later tested and variables investigated are identified. From here data can be collected, an experiment can be conducted, and results can be tested to explain the implications of the findings. In this research, quantitative research is used for these purposes of collecting data, conducting an experiment, and calculating and explaining conclusions.

The methodology for this study begins with qualitative data and merges into quantitative data. The system of methods begins with identifying the advantages and disadvantages of the field of study. It then recognizes the problem and formulates a hypothesis. From here building studies in the form of case studies and precedent studies are made to investigate and observe current conditions and strategies. After this, a strategy or method is created that will be implemented in testing the hypothesis consisting of a fundamental and design methodology. Then, an experiment is conducted that utilizes previous methodologies and that demonstrates a method or series of steps this project uses and can also be used for future researchers. The experiment conducted uses the steps outlines and is a comparison to test the variable to the constant. The purpose is to check if the independent variable positively affected the dependent variable. At this point the data is collected and analyzed so that the results can be explained to demonstrate the findings of this research.

# CHAPTER 9. BUILDING STUDIES

In this chapter, buildings are studied and examined to investigate and observe current conditions and strategies used. This chapter will begin with case studies of innovative structures in relation to the main topics, next it will look at precedent structures relevant to this research, then prefabricated high-quality structures in the same state of the site will be examined, followed by a study of the conventional high-rise structure this project will use for comparison. The case studies and precedent studies look at buildings with innovations relevant to the main topics of prefabricated modular design for high-rise structures with customizations. The intent is to gain knowledge on how certain features such as the height achieved, the module sizes and connections, the amount of modularization, and the customizations and how they were accomplished, so that these aspects can be utilized in this project. The examples in Hawaiʻi next are meant to show the current status of prefabricated modules in the state and how they achieve high-quality design. The purpose is also to help reinforce design decisions with proof of existing built structures. The Waiea tower is then explained to document current conditions of form, program, plan, and features to ensure that an accurate comparison can be performed later in the research.

## CASE STUDY

### Victoria Hall-Wolverhampton

Figure 9.1 - Victoria Hall Entrance. Victoria Hall Wolverhampton. Unilodgers. Accessed March 24, 2018. https://www.unilodgers.com/uk/wolverhampton/victoria-hall-wolverhampton.

Figure 9.2 - Victoria Hall Construction. Pushing the limit of modular design. Miletus Group. Accessed March 24, 2018. http://miletusgroup.com/blog/tag/victoria-hall/.

Figure 9.3 - Completed Victoria Hall structure. Hayes, Jenny. N.d. “Victoria Hall, Wolverhampton and Off-site Modular Construction.” Accessed March 25, 2018. http://ciria.org/buildoffsite/pdf/090506%20BERR%20Off%20Site%20Presentation.pdf

Project name: Victoria Hall

Architect: O'Connell East Architects

Location: Wolverhampton, UK

Description:

At twenty-five stories tall, this student residence was the tallest modular building in the world when it was built. Here, a total of 820 modules were installed over a nine-month period and the total construction time was fifteen months. There are three blocks of eight to twenty-five stories tall. Block A is twenty-five stories high on the Southern side and eighteen stories high on the Northern side. The modules the comprise this building are ground supported on a reinforced concrete slab and rest on a podium. The third, seventh, twelfth, and eighteenth floors have a setback on one side that forms a cantilever to the floors above, which is supported by a steel frame. An important feature of the modules in this configuration is that they have integral corridors that create a watertight envelope for a group of them. The horizontal loads are transferred in-plane by the modules, the vertical loads are resisted by the walls in the modules, and the concrete core provides the overall stability. Each module has a concrete floor cast within 150-millimeter-deep parallel flange channel (PFC) sections, and 60 x 60 millimeter square hollow section posts. It is important to note that larger rectangular hollow sections are used in the lower modules. For the higher levels, 14% of the module weight was steel, while at the lower levels 19% of the module weight was steel. These modules used are 4 meters wide by 8 meters long with a 1.1-meter-wide corridor. The average size of a module was twenty-one square meters, but some went up to thirty-seven square meters. Horizontal ties were provided on the modules at the corners and at intermediate points along their sides. The cladding used on the lower levels was ground supported, but a mixture of insulated render, composite panels, and rain screen panels was used on the upper levels that attached to the external face of the modules. A tower crane with a thirty ton lifting capacity and a twenty-meter radius was used for the installation because the modules were from ten to twenty-five tons. Looking at the main factors in the modules weight, fourteen percent of it was in steel components and fifty-six percent in the concrete floor slab. The average rate of construction was about seven modules per day, but sometimes up to fifteen modules per day. Part of this was an effect of site deliveries, which was about six major deliveries per day excluding the six to twelve modules delivered per day. The concrete core was constructed at the rate of one story every three days. The estimated reduction in time was over fifty weeks, or about forty-five percent of the entire construction period. Looking at the waste amount, a typical construction method produces an average of ten to thirteen percent of the buildings weight in waste, but this building only produced five percent.

Figure 9.4 – Floor plan of Victoria Hall (left) highlighting the main tower, building A (right). Hayes, Jenny. N.d. “Victoria Hall, Wolverhampton and Off-site Modular Construction.” Accessed March 25, 2018. http://ciria.org/buildoffsite/pdf/090506%20BERR%20Off%20Site%20Presentation.pdf

This student accommodation building in Wolverhampton brought an interesting complication to the structural system that allowed it to cantilever modules out of the main building mass. This building has a few recessed floors that create the cantilevers. This creates high loads in the first stud at the base of the cantilever and exceed capacity. With the height of the building and the magnitude of the loads, the building already needed a system of a box section. Additionally, some cold formed sections were treated to achieve capacities of hot formed sections, so an alternative structural solution was sought out. The support system created for the cantilevers in the modules was an independent beam and column arrangement that had continuous columns from the foundation to the underside of the modules above the last recess along with deep steel beams under each cantilever at various levels. The placement of the beams was erected tight to the face of the recessed modules so that the last continuous load bearing stud was efficient. The beams deflection characteristic and elastic shortening of the studs was very different, so when load is applied to the two members, the column takes most of the load while the beam deflects. It is stated that the vertical movement of the stud relates to the elastic shortening only, while beam deflections under the same load are magnitudes larger. Thus, if the unloaded beam is placed close to the stud and pressed tight against it, the amount of load sharing depends on the relative stiffness causing little load to be transferred to the beam. The beams needed to be pre-deflected to the load consistent with the load sharing due to this.

Figure 9.5 - Cantilever diagrams of modules. Hough, Michael. 2013. "World's Tallest Modular Building." Accessed October 30, 2017. http://modularengineer.blogspot.com/2013/06/world-tallest-modular-building_17.html.

Figure 9.6 - Structural Frame supporting cantilever. Hayes, Jenny. N.d. "Victoria Hall, Wolverhampton and Off-site Modular Construction." Accessed March 25, 2018. http://ciria.org/buildoffsite/pdf/090506%20BERR%20Off%20Site%20Presentation.pdf

During construction, a series of flat jacks were used on the beams to introduce deflections and take loads off the structural studs. After the modules were erected, the flat jack was inserted on top of the beam and pushed tight to the underside of the module. Then, a predetermined amount of load was pressurized into the flat jack resulting in axial load in the column and beam system and a reduced load on the modules. This process prevented the overturning of the modules and required enough modules above the flat jacks to resist the uplift forces generated.[60] [61] [62] [63]

Figure 9.7 - Elevation view Victoria Hall. Hayes, Jenny. N.d. “Victoria Hall, Wolverhampton and Off-site Modular Construction.” Accessed March 25, 2018. http://ciria.org/buildoffsite/pdf/090506%20BERR%20Off%20Site%20Presentation.pdf

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[60] Mark Lawson, Ray Ogden, and Chris Goodier. 2014. *Design in Modular Construction*. Boca Raton, Florida: CRC Press.

[61] Mark Lawson, Ray Ogden, and Rory Bergin. 2012. “Application of modular construction in high-rise buildings.” *Journal of Architectural Engineering* 18, no.2 (June): 148-154.

[62] Sri Velamati. 2012. “Feasibility, benefits and challenges of modular construction in high rise development in the United States: A developer’s perspective.” Thesis, Massachusetts Institute of Technology.

[63] Michael Hough. 2013. “World’s Tallest Modular Building.” Accessed October 30, 2017. http://modularengineer.blogspot.com/2013/06/world-tallest-modular-building_17.html.

**Atlantic Yards B2**

Figure 9.8 - The building massing broken into three blocks. Farnsworth, David. “Modular Tall Building Design at Atlantic Yards B2.” Council on Tall Buildings and Urban Habitat Conference Proceedings, Shanghai, China, 2014.

Figure 9.9 - Setting and placing the modules by stacking. Field condition. 2014. “Atlantic Yards B2.” Accessed March 25, 2018. http://fieldcondition.com/blog/2014/4/11/atlantic-yards-b2-april-10-2014.

Figure 9.10 – The B2 building nearing completion. Atler, Lloyd. 2015. “What went wrong: The story behind the Atlantic Yards prefab tower.” Accessed March 25, 2018. https://www.treehugger.com/modular-design/what-went-wrong-story-behind-atlantic-yards-prefab-tower.html.

Project name: B2 Atlantic Yards

Architect: SHOP Architects

Location: 461 Dean Street, Brooklyn, New York

Description:

Atlantic Yards B2 Tower is the tallest prefabricated modular tower in the world at thirty-two stories and three hundred and twenty-two feet tall. In 2011 Forest City commissioned SHOP Architects and Arup Engineers to develop a modular construction system suitable for a building that was designed to be done conventionally with concrete flat slabs. The goal of this project was to design a modular approach that would result in cost savings and improved quality compared to a conventional scheme. This building is part of a larger plan of fifteen affordable housing towers. The developer stated that due to current conditions, it is difficult to make conventional construction work for the goal he was striving for. The massing of the building is broken up into three blocks, which give scale and avoid a monolithic extrusion appearance. The architects used setbacks, cantilevers, and façade differences to help break down the form as well. It is important to note that there is a conventional substructure underneath the modules.

The layout of the building was straight forward with a central double-loaded corridor. The floorplate is divided into modules that could be efficiently fabricated and fit out before arriving to the site. The largest floorplate has 36 modules and the building contains 930 modules. Of all the modules, there are 225 unique types that create 363 units. Studio apartments consisted of one module, one-bedroom apartments of two modules, and two bedroom apartments of three modules. The details and methodologies remain consistent, but each module is constructed to its own design. The elevator core and stairwells were also constructed using modules. Transportation and lifting requirements limited the size and weight of the modules to 15’x50’x10.5’ and 26.5 tons. Module weights ranged from seven tons at the lightest, to twenty-four tons at the heaviest.

Into the construction, the ground floor consists of a lobby and retail spaces conventionally constructed with ninety-foot transfer girder spans over this floor supporting nineteen stories of modules above. The substructure is of reinforced concrete perimeter walls, a base slab, and steel floor framing with slabs on metal decking. The buildings base is constructed with reinforced concrete base slabs and perimeter walls, steel-framed cellar and ground floors, and a steel-framed plinth level above the ground floor. This provided a platform to stack modules upon.

Figure 9.11 - Conventionally constructed steel podium. Forest City Ratner, “Building 2 at Atlantic Yards.” Presentation to the public, November 9, 2012.

Figure 9.12 - Typical floor plan. Farnsworth, David. “Modular Tall Building Design at Atlantic Yards B2.” Council on Tall Buildings and Urban Habitat Conference Proceedings, Shanghai, China, 2014.

A fully welded steel-framed chassis is the basic building block of this modular system. The side of the module acts as a welded vierendeel truss spanning between corner columns. This occurs where the module columns below carry the weight of all modules above. Columns in the modules are typically 6” square tubes with a plate thickness varying up to 1.5” as built-up sections at the base of the tower. The bottom chords of the module are typically an 8”x4” structural tube, the top chord is usually a 4”x4” structural tube, and the intermediate posts are 2” x 3”. At places with walls along the sides of the module, thin-gage diagonal strapping is utilized to minimize deflections and the steel weight. Into the modular floor system, it consists of 6”x3” tube steel purlins supporting 2” metal decking that runs parallel to the long side of the module. A 3/4” layer of cementitious particle board acts as the subfloor, followed by a 1/4” layer of resilient acoustic padding and floor finishes to complete the floor buildup. Into the modular roofing system, each module has its own roof of 1” metal deck supported by 3” tube steel roof purlins. Two layers of 5/8” gypsum wall board are hung from the underside of the ceiling purlins to complete the ceiling assembly which provides membrane fire protection to the floor and ceiling members. The total floor to ceiling sandwich for the modular system is 1’5” thick, and with 9’11” floor-to-floor spacing, that provides 8’6” clear ceiling heights. With no concrete in the modules, the system is light in comparison to conventional flat-slab construction at about sixty five percent of its weight. The huge reduction in superstructure weight is monetized as savings in foundation quantities and transfer steel.

Figure 9.13 - Base chassis of module. Farnsworth, David. “Modular Tall Building Design at Atlantic Yards B2.” Council on Tall Buildings and Urban Habitat Conference Proceedings, Shanghai, China, 2014.

The modules carry their vertical loads to the ground and the roofs of the modules act as a lateral diaphragm, carrying wind and seismic loads across floor plates to a series of braced frames. Two braced frames were placed in each primary direction and were tied together at the roof with a hat-truss. Therefore, lateral loads are carried wholly by the conventional braced frames. The decision to use the module roof as the diaphragm helped accomplish the goal of finishing as much of the apartment in the factory as possible and turned out to be a key of the phasing puzzle. The building has a set of two 100-ton tuned mass dampers (TMD’s) that limit acceleration under wind.

Originally, the building was designed with modules placed around a reinforced concrete core, but the steel solution was chosen to minimize the number of trades on site, ensure compatible tolerances between all systems, and due to long term deflection of a concrete core the connections between systems would be complicated. The only steel option enabled a single subcontractor to be responsible for the module fabrication as well as the steel braced frame erection.

Figure 9.14 - Internal structural system (left) and structure with chassis modules (right). Forest City Ratner, “Building 2 at Atlantic Yards.” Presentation to the public, November 9, 2012.

Figure 9.15 - Construction process from start to finish. Provost, James. 2018. “Modular construction.” Accessed March 25, 2018. https://jamesprovost.com/portfolio/modular-construction.

Looking into the fit-out of the modules, the chassis is constructed first and then shipped to be fit-out. In the factory, a group of modules are placed adjacent to each other in a geometry matching that of positioning on site so that workers can align finishes and systems. Pedestals in the factory that the modules are set on match the geometry of the jigs and the final setting pins used on site to ensure tolerances. In the fit-out, wall panels and ceiling gypsum board is placed first. Light-gage stud framed wall panels are placed between posts that support two layers of 5/8” gypsum wallboard on each side of the module. Once the perimeter walls and ceilings are completed, pre-assembled bathroom and kitchen pods are inserted into the module that are completed with tiling, fixtures, plumbing, wiring, etc. The MEP system is arranged so that vertical risers service each stack of modules including all sanitary drain piping, vent piping, hot and cold potable water, and heating water. This is located as part of the bathroom pod so the riser backs up to the central corridor, allowing it to be accessed for site connections from one area in the module that won’t be finished to completion in the factory. The MEP systems branch out from the riser at the bathroom pod to service the rest of the apartment. The next step was the installation of the packaged terminal air conditioning unit that is installed in the façade. Prefabricated curtain wall panels are installed on the modules after this, which have a compression gasket fitted around the perimeter and is compressed to form a seal when sat next to and on top of adjacent modules. After the finishes are completed, the modules are weatherproofed with an EPDM roof membrane and a perimeter Tyvek vapor barrier before being shipped to the site.[64] [65]

Figure 9.16 - Internal fit-out. Farnsworth, David. “Modular Tall Building Design at Atlantic Yards B2.” Council on Tall Buildings and Urban Habitat Conference Proceedings, Shanghai, China, 2014.

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[64] David Farnsworth. “Modular Tall Building Design at Atlantic Yards B2.” Council on Tall Buildings and Urban Habitat Conference Proceedings, Shanghai, China, 2014.

[65] Sri Velamati. 2012. “Feasibility, benefits and challenges of modular construction in high rise development in the United States: A developer’s perspective.” Thesis, Massachusetts Institute of Technology.

Figure 9.17 - Process of turning chassis into completed module. Forest City Ratner, “Building 2 at Atlantic Yards.” Presentation to the public, November 9, 2012.

Figure 9.18 - Process of internal fit-out and exterior enclosure (left to right). Evans, Lauren. 2013. “Photos: How to build an atlantic yards skyscraper in a brooklyn warehouse.” Accessed March 25, 2018. http://gothamist.com/2013/12/06/modular_housing_is_coming_to_atlant.php#photo-8.

**Moho**

Figure 9.19 - Moho building. ShredKM. “Moho Project Information.” Accessed November 1, 2017. http://www.shedkm.co.uk/work/moho/.

Figure 9.20 - Moho Building Plan. Skyscrapercity. N.d. “Moho.” Accessed March 25, 2018. http://www.skyscrapercity.com/showthread.php?t=1927466.

Project name: Moho

Architect: ShedKM

Location: Castlefield, Manchester

Description:

This is a seven-story apartment building that consists of six residential floors over one commercial and retail floor and two levels of basement parking. It contains one hundred and two apartments that are of one and two bedroom units. Each apartment has an enclosed balcony, kitchen, and bathroom. Most of the apartments are designed around a central kitchen and bathroom with bedrooms and living area on either side. An important part of the design is that the units are placed parallel rather than perpendicular to the façade. The reason for rotating units ninety degrees was to maximize window frontage and allow for the base module to be extended. The modules were manufactured with fully glazed side walls from floor to ceiling. The modules have one open side and use the corner post structural system. The innovative part of this structure is that the balconies and access walkways were constructed first with a conventional steel frame in order to provide stability and also takes the horizontal loads from the modules. Then the modules were attached to the steel framework. After this, the external balcony attachments were connected to the modules. In other words, the walkways are supported by a self-standing steel structure, modules are attached to this, and then balconies are attached to corner posts on the modules other side. This is what allowed modules to have an open side that added to the openness and extended the space into the enclosed balcony.

Figure 9.21 - Module supported by steel framework (left), balcony external attachment to module (right). Lawson, Robert. 2007. “Building Design Using Modules.” *The Steel Construction Institute* 348, (September): 1-16.

The apartment sizes ranged from thirty-eight to fifty-four square meters excluding the balconies, where two modules comprised the two bedroom units. These modules had one-hundred-millimeter square hollow sections as intermediate posts and exterior dimensions of 4.1 x 9.1 meters. The largest apartment with a 12.1-meter length was created by extending the basic module using a second bedroom module. In this building, vertical loads are transferred through corner and intermediate posts to the transfer structure. Pods were inserted into the modules such as kitchen pods, bathroom pods, and even dining room pods that helped extend the space out into the balcony. The external structure of the balconies and walkways are connected to the corners of the modules for adequate load transfer. They also utilize intermediate diagonal tension members tied the corner posts at places that will not cause an obstruction. In construction, the modules took five weeks to install and six were installed per day. This equated out to a total construction time of seventeen months, cutting seven months of time out in compared to traditional methods.[66] [67]

Figure 9.22 - Exploded modular unit (left) and process of assebly (right). Urbansplash. N.d. “Moho in Manchester.” Accessed March 25, 2018. urbansplash.co.uk.

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[66] Mark Lawson, Ray Ogden, and Chris Goodier. 2014. *Design in Modular Construction*. Boca Raton, Florida: CRC Press.

[67] ShredKM. “Moho Project Information.” Accessed November 1, 2017. http://www.shedkm.co.uk/work/moho/.

Figure 9.23 – Typical unit interior. O'Callaghan, Bren. 2004. "My first module." Accessed March 25, 2018. http://www.bbc.co.uk/liverpool/culture/2004/06/archweek/moho/index.shtml.

Figure 9.24 - Typical unit floor plan. Taylor Bond. 2015. "Ellesmere Street, Manchester City Centre, M15, Manchester." Accessed March 25, 2018. http://taylorbond.co.uk/detaillt.php?unid=626.

# PRECEDENT STUDY

## Victoria Hall-Wembley

Figure 9.25 - Completed Victoria Hall student residence. Archiexpo. N.d. “Victoria Hall Student Residence Wembley.” Accessed March 25, 2018. http://www.archiexpo.com/prod/alucobond/product-1616-1424533.html.

Figure 9.26 - Modules stacked around in-situ concrete core. Brogan Group. 2010. “Access expands at Victoria Hall.” Accessed March 25, 2018. https://www.brogangroup.com/news/access-expands-at-victoria-hall/bp494/.

Project name: Victoria Hall

Architect: O’Connell East Architects

Location: Wembley, UK

Description:

This is a modular student housing building that is nineteen stories high and is split into three wings that wrap around a central spiral shaped tower. The decision to use modular construction was because the contractor wanted to accelerate the completion time. With views of Wembley stadium, the building has 435 student rooms and varies it height in response of its surrounding buildings and amenities. Prominent features of this structure are the double height entrance and two landscaped areas for gathering in ample outdoor space. Another important part of this project is concrete core and circular concrete floor plans that have North, East and West wings extending from it. The West wing is seventeen stories of modules stacked on top of a two-story concrete podium, while the North and East wings are comprised of four and seven story stacked modules respectively. This project is a first in terms of the size of the modules that were manufactured and installed. These 52-foot-long by 12.5-foot-wide modules achieved a solution to creating a two-room module with a twin corridor in the modular system which also minimized site work. C section steel frames with a top hat section created a rigid form to enable the use of these large modules. The modules in this building were installed over a fifteen-week period with the construction of the core occurring simultaneously. The architect noted that each wing had ten modules per floor which led to three floors being installed per week. Construction started in July 2010 and ended August 2011. Of the modules, ten study bedrooms of 2.7 meters in width and two kitchens of 3.8 meters in width comprised each building wing. These modules were delivered fully insulated and watertight as well. To reduce acoustic transmission and to allow for tolerances, a resilient strip was placed between the modules. A maximum tolerance of five millimeters between modules was accomplished by resetting positions on each floor. On the exterior, this building cladding is a lightweight rain screen that is attached to horizontal rails on the modules.[68] [69]

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[68] Mark Lawson, Ray Ogden, and Chris Goodier. 2014. *Design in Modular Construction*. Boca Raton, Florida: CRC Press.

[69] Sri Velamati. 2012. “Feasibility, benefits and challenges of modular construction in high rise development in the United States: A developer’s perspective.” Thesis, Massachusetts Institute of Technology.

**Paragon**

Figure 9.27 - Paragon apartment complex. Caledonian. 2018. “Paragon, Brentford.” Accessed March 25, 2018. http://www.caledonianmodular.com/portfolio/paragon-brentford/.

Project name: Paragon

Architect: Carey Jones

Location: Brentford, West London, UK

Description:

This building was the first high-rise use of modular construction and is a 17-story student residence. The project chose to use a modular system because it need a short construction time and the developer wanted to minimize logistical problems on site. There are also 4, 5, 7, and 12 story buildings that are part of the project. The height was achieved by using a concrete core to provide the overall stability and the modules resisted vertical loads through their corner posts.

The corner posts were square hollow sections and while the thickness of the posts increased toward the bottom, the external dimensions stayed the same allowing them to remain hidden inside the light steel framed walls. The modules were attached to the concrete core through steel angles fixed to channels cast into the concrete. There is a range of modules used in this project including ones with open sides and integral corridors. In the 17-story building, 413 modules were used that created 600 student rooms, 114 studio rooms, 44 one-bedroom and 63 two-bedroom worker apartments. The modules are one and two-bedroom units and a typical module size was 12 x 2.8 meters, but some were up to 4.2 meters wide. These had floor level edge beams of 200 x 90 mm PFC's and ceiling level of 140 x 70mm. Using corner posts, combined floor and ceiling depth of 400mm, and light steel walls, sound reduction was achieved, as well as adequate fireproofing. In this project, the one and two bedroom apartments used two or three modules that were 35 or 55 square meters and the longer modules incorporated corridors, thus speeding up the construction time also. These modules were fully modular, fit out with windows, doors, finishes, fixtures, and MEP. At the time of construction this was the tallest modular building in the world. It took twenty-two months to complete, saving twelve months from if it were done with conventional construction. This gave benefits of early occupation and therefore, revenue generation for the developer.[70] [71]

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[70] Mark Lawson, Ray Ogden, and Chris Goodier. 2014. *Design in Modular Construction*. Boca Raton, Florida: CRC Press.

[71] Sri Velamati. 2012. "Feasibility, benefits and challenges of modular construction in high rise development in the United States: A developer's perspective." Thesis, Massachusetts Institute of Technology.

### Phoenix Court

Figure 9.28 - Exterior façade of Phoenix Court. Hotel Room Search. 2016. “Phoenix Court Photos.” Accessed March 25, 2018. http://www.hotelroomsearch.net/united-kingdom/phoenix-court.

Figure 9.29 - Floor plan of Phoenix Court. Lawson, Mark, Ogden, Ray, and Goodier, Chris. 2014. *Design in Modular Construction.* Boca Raton, Florida: CRC Press.

Project name: Phoenix court

Architect: Stride Treglown

Location: Bristol, UK

Description:

This is an eleven story modular student housing building that has a wide range of configurations, from studios to six bedroom units. Studios and most of the units were brought to the site equipped with furniture, fixtures, equipment, and kitchens. They also had air and water tight units as well as insulation contained inside the modules before delivery. This is the first building to incorporate cold rolled steel modules at eleven stories high. These modules were combined with concrete or steel frames to increase their flexibility in the floor plan. These modules sit on top of a two story steel framed podium or platform structure to provide open space for retail or commercial use as well as parking. This is known as an adaptive modular technology. The modules are arranged on a twenty to twenty-six-foot grid and have support beams that line up with the walls. The four hundred bedroom modules are nine feet wide and about one-hundred of them are combined to form larger spaces. Stability is provided here by four braced steel cores, and a maximum of seven modules can fit between each core in order to limit the forces in the connections. These also have double loaded corridors. On the exterior, the building used a lightweight system of a rain screen that has its weight supported by the modules themselves.[72] [73]

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[72] Mark Lawson, Ray Ogden, and Rory Bergin. 2012. "Application of modular construction in high-rise buildings." *Journal of Architectural Engineering* 18, no.2 (June): 148-154.

[73] Sri Velamati. 2012. "Feasibility, benefits and challenges of modular construction in high rise development in the United States: A developer's perspective." Thesis, Massachusetts Institute of Technology.

## HAWAI‘I PREFABRICATED PRECEDENT STUDY

### Energy Positive Portable Classroom

Figure 9.30 - Energy Positive Portable Classroom. Anderson Anderson Architecture. “Energy Positive Portable Classroom.” Accessed February 18, 2018. http://andersonanderson.com/2013/02/01/energy-positive-portable-classroom/.

Location: Ewa Beach, Hawai‘i

Project size: 960 sqft

Building type: Education-School classroom

Company: Anderson Anderson Architecture

Affiliate: Blazer Industries INC and Hawai‘i Modular Space

Description:

This modular structure that was prefabricated off-site is a classroom meant to serve as a new model to replace the current state inventory of portable classrooms. Most of the fit out was completed in Oregon prior to transportation to Hawaiʻi. It was transported by a sea barge. The manufacturing, delivery process, and materials were selected for minimum environmental impact. The building is composed of three prefabricated modules which are connected on site. This reduces the initial cost as well as enabling future relocation or reuse minimizing waste. The modules are constructed of a steel frame chassis and a steel-rigid foam sandwich panel composes the floor and roof system. This minimizes materials, maximizes insulation, and deters pests. A double-wall metal cladding is used with metal roofing that sits below a three inch ventilation space and solar panels. Glulam beams combined with steel trusses constitute the primary structural forces. High-quality interior surfaces were added to the modules for good air quality and interior aesthetics. All of the same high quality glazing and skins used in conventional construction are able to be employed in this project as well. This building was able to prove that factory built modular buildings can be equal to or superior than traditional buildings in quality, while also minimizing energy and material waste[74] [75]

### Project Frog

Figure 9.31 - Llima Intermediate School Frog Building. Project Frog. “Llima Intermediate School.” Accessed February 18, 2018. http://projectfrog.com/projects/ilima-intermediate-School.

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[74] Modular Building Institute. n.d. “Energy Positive Portable Classroom.” Accessed February 18, 2018. http://modular.org/Awards/AwardEntryDetail.aspx?awardentryid=1221.

[75] ArchDaily. 2014. "Energy Positive Relocatable Classroom / Anderson Anderson Architecture." Accessed February 18, 2018. https://www.archdaily.com/550780/energy-positive-relocatable-classroom-anderson-anderson-architecture.

Figure 9.32 - Construction of Llima Frog Building. S&Z Contractors. “Ewa Beach Ilima Intermediate School.” Accessed February 18, 2018. http://www.szcontractors.com/moreinfo.html.

Location: Llima Intermediate School in Ewa Beach, Hawaiʻi

Project size: 1200 sqft

Building type: Education-School classroom

Company: Project Frog

Affiliate: MKThink

Description:

Project Frog is a company in California specializing in prefabricated structures. Their principles in developing these buildings is to reduce construction schedules up to 50%, the main driver for prefabricated structures, create flexible spaces that can be modified based on location, and simplicity for ease of construction and permitting. The product is delivered to the site in the form of an easy to erect kit. Project Frog worked with the Hawaiʻi Natural Energy Institution and a test site located in Ewa Beach, Oahu is looked at here. The freestanding structure is a high performing classroom with overhangs, clearstory windows, low-e glazing, and a state of the art monitoring systems. This classroom is composed of a single prefabricated module made of steel and timber and was constructed on site. It took four weeks to install the kit once on site showing the rapid construction that accompanies prefabrication methods.[76] [77]

### Ko’olani Luxury Sales Office

Figure 9.33 - Ko’olani sales office. Hawai‘i Modular Space. “Ko’olani Luxury Sales Office.” Accessed February 18, 2018. http://www.hawaiimodular.com/koolani.html.

Location: Kapolei, Hawai‘i

Project size: 3660 sqft

Building type: Commercial-Luxury Sales Office

Company: Hawai‘i Modular Space

Affiliate: Mitchell Freedland Design

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[76] Project Frog. 2018. “Component Buildings Offer.” Accessed February 18, 2018. http://projectfrog.com/.

[77] Project Frog. 2018. “Llima Intermediate School.” Accessed February 18, 2018. http://projectfrog.com/projects/ilima-intermediate-school.

Description:

This building is a sales office for luxury condominiums at Ko’olani. Ko’olani is a master planned vacation and residential community. The reason a prefabricated modular solution was chosen is because the developers needed a luxury sales office immediately and prefabricated modular has the capability of both of these needs. The speed and quality were both able to be achieved with prefabricated modular construction. In this project, four modular units are connected and transformed into luxury office space and it met the time schedule, budget, and aesthetics that the client wanted. The structure had to reflect the quality and style of the conventionally constructed condominium also and this project demonstrated that on the exterior and interior. This customized modular building proved that it is able to achieve high-end needs with modular structures that was not available previously. Besides the typical sales office spaces, this building took prefabrication further and also included a model kitchen and bathroom featured in the condominiums. Rather than the typical prefab office, this one exceeded past examples.[78]

### Hawai‘i Modular Space Corporate Office

Figure 9.34 - Hawai‘i Modular Space Office. Hawaii Modular Space. n.d. “Hawaii Modular Space Corporate Office.” Accessed February 18, 2018. http://www.hawaiimodular.com/hms.html.

Location: Kapolei, Hawai‘i

Project size: 3342 sqft

Building type: Commercial-Corporate Office

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[78] Hawaii Modular Space. n.d. “Ko’olani Luxury Sales Office.” Accessed February 18, 2018. http://www.hawaiimodular.com/koolani.html.

Company: Hawai‘i Modular Space

Description:

The prefabricated modular structure here houses the Hawai‘i Modular Space Corporate Office. It is a unique innovative structure that combines site-built construction with modular prefabricated construction. The building is composed of four modules and was constructed on site in four days. The central module demonstrates that spaces of modules are not constrained to small low spaces and is 14’ wide x 53’ long and features a 14’ tall ceiling. The marble floors also show that finishes can be of high quality. Another interesting aspect is that the structure rests at grade and is not a typical lifted frame. It was accomplished by using a site-built pit foundation to effectively lower the profile. The modules then connect to the site-built portion through a structural framing system.[79]

## WAIEA CONDOMINIUM

Figure 9.35 - Waiea from North East street corner (left) Waiea from South East corner (right). WCIT Architecture. 2018. “Waiea at Ward Village.” Accessed January 22, 2018. http://wcitarch.com/waiea/#!.

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[79] Hawaii Modular Space. n.d. “Hawaii Modular Space Corporate Office.” Accessed February 18, 2018. http://www.hawaiimodular.com/hms.html.

Project name: Waiea

Location: 1118 Ala Moana Blvd, Honolulu, Hawaiʻi

Neighborhood: Kaka’ako

Architect: James K. M. Cheng in collaboration with Rob Iopa and WCIT Architecture

Interior: Ingrao Interiors lead by Tony Ingrao

Client: Howard Hughes Corporation

Year Built: 2016

Building price: $417.3 million

Floors: 36

Units: 174

Height: 418 feet

Description:

The Waiea building presents a new level of luxury in Hawaiʻi as the pinnacle of high end living. It is part of the new Ward Village masterplan for Kaka’ako and is located on an existing parking lot. Kaka’ako has physically and socially changed a lot in a short amount of time, so overlapping events and the location it’s in allowed inspiration to be drawn from both time and place. The basis of the design has roots in Hawaiʻian history and cultural context while celebrating past traditions and referencing the surrounding environment. The location of this building once sat in the reefs of Kukuluāeʻo and Kewalo. In Hawaiʻian mythology, a father and son once traveled around the islands teaching fishing techniques, stewardship of the sea, net making, and are have said to have stopped here along their journey. Infused with Hawaiʻian stories and the history of Kaka’ako, the design of the tower also references water, one of the most treasured resources. Waiea is a Hawaiʻian term for “water of life”, and the design honors its life-giving role. Thus, inspiration from water and fishing nets are seen in the sweeping glass façade. Some say that the façade resembles waves, but it also depicts a fishing net draped over the father and son before throwing it.

The site of the Waiea tower is 81, 446 square feet, standing 36 stories high and containing 174 residences. Of the residences, twelve of them are penthouses, and two are grand penthouses. There is a townhome building on the site that is occupied by ten residences also. The porte-cochere entrance is 20 feet high. The structure is all concrete with post-tensioned concrete slabs. The building façade is made of high-performance, double-glazed, low-e coated glass to target LEED certification. A centralized high efficiency air-conditioning and hot water system also help sustainability along with LED lighting. The interior has 9’ 6” ceiling heights for most units, but has a 10’ 6” ceiling height for penthouses and 11’ 6” ceiling heights for grand penthouses. Units feature hardwood and stone flooring, quartz counters, spacious bathrooms, double walk-in closets, European cabinetry, Miele kitchen appliances, gas stoves, and motorized window shades. The core contains four elevators and two staircases.[80] [81] [82] [83] [84] [85]

Figure 9.36 - Interior and exterior view of the Undulating façade glazing. Hawai‘i Life Real Estate Brokers. 2018. “Brand new Waiea grand penthouse.” Accessed March 25, 2018. http://www.hl1.com/waiea-penthouse/.

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[80] Howard Hughes. 2016. “The Waiea Grand Penthouses.” Accessed January 22, 2018. http://waieagrandpenthouse.com/.

[81] Howard Hughes, *Waiea Mini Book: Waiea Ward Village.*

[82] Pacific Building News. 2017. “Howard Hughes sues contractor over alleged construction defects at Honolulu tower.” Accessed January 22, 2018. https://www.bizjournals.com/pacific/news/2017/11/22/howard-hughes-sues-contractor-over-alleged.html.

[83] WCIT Architecture. 2018. “Waiea at Ward Village.” Accessed January 22, 2018. http://wcitarch.com/waiea/#!.

[84] Ward Village. 2018. “Waiea at Ward Village.” Accessed January 22, 2018. https://www.wardvillage.com/articles/waiea.

[85] Hawaii Living. 2018. “Waiea Condos.” Accessed January 22, 2018. https://www.hawaiiliving.com/oahu/honolulu/metro/waiea-kakaako-condos-for-sale/.

Figure 9.37 - Bathroom and kitchen in units. Howard Hughes, *Waiea Mini Book: Waiea Ward Village.*

Program:

Figure 9.38 - Waiea building section. Building Section. HiCondos. 2018. Accessed January 23, 2018. http://www.hicondos.com/hawaii-Condos/Waiea.asp.

Floor 1: The first floor has retail space used as a restaurant, a concierge and lobby, outdoor seating, mechanical and service spaces, a driveway to the parking garage, and townhomes.

Floor 2-6: The second through the sixth floor contain the parking garage.

Floor 7: The seventh floor is the amenity level. It contains a barbecue space, children's play area, lawn, fitness center, yoga room, active fitness room, locker rooms, sauna, hot tub, infinity pool, poolside cabanas, a bar, quiet lounges, a kitchen, a dining room, a theater, dog park, and a golf simulator.

Floor 8-31: There are 6 units, A through F, on all of these floors.

Figure 9.39 - Floor plans for level 8-31. Waiea High Rise Floorplates. HI Pro Realty. 2018. Accessed January 23, 2018. https://www.hiprorealty.com/-waiea-floor-plans.

Unit A:

This unit has a curved exterior wall so the square footage is an average.

Rooms - 3 bedrooms, 3.5 bathrooms

Interior - ~ 2,750 Sq Ft

Foyer - 214 Sq Ft

Lanai – 142 Sq Ft

Unit B:

A private elevator opens to a foyer.

Rooms - 3 bedrooms, 3.5 bathrooms

Interior - 2,403 Sq Ft

Foyer - 214 Sq Ft

Lanai - 357 Sq Ft

Unit C:

Rooms - 1 bedroom, 2 bathrooms

Interior - 1,138 Sq Ft

Lanai - 74 Sq Ft

Unit D:

Rooms - 2 bedrooms, 2 bathrooms

Interior - 1,468 Sq Ft

Foyer - 68 Sq Ft

Lanai – 167 Sq Ft

Unit E:

This unit has a curved exterior wall so the square footage is an average.

Rooms - 3 bedrooms, 2.5 bathrooms

Interior - ~2000 Sq Ft

Foyer - 140 Sq Ft

Lanai - ~69 Sq Ft

Unit F:

This unit has a curved exterior wall so the square footage is an average.

Rooms - 2 bedrooms, 2.5 bathrooms

Interior - ~1,950 Sq Ft

Floor 32-34: There are 4 penthouse units, A through D, on each floor.

Figure 9.40 - Floor plans for level 32-34. Waiea High Rise Floorplates. HI Pro Realty. 2018. Accessed January 23, 2018. https://www.hiprorealty.com/-waiea-floor-plans.

Penthouse A:

This unit has a curved exterior wall so the square footage is an average.

Rooms – 4 bedrooms, 4.5 bathrooms

Interior - ~4,147 Sq Ft

Foyer - 207 Sq Ft

Lanai - 142 Sq Ft

Penthouse B:

Rooms - 3 bedrooms, 3.5 bathrooms

Interior - 3,033 Sq Ft

Foyer - 244 Sq Ft

Lanai - 363 Sq Ft

Penthouse C:

Rooms - 2 bedrooms, 2.5 bathrooms

Interior - 2,077 Sq Ft

Foyer - 63 Sq Ft

Lanai - 159 Sq Ft

Penthouse D:

This unit has a curved exterior wall so the square footage is an average.

Rooms - 3 bedrooms, 3.5 bathrooms

Interior - ~2,656 Sq Ft

Foyer - 130 Sq Ft

Lanai - ~84 Sqft

Floor 35-36: There is one grand penthouse on each floor. It contains a rooftop infinity pool, outdoor kitchen, and pool house.

Figure 9.41 - Grand Penthouse floor 35. Grand Penthouse Floorplans. Howard Hughes. 2016. Accessed January 23, 2018. http://waieagrandpenthouse.com/.

Grand penthouse floor 35:

Rooms - 6 bedrooms, 6.5 bathrooms

Interior - 8,532 Sq Ft

Lanai - 2,043 Sq Ft

Figure 9.42 - Grand Penthouse floor 36. Grand Penthouse Floorplans. Howard Hughes. 2016. Accessed January 23, 2018. http://waieagrandpenthouse.com/.

Grand penthouse floor 36:

Rooms - 5 bedrooms, 5.5 bathrooms

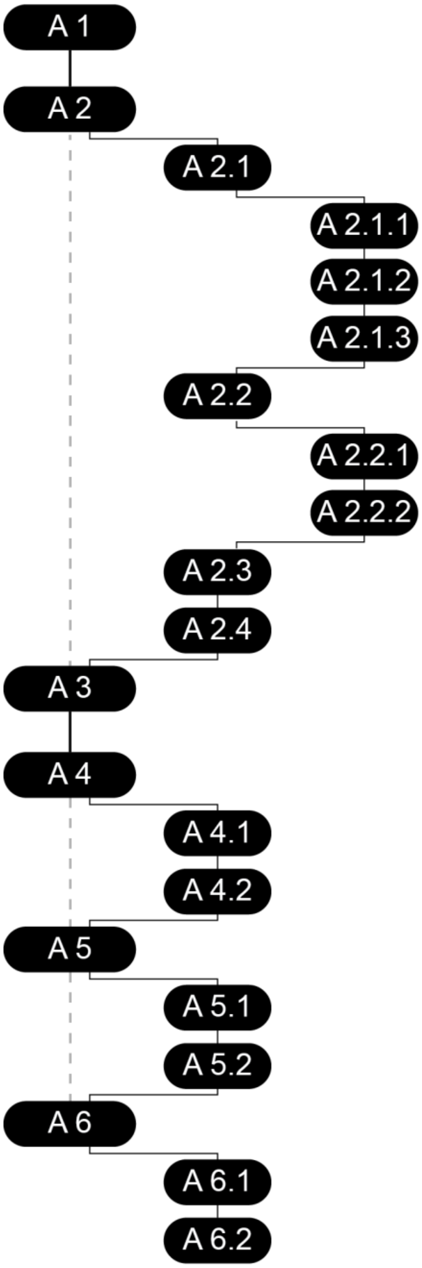
Interior - 10,076 Sq ft

Lanai - 1,357 Sq Ft

# CHAPTER 10. METHODOLOGY – FUNDAMENTAL DECISIONS

Many high-rise buildings with complex geometries remain unbuilt today due to the structural and economic limitations that are imposed on them. Prefabricated modular construction methods, which have mostly been limited to low-quality, low-rise, box-shaped buildings, have the potential to create high-quality, high-rise, biomimetic buildings that are economically feasible and structurally stable. The purpose of this pre-design methodology is therefore to assess the fundamental aspects of design decisions that will enable a high-rise modular building with a complex geometrical form to be structurally stable and economic feasibility. In pursuit of creating a prefabricated modular high-rise that can be economically compared to the Waiea Tower, a high-rise building in Honolulu with a complex geometrical form, the same construction system of a core and podium that it utilized will be used. This will explain early design decisions that must be made. These decisions are important because each one will affect the exterior form as well as the interior space. Thus, this pre-design methodology will serve as a decision making guide by considering various fundamental aspects in the design of a high-rise modular building that uses a core and podium system that enable it to be structurally sound and economically feasible.

## FUNDAMENTAL METHODOLOGY MAP



A 1: MATERIAL

A 2: SYSTEM
    A 2.1: STRUCTURE
        A 2.1.1: LATERAL LOADS
        A 2.1.2: PODIUM
        A 2.1.3: SKELETON
    A 2.2: SKIN
        A 2.2.1: ENCLOSURE
        A 2.2.2: BALCONY
    A 2.3 SERVICES
    A 2.4 SPACE

A 3: GRID

A 4: ROOM MODULE
    A 4.1: DIMENSIONS
    A 4.2: TYPE

A 5: FABRICATION
    A 5.1: PRODUCT MANUFACTURING
    A 5.2: MASS CUSTOMIZATION

A 6: DELIVERY
    A 6.1: TRANSPORTATION
    A 6.2: CRANING

Figure 10.1 - Fundamental design decisions map.

## MATERIAL (Step A 1)

Although metal, timber, or concrete can be used to construct both the structural frame and the modules, the scope of this publication does not address concrete or timber. Metal will be the material focused on, due to the fact that there are so many types and forms of metals that can be used for both the overall structure and the module structure. The primary reason for not using timber is that there is still a height limitation when using wood framing, which limits it from being used in high-rise buildings in many areas. The primary reason for not using concrete is because it's such a heavy material, that transportation and craning prices dramatically increase. Starting with the variety of metals, the design will have to coordinate with the engineer to choose the right kind for the environment. Some of the choices that will be decided on will be between using, cast or wrought iron, mild steel, stainless steel, aluminum, copper, zinc, and titanium. It will also have to be decided on which metal will be used for specific elements, such as the primary load bearing structure and the partition walls. After the material is chosen, the shape of the section is another design and structural issue that needs to be chosen. The figure below shows common sections.[86]

Figure 10.2 - Common steel sections (left) and common aluminum sections (right).
Smith, Ryan and Timberlake, James. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

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[86] Ryan Smith and James Timberlake. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

## **SYSTEM** (Step A 2)

### **Structure** (Step A 2.1)

When looking at modular high-rise buildings, they can be separated into three methods according to Park and Ock. The core method, the core and podium combination method, and the modular in-fill method. The individual modules can then be classified in two categories of panel based modules and load bearing modules. The panel based option is a self-standing module without structural components of columns and beams which cannot transfer loads to each other. It consists of wall and ceiling panels and they are connected using mechanical devices and chemical glue. The load bearing option has two categories of load bearing wall and load bearing frame. The load bearing wall has studs spaced at 300-600mm intervals. The load bearing frame transfers loads vertically through beams and pillars, anchored using bolts and welded to each other. This means that the corner posts must all be aligned in this type. The first method of structure is the core method and this is a technique that builds uses a core for circulation and stacks modules around the perimeter. One option is to directly connect to the core for overall stability and have vertical loads transfer through the modules. Another option is to extend a corridor off the core and have horizontal loads transfer through in-plane trusses while also connecting to the core. The second method of structure is the core and podium, which is good in situations when dimensions may be less strict. The podium is used for shops or parking and is currently used by the world’s tallest modular building, Atlantic Yards B2. The third method of structure is the modular in-fill, where frames are built of reinforced concrete or steel in the field at the same time modules are manufactured in a factory. These independent structures are sub sequentially placed into the frames.[87]

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[87] Hyung Keun Park and Jong-Ho Ock. 2015. “Unit modular in-fill construction method for high-rise buildings.” *KSCE Journal of Civil Engineering* 20, no.4 (June): 1201-1210.

Lateral loads: (Step A 2.1.1)

When designing a core and podium high rise modular structure over ten stories, the first thing to consider is that there will need to be additional lateral support either through a core, structural frame system, or a combination of both on order to resist the wind loading and provide stability for the modules.[88] This can be provided in a variety of ways and the dimensions and placement will be decided upon by the structural engineer and architect for functionality and form. Looking at the lateral stability options and starting with the core, a decision to make here is whether you will need only one, or a multiple of them while also considering their placement for life safety. When choosing a structural frame if needed, it can be a brace frame, a shear wall, or a rigid frame. The braced frame is the most economical, but can limit flexibility and create spatial obstructions. The shear wall can infill between bays, but will also limit flexibility. While the rigid frame can be hidden on the interior of the structure, it must be placed here to limit thermal bridging.[89]

Figure 10.3 - Latral load resisting systems: left (brace frame), middle (rigid frame), right (shear wall). Smith, Ryan and Timberlake, James. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

Podium: (Step A 2.1.2)

The purpose of the podium is provide a level surface for modules to be stacked upon and create large open spaces underneath for either parking or other mixed uses. A decision to make here is

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[88] Mark Lawson, Ray Ogden, and Chris Goodier. 2014. *Design in Modular Construction*. Boca Raton, Florida: CRC Press.
[89] Ryan Smith and James Timberlake. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

that the podium could be built conventionally or with a modular system, and the structure is generally braced by some form, so it is up to the designer to decide and coordinate with the engineer. In the podiums structure, the columns should allign with the ends of modules above it to allow the vertical load transfer to the ground linerally, but an alternative option is that you can also use transfer beams and space columns based upon a multiple of modules.[90] This provides greater flexibility on the ground floor, but also costs extra and would be a decision of cost vs. value. The podium determines the base floor height, therefore high-ceilings and multiple stories are possible on the ground floor.[91]

Figure 10.4 - Podium structure with cellular beams: Left (columns allign with each module), Right (columns allign with alternate modules). Lawson, Mark, Ogden, Ray, and Goodier, Chris. 2014. *Design in Modular Construction.* Boca Raton, Florida: CRC Press.

<u>Skeleton:</u> (Step A 2.1.3)

Structures contain the load bearing and lateral resisting systems that transfer the buildings loads to the ground. High-rise modular buildings generally consist of two different types of systems to resist the vertical and horizontal loads, endoskeleton or mass structures, and exoskeleton or frame structures. Deciding on this early in the design is important because it will depict many of the future choices that will be made, such as the choice of using load-bearing or non-load bearing

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[90] Robert Lawson. 2007. "Building Design Using Modules." *The Steel Construction Institute* 348, (September): 1-16.

[91] Mark Lawson, Ray Ogden, and Chris Goodier. 2014. *Design in Modular Construction*. Boca Raton, Florida: CRC Press.

modules. The mass structure (endoskeleton) is a solid structure that conceals its structural members and is built by stacking load bearing modules on top of each other. The frame structure (exoskeleton) is a skeletal load bearing structure that is built by constructing the frame and then infilling non-load bearing modules into it.[92]

Figure 10.5 - Endoskeleton or mass structure (left) and exoskeleton or frame structure (right). Knaack, Ulrich, Chung-Klatte, Sharon, and Hasselbach, Reinhard. 2012. *Prefabricated Systems: Principles of Construction.* Basel, Switzerland: Birkhauser.

**Skin** (Step A 2.2)

Enclosure: (Step A 2.2.1)

The enclosure is what mediates between indoor and exterior environments and provides protection from outdoor environments. Architecturally, this is the primary aesthetic communication and will depict how the community perceives the building. The four things to consider when designing the enclosure is the function, construction, form, and environment. How all these aspects are dealt with will heavily determine the overall project budget. The enclosure system determines the weight and sizing of the structure as it can either be load-bearing or non-load bearing.[92] One of the most important aspects about the enclosure is the connection to the

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[92] Ryan Smith and James Timberlake. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

structure because of the joints. The aesthetic due to these connections can emphasize the buildings concept by either hiding or expressing the joints.[93]

Figure 10.6 - Modular component façade. Knaack, Ulrich, Chung-Klatte, Sharon, and Hasselbach, Reinhard. 2012. *Prefabricated Systems: Principles of Construction*. Basel, Switzerland: Birkhauser.

Figure 10.7 - Façade panel. Smith, Ryan and Timberlake, James. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

<u>Balcony:</u> (Step A 2.2.2)

Balconies are important features because they create usable spaces on the façade that can also add variation to a bland prefabricated modular building. They can either be constructed as part of

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[93] Shonn Mills, Dave Grove, and Matthew Egan. “Breaking the Pre-fabricated Ceiling: Challenging the limits for modular High-rise.” Paper presented at the conference on Global Interchanges: Resurgence of the Skyscraper City, 2015.

the module or added on as a component. When selecting a balcony to use there are many options. There are ground supported balconies that are stacked and use columns as support. There are additional external steel balconies that are braced and attached, independent of the module. Integral balconies are a choice that are manufactured as part of a module. Balconies can also be supported by the sides of the module or suspended by ties off of corner posts.[94] [95]

Figure 10.8 - Balcony tied to corner posts (left) and balcony supported by separate structure (right). Lawson, Mark, Ogden, Ray, and Goodier, Chris. 2014. *Design in Modular Construction.* Boca Raton, Florida: CRC Press.

**Services** (Step A 2.3)

Typically, services located within modular systems are installed in the factory and the connections to the central services and drains are made on site. The services in a building include: heating, cooling, ventilation, plumbing, electrical, plant rooms, lifts, and stairs. One of the first things to decide here is how to pre-fit the services and equipment into modules. The designer needs to decide whether these services will be incorporated into modules and inserted as pods or if they will be constructed conventionally. Bathrooms, kitchens, and utility rooms have potential to be outfitted and inserted into the module.  How these services are accessed is another important decision. These services can be accessed from inside or outside the module and the choice will affect how these services are distributed throughout the building. The placement of the vertical

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[94] Mark Lawson, Ray Ogden, and Chris Goodier. 2014. *Design in Modular Construction*. Boca Raton, Florida: CRC Press.
[95] Robert Lawson. 2007. “Building Design Using Modules.” *The Steel Construction Institute* 348, (September): 1-16.

service ducts, thus becomes a deciding factor of where services are located. Service strategies commonly either use the corridor, floor, or ceiling for distributing ducts, pipes, cables, and other services.[96] [97]

Figure 10.9 - Bathroom service pod. Smith, Ryan and Timberlake, James. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

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[96] Ryan Smith and James Timberlake. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

[97] Mark Lawson, Ray Ogden, and Chris Goodier. 2014. *Design in Modular Construction*. Boca Raton, Florida: CRC Press.

Figure 10.10 - Placement of service riser. Lawson, Mark, Ogden, Ray, and Goodier, Chris. 2014. *Design in Modular Construction.* Boca Raton, Florida: CRC Press.

### **Space** (Step A 2.4)

The interior space provides the primary dimension of how inhabitants experience spaces. They are also the most temporal and most expensive aspects. Materials are what are define these spaces, so the level of finish is an important decision that a designer must make. This can make the difference from an affordable apartment to a luxury apartment. What is critical is the decision to either use a high level of finishes or a low level or quality of finishes and there are no barriers on applying high quality materials in prefabricated modules. Therefore, the materials and finishes are a deciding factor of the economy and overall feeling of a space. Materials are used on the floor, walls, and ceiling and can be broken down into categories of panels, tiles, coatings, and coverings. The choice of what material to use and of what category will affect the way occupants feel in the space and view it. The interior space is also the most temporary aspect of the module. Besides the materials and finishes, the space is defined by the interior walls, but the placement of the walls and whether they are load-bearing or non-load-bearing is determined by the type of support structure and modular structure being used.[98]

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[98] Ryan Smith and James Timberlake. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

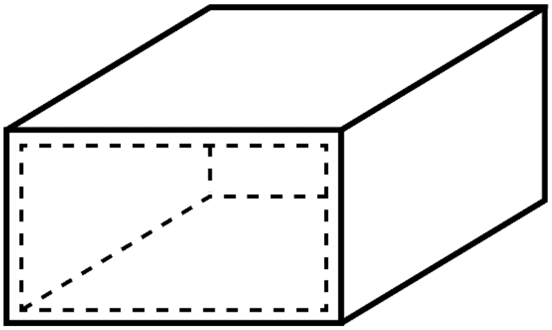

Figure 10.11 - Interior space is defined by materiality and partitions.

## **GRID** (Step A 3)

The grid, which is a geometrical system determining the position and dimension of modular elements, must be decided upon in the early phase of design. This is because it is the basis of a spatial network of dimensional lines for the building. The grid determines where columns will be placed, the size of the modules, and the spacing between elements. It is usually based on a square or rectangular system, but can vary depending on the shapes of the modules. These dimensions for the grid come from the primary modules or multiples thereof, defining elements relationships to each other. The grid for load bearing elements can be different than the grid for the internal fit out. There are two grids that must be determined in the early phases of design, the axial grid and the modular grid, while the internal fit out grid can be determined later into the design process. The reason that the axial grid needs to be developed at the same time as the modular grid is because the both depend on each other. The axial grid is designed to layout a column grid and the modular grid is designed to decide module dimensions. These grids must line up at certain points so that vertical loads can be transferred to the ground properly.

In an axial grid, the central axis of building elements is the same as the line of reference of the grid. Thicknesses should not be taken into account and overlapping elements will occur here at connection points. The axial grid will determine the spacing of the columns at the podium level.

In a modular grid, the location of building elements and their actual dimensions are taken into account. Modular grids are helpful and should be used when elements of building systems are butt jointed. Thus, the location and dimension of an element are defined by at least two lines in the reference system. The modular grid becomes a perimeter line that modules must remain inside.

There is also an internal fit out grid that is applied to modules. These grid lines are not dependent on the axial or modular grid and determine the layout of the module by defining the location of all space enclosing elements. The internal layout grid will divide the module into spaces and occur where partition walls occur, such as for bedrooms and bathrooms.[99] [100]

Figure 10.12 - Grid and reference lines- Left (axial grid), Middle (modular grid), Right (combination of grids). Staib, Gerald., Dörrhöfer, Andreas, and Rosenthal, Markus J. 2008. *Components and Systems: Modular Construction: Design, Structure, New Technologies.* Basel, Switzerland: Birkhauser.

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[99] Gerald Staib, Andreas Dörrhöfer, and Markus Rosenthal. 2008. *Components and Systems: Modular Construction: Design, Structure, New Technologies*. Basel, Switzerland: Birkhauser.

[100] Ryan Smith and James Timberlake. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

## ROOM MODULE (Step A 4)

### **Dimensions** (Step A 4.1)

There are multiple factors that all need to be taken into account that will influence the dimensional planning and overall size of the room module. The size and shape of the lot, access, and circulation all have requirements that the designers need to find out. The building form will also depict dimensional planning. Then, there is the transportation requirements. These are generally the most restrictive and vary upon the location, so it is important to find local transportation codes for road, rail, and sea transportation. This will give insight to the maximum legal length, width, and height of a module in the area of the site. There are also permits that can maximize these dimensions, so it is imperative to find out the dimensions in the early design phase so the modules are able to be transported to the site. The internal grid may also affect the dimensions, due to code and constraints, therefore must be planned out in the early design phase as well.[101] Another constraint that can influence the module dimension is the cladding requirements, which includes alignment with the external dimensions. The façade must be able to attach to reach a distance equal to the exterior module opening. The planning grid imposes another constraint that must be calculated. The designer must standardize the grid for maximum efficiency and that may mean that modules have to use a minimum or maximum dimension. Therefore, the maximum dimensions permitted for transportation may not need to be used.[102]

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[101] Mark Lawson, Ray Ogden, and Chris Goodier. 2014. *Design in Modular Construction*. Boca Raton, Florida: CRC Press.

[102] Robert Lawson. 2007. “Building Design Using Modules.” *The Steel Construction Institute* 348, (September): 1-16.

Figure 10.13 - Standardized module dimensions. Lawson, Mark, Ogden, Ray, and Goodier, Chris. 2014. *Design in Modular Construction*. Boca Raton, Florida: CRC Press.

**Type** (Step A 4.2)

Room modules are building units that can be interconnected on site to create a building and can be either load-bearing or non-load-bearing. This is one of the most influential decisions to make because load-bearing modules can be stacked while non-load bearing can be inserted into larger frames. The choice of the module type will determine the overall structure and aesthetic. In a room module the structural system is prefabricated along with various elements of the internal fit-out. Room modules can have a very high level of prefabrication with all of the necessary service installations, furnishing, and fittings included. Windows and doors can be included too. For a more flexible layout, the modules can be constructed with only two closed sides.[103]

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[103] Gerald Staib, Andreas Dörrhöfer, and Markus Rosenthal. 2008. *Components and Systems: Modular Construction: Design, Structure, New Technologies*. Basel, Switzerland: Birkhauser.

Figure 10.14 - Room module systems- Top left (combined with large panels), top right (load bearing with open side), bottom left (open transverse end), bottom right (all sides closed). Staib, Gerald., Dörrhöfer, Andreas, and Rosenthal, Markus J. 2008. *Components and Systems: Modular Construction: Design, Structure, New Technologies*. Basel, Switzerland: Birkhauser.

Starting with load bearing modules, there is a few choices. First, the load bearing module can have load bearing walls. These are known as four sided modules or continuously supported modules. They bear on the walls of the module below and typically have doors and windows on the ends. Another choice of a four sided module is a variation that has on open end. A rigid frame is provided for stability to the end and it allows for connections to circulation or balconies.[104]

Figure 10.15 - Typical four sided module. Lawson, Robert. 2007. "Building Design Using Modules." The Steel Construction Institute 348, (September): 1-16.

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[104] Robert Lawson. 2007. "Building Design Using Modules." *The Steel Construction Institute* 348, (September): 1-16.

Figure 10.16 - Four sided open ended module. Lawson, Mark, Ogden, Ray, and Goodier, Chris. 2014. *Design in Modular Construction.* Boca Raton, Florida: CRC Press.

The next type of load bearing module that can be chosen is an open-sided or corner supported module. These transmit their vertical loads through corner and intermediate posts and allow an integral corridor to be used within the module. There are variations of this type of load bearing module to choose from. The first is partially open sided modules, which still has four walls, but contains openings that allow modules to be placed together to create wider spaces. Next is the corner supported module that is designed to be able to have fully opened sides and also able to connect with other modules creating large open spaces.[105] [106]

Figure 10.17 - Corner supported partially open sided module. Lawson, Robert. 2007. “Building Design Using Modules.” The Steel Construction Institute 348, (September): 1-16.

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[105] Robert Lawson. 2007. “Building Design Using Modules.” *The Steel Construction Institute* 348, (September): 1-16.

[106] Mark Lawson, Ray Ogden, and Chris Goodier. 2014. *Design in Modular Construction*. Boca Raton, Florida: CRC Press.

Figure 10.18 - Corner supported open sided module. Lawson, Mark, Ogden, Ray, and Goodier, Chris. 2014. *Design in Modular Construction.* Boca Raton, Florida: CRC Press.

In non-load-bearing modules, these units are not designed to resist any loads except their own weight plus the forces of initial lifting. These are supported by the floor or structure that they rest on and are meant to be slid into place. These are commonly called pods and are used primarily for bathrooms, kitchen, plant rooms, and other service rooms.[107]

Figure 10.19 - Non load bearing pod. Lawson, Robert. 2007. "Building Design Using Modules." The Steel Construction Institute 348, (September): 1-16.

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[107] Robert Lawson. 2007. "Building Design Using Modules." *The Steel Construction Institute* 348, (September): 1-16.

## FABRICATION (Step A 5)

### Product manufacturing (Step A 5.1)

The primary concerns when manufacturing products is the cost, lead time, and flexibility. There are different levels of prefabrication that a designer can choose from, each with varying costs, times, and customizations. The level of prefabrication is important in design because as the level of flexibility or customization increases, so does the lead time and price. Four types of product prefabrication will be explained starting with the lowest level of cost, lead time, and customization and ending with the highest. Depending on the overall cost constraint or level of customization, one should be chosen.

Figure 10.20 - Proportions of customization to cost and lead time. Smith, Ryan and Timberlake, James. 2010*. Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

Starting with ‘made-to-stock’, this type resembles inventory replacement which means that standardization and repetition are the key to success. With a low level of cost and customization, inventory can be regularly stocked and this can be seen in warehouse goods. Next, ‘assembled-to-stock’ is a type where products have set geometries, but contain variations through mass customization. This would be known as standardized variation. Products may still be stocked to shelves, but contain slight variations. An example of this could be seen in shoe design, where you can modify certain elements, but it will only result in a low number of possible combinations that are already pre-made. ‘Made-to-order’, is a type of product that cannot be found on a shelf or in a catalogue because it is customized specifically to a dimension and arrives right on time. These products are not standard and therefore take longer to fabricate and cost more. An example of this would be custom elements that fit specifically into a building, such as windows. Lastly, the 'engineered-to-order' type are the most complex and can also be called designed-to-order. These products offer the most customization, but also cost the most and take the longest to fabricate. Examples of these products include facades, precast elements, or other project specific designs.[108] After deciding on the level of customization, one of two product customization options must be chosen. The first is based on a common platform that offers additional options of modules, and the second is based on mixing and matching modules to achieve differentiation. Choosing whether the structure will be constructed using stocked parts or customized parts is the deciding factor in the level of customization and final price of the product. The first figure below shows the modularization characteristic curve shaped by the interface constraints and the amount of customization able to be achieved. It explains that if mass customization is utilized, then the least amount of interface constraints occurs at the component level which also has the highest opportunity for modularization. Conversely, as the opportunity for modularization decreases, it creates a large change in the interface constraints because less standardization leads to more interface variations.[109] The second figure below is showing how the level of customization is linked to its value to the customer. It demonstrates that after a little customization, the value to the customer is the same as if it had a lot of customization.  Too much variety will actually create frustration, and backfire, such as when Nissan offered eighty-seven varieties of steering wheels and did not see an increased value with increased options.[110]

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[108] Ryan Smith and James Timberlake. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

[109] Juliana Mikkola and Tage Skjott-Larsen. 2004. "Supply-chain integration: implications for mass customization, modularization and postponement strategies." *Production Planning & Control* 15, no.4: 352-361.

[110] Juliana Mikkola. 2007. "Management of Product Architecture Modularity for Mass Customization: Modeling and Theoretical Considerations." *IEEE Transactions on Engineering Management* 54, no.1: 57-69.

Figure 10.21 - Modularization characteristic curve. Mikkola, Juliana, and Skjott-Larsen, Tage. 2004. “Supply-chain integration: implications for mass customization, modularization and postponement strategies.” Production Planning & Control 15, no.4: 358.

Figure 10.22 - Cost and value of customization. Kumar, Ashok. 2005. “Mass Customization: Metrics and Modularity.” *The International Journal of Flexible Manufacturing Systems* 16, no.4: 287-311.

**Mass customization** (Step A 5.2)

In order to create economical biomimetic forms, variety has to be achieved while limiting the final cost. Reynolds states that this can be achieved by having each module contain a standard component the is mass produced, while other components can be modified. This enables orders to be mass customized at the same time as mass produced.[111] To create variety within modules, which are mass produced, a certain level of mass customization should be used. Choosing the level of variety and the number of products that vary is the most important decision for designers.

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[111] Jordan Reynolds. 2014. “Modern Mass Customization – Rule 1: Modularize your People, Processes and Products.” Accessed October 17, 2017. http://viewpoints.io/entry/modern-mass-customization-rule-1-modularize-your-people-processes-and-produ.

Mass customization is a result of digital technologies and architects must work closely with manufacturers to realize the benefits of this method of fabrication. There are a few types of mass customization models that are currently used, so it is imperative that a designer chooses the model that will work best for the specific project and lend the most beneficial qualities. The choice of model will translate into how the product is manufactured or fabricated.[108]

When deciding on a mass customization strategy, one must decide on one of the two extremes of soft or hard customization. This is important because soft customization refers to changing out components and hard customization refers to swapping out main body components. Soft mass customization can be described as implementing components that can be swapped around due to a standard interface. The basic body of the product remains constant, while various components can be attached. Hard mass customization is described as allowing all parts of a products components to be interchangeable. This could be a library of different products that can all connect in different ways for example.

Figure 10.23 - Forms of mass customization. Salvador, Fabrizio, Forza, Cipriano, and Rungtusanatham, Manus. 2002. “How to mass customize: Product architectures, sourcing configurations.” *Business Horizons* 45, no.4: 61-69.

There are a few models of mass customization to choose from and the first model is called ‘component sharing’, where the same components are used for each product, but the external appearance can be changed. This means that the external façade can vary, but the remainder of the product remains similar. The next model is ‘component swapping’, and in this model a variety of components are created and that be changed out. An example would be changing out bathrooms, kitchens, or balconies. Then there is the ‘cut-to-fit model’, which allows varying lengths, widths, and heights because products are based upon a fixed module. This would translate into standard components being fitted to a maximum size and then modified in production. The ‘mix modularity’ model creates variation by mixing products, such as cladding with multiple layers that can be increased or decreased. ‘Bus modularity’ is a model where a base structure can support a variation of attachments. This is often called platform design because of the base platform used in all products. The last model that can be chosen to create mass customization is ‘sectional modularity’. In this model parts can vary, but the connection method is standardized. An example is having a base chassis with different components able to be attached at the same locations on the chassis in different iterations.[112]

Figure 10.24 - Types of mass customization. Miller, Thomas and Elgard, Per. 1998. Defining Modules, Modularity, and Modularization: Evolution of the Concept in a Historical Perspective. Lyngby: IKS.

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[112] Ryan Smith and James Timberlake. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

## DELIVERY (Step A 6)

### **Transportation** (Step A 6.1)

The fundamental aspect of transporting a modular structure is breaking the building down into individual building elements so that they can be transported from a factory to the site. This is the decision of the architect that's based on the most restrictive requirements for transportation, which is road transportation maximum dimensions of length, width, and height. These dimensions vary by location so the architect must find the legal road transportation laws. Modules cannot exceed the maximum transportation dimensions unless a permit is issued. If there are to be long distance deliveries, rail and sea are proven to be economical solutions, but it should be remembered that the last stage of delivery will generally be by truck. Therefore, the truck transportation dimensional limits are generally the most restrictive and should be considered.[113]

A decision the designer has to make in terms of how to break down the structure into modules and transport them is whether container shipping or dimensional shipping will be used. Container shipping is based upon using the standard ISO container dimensions that have standardized sizes and pick up points. Dimensional shipping is defined as using custom dimensions of height, width, and length that do not fit within ISO container dimensions. Choosing container shipping is the most economical, but the more restrictive choice. Looking further into dimensions and transportation requirements, the architect must understand the types of trucks and trailers available and choose the one that will help accomplish the most economical price. Different trailers and trucks can accommodate either longer or taller loads.[114]

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[113] Gerald Staib, Andreas Dörrhöfer, and Markus Rosenthal. 2008. *Components and Systems: Modular Construction: Design, Structure, New Technologies*. Basel, Switzerland: Birkhauser.

[114] Ryan Smith and James Timberlake. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

Figure 10.25 - General unusual sized transportation requirements. Lawson, R, Grubb, P, Prewer, J, and Trebilcock, P. 1999. *Modular Construction using Light Steel Framing: An Architect's Guide.* Silwood Park, Ascot: The Steel Construction Institute.

Figure 10.26 - Standard trailer types- top (flatbed), middle (single drop), bottom (double drop). Smith, Ryan and Timberlake, James. 2010. *Prefab Architecture: A Guide to Modular Design and Construction.* Hoboken, New Jersey: John Wiley & Sons, Incorporated.

**Craning** (Step A 6.2)

When hoisting modules with a crane, maneuvering forces cause different internal stresses from the normal conditions. This causes particularly high forces at lifting positions and temporary bracing is often used. Hot rolled sections should be used at these positions, but these positions will vary depending on the lifting technique, so it is up to the architect to decide on the appropriate lifting placement of the projects modules. Lifting is often done from the top and the figure below shows the various techniques of lifting from one point, a secondary frame, a cross beam, and a pair of cross beams. The optimum lifting points are twenty percent of the length in either direction for stability.[115]

Selecting a crane will depend on the weight, height clearance, mobility needed, reach (radius), and number of lifts. Two types of cranes are mobile cranes and fixed cranes. Tower cranes (fixed) are more expensive, but can be economical depending on the number of modules that need lifted. They also carry greater loads, greater distances and heights. [116]

Figure 10.27 - Lifting methods of modules. Lawson, R, Grubb, P, Prewer, J, and Trebilcock, P. 1999. *Modular Construction using Light Steel Framing: An Architect's Guide.* Silwood Park, Ascot: The Steel Construction Institute.

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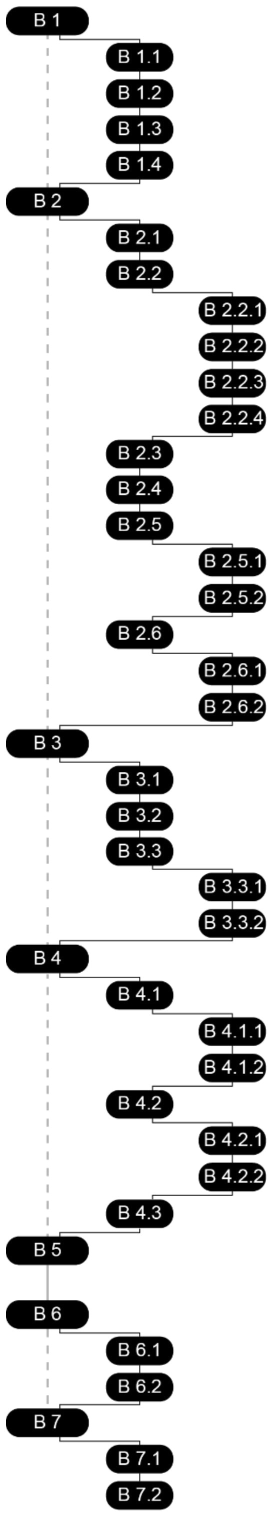
[115] R. Lawson, P. Grubb, J. Prewer and P. Trebilcock. 1999. *Modular Construction using Light Steel Framing: An Architect's Guide*. Silwood Park, Ascot: The Steel Construction Institute.
[116] Ryan Smith and James Timberlake. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

# CHAPTER 11. METHODOLOGY – DESIGN DECISIONS

Building upon the fundamentals that were outlined in the pre-design methodology, this design methodology will access design decisions in more depth, giving general guidelines to follow, as well as decisions made for this project. It will explain how and why design decisions were made with regards to this project and show general rules of thumb that other designs can follow. It is meant to provide further understanding into how a modular high-rise building can be built economically with customized forms. This design methodology provides general steps that have to be taken and considered when designing this type of structure and will not cover the detailed technical aspects of the construction. The same process can be utilized by other designers by following the framework and making decisions based upon the specific site and structure of the project. The purpose of this chapter is to go through the conceptual design process for a modular high-rise to a certain extent, so that these guidelines can be followed and implemented in later design applications, enabling a general cost and space comparison to the Waiea tower.

# DESIGN METHODOLOGY MAP



- B 1: SITE
  - B 1.1: LOCATION
  - B 1.2: ZONE
  - B 1.3: STAGE
  - B 1.4: SITE CIRCULATION

- B 2: MODULE
  - B 2.1: MATERIAL
  - B 2.2: TYPE
    - B 2.2.1 LOAD BEARING FRAME
    - B 2.2.2 FLOOR
    - B 2.2.3 ROOF
    - B 2.2.4 WALL
  - B 2.3 CIRCULATION
  - B 2.4 DIMENSIONS
  - B 2.5 SPACE
    - B 2.5.1 INTERIOR PARTITION
    - B 2.5.2 FINISHES
  - B 2.6 SKIN
    - B 2.6.1 ENCLOSURE
    - B 2.6.2 BALCONY

- B 3: SERVICES
  - B 3.1: BATHROOM
  - B 3.2: KITCHEN
  - B 3.3: VERTICAL CIRCULATION
    - B 3.3.1: STAIR
    - B 3.3.2: ELEVATOR

- B 4: STABILIZATION
  - B 4.1:LATERAL LOADS
    - B 4.1.1: CORE
    - B 4.1.2: STRUCTURAL FRAME
  - B 4.2: VERTICAL LOADS
    - B 4.2.1: CORNER POSTS
    - B 4.2.2: PODIUM
  - B 4.3: CANTILEVER

- B 5: GRID

- B 6: FABRICATION
  - B 6.1: PRODUCT MANUFACTURE
  - B 6.2: MASS CUSTOMIZATION

- B 7: DELIVERY
  - A 7.1: TRANSPORTATION
  - A 7.2: CRANING

Figure 11.1 – Design decisions map.

## **SITE** (Step B 1)

When choosing to use a modular building system, one of the first things to consider is the site. The site used may have plenty of open space, or it may be in a tight urban location or a remote area, so the architect must decide on where the modules are coming from (manufacturer), where they will be set down before being brought to the site (staged), and the zoning regulations that will dictate decisions. If the manufacturer is located too far away, there is no open space for staging, or the zone doesn't permit modular methods, this type of construction might not be feasible. According to Velamati, the largest clusters of module manufacturers in North America are in Pennsylvania, Georgia, Texas, Indiana, and California. The companies at these locations state that they can competitively transport modules by road for distances up to 500 miles, but have also began using sea barges for remote islands.[117] This project takes place on a remote island and will use sea barges to transport the modules from the manufacturer on the United States West cost to the site.

### **Location** (Step B 1.1)

The location of this project is at 1118 Ala Moana Blvd, Honolulu, HI 96814, Waiea Condominium complex. I chose this site because the Waiea Tower is a high-rise building that has a complex geometrical form and was recently completed using conventional construction methods at this location. By utilizing the same site, this project will be able to compare 'apples to apples', because it will take place in the identical location enabling a cost-effective and aesthetic comparison. Waiea Tower will be the controlled variable which I can compare results to. The advantage of placing my proposed building on a site that has been recently developed, versus a site nearby a recently developed building, is that is gives the most accurate comparison with all of the same conditions that the controlled variable had to consider. This includes, but it is not limited

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[117] Sri Velamati. 2012. "Feasibility, benefits and challenges of modular construction in high rise development in the United States: A developer's perspective." Thesis, Massachusetts Institute of Technology.

to climatic conditions, zoning regulations, and surrounding context. Hawaiʻi was also chosen as the location for this project because there is a small temperature difference causing less expansion and contraction of materials. This is important because the tolerances when working with prefabricated modules is very high, and if materials are moving it will lead to issues of tightness and leaking. According to the US climate data, the average low temperature for the year in Honolulu is 66 degrees and the average high temperature is 89 degrees. This is a 23 degree difference which is small and also occurs at opposite times of the year, so the temperature gradually rises and falls.[118] The Waiea tower that was constructed here is not your typical extruded box. It mimics water and a fishing net in its form, and in this project, the same natural inspiration will be used for the design. This is to be sure that the comparable building had the same structural principles, as well as design principles. As this site is located on the island of Oahu, a module manufacturer on the United States West coast in California will be used, and a sea barge will transport the modules. While there are many sea barge companies that make the trip from California to Hawaiʻi, Matson is the sea barge company selected for this project and the sea barge will need to be rented out due to the number of modules that will be shipped. The modules will arrive at Honolulu Harbor, where modules will be unloaded at sand island.

Figure 11.2 - Location of project. Google Maps. 2017. “Honolulu project location.” Accessed November 29, 2017. https://www.google.com/maps/@21.2937858,-157.8539894,239m/data=!3m1!1e3.

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[118] US Climate Data. 2018. “Climate Honolulu-Hawaiʻi.” Accessed March 24, 2018. https://www.usclimatedata.com/climate/honolulu/hawaii/united-states/ushi0026.

Figure 11.3 – Construction of the Waiea tower at this projects location. *Waiea.* Accessed November 29, 2017. https://www.wardvillage.com/articles/constructing-a-community.

**Zone** (Step B 1.2)

The zone of the site will impose regulations to adhere by, so it is important to find and understand the restrictions that will be imposed. In the case of this site, it is in the Auahi (AU) Zone. According to Chapter 217 in the Makua Area Rules, it is stated that the maximum building height is four-hundred feet. In terms of setbacks, there are no requirements on the sides (North and South) or rear (West) of the site. The restriction on the front (East) of the building is that the front build to line is N/S – fifteen feet. This means that the building cannot come within fifteen feet of the East side of the site. The maximum density floor area ratio (FAR) is another consideration to take into account, and for this site it is 3.5.[119]

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[119] Department of Business, Economic Development and Tourism. “Makua Area Rules.” Chapter 217 of Title 15. Hawaii Administrative Rules.

Figure 11.4 - Neighborhood zones with the site shown in the Auahi zone. Department of Business, Economic Development and Tourism. “Makua Area Rules.” Chapter 217 of Title 15. Hawaii Administrative Rules.

Figure 11.5 - Building height limits with site shown. Department of Business, Economic Development and Tourism. “Makua Area Rules.” Chapter 217 of Title 15. Hawaii Administrative Rules.

**Stage** (Step B 1.3)

Staging is important to modular construction because after the modules are manufactured they need a place to be stored before placed within a building. The staging ground could be on site if there is enough available open land, but in tight urban settings, an adjacent site to stage the modules is needed. If the site is too small, an adjacent site no farther than 10 miles away should be utilized. This will allow an inventory to be built up, limit the number of delays, and decrease the number of days needed to rent a crane.[120]

The site used for this project is in a tight urban setting and there will not be enough room on site to store modules. The modules will also be arriving by ship, so that means that a large number of modules will be arriving at one time, therefore an adjacent staging ground is needed. The staging ground for this project will be located at the shipping container drop off area at Sand Island in the Honolulu Harbor. The company Matson selected to ship the modules on a barge has a shipping container staging area located here that would have to be rented out. This location is 4.6 miles away from the site and meets the requirements of the maximum distance from the stage location to the site. The roads used to get from the stage to the site are Sand Island access road, N Nimitz Hwy, and Ala Moana blvd.

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[120] Peter Cameron and Nadia DiCarlo. 2007. “Piecing together modular: Understanding the benefits and limitations of modular construction methods for multifamily development.” Thesis, Massachusetts Institute of Technology.

Figure 11.6 - Staging ground and site shown connected with road transportation path.

**Site circulation** (Step B 1.4)

The designer must consider the site circulation and access routes. This is important because the roads chosen have to accommodate the trucks turning radius. If the travel routes to the site have limitations, often times manufacturers or transporters will drive the route to access how to modify the plan accordingly. Understanding primary and secondary routes will also help plan for road sizes and for traffic conditions.[121]

The route chosen for this project fits within a truck turning radius by only utilizing three primary access roads with enough room for turns: Sand Island access road, N Nimitz Hwy, and Ala Moana blvd. shown previously. It also doesn’t go under any bridges or through tunnels that would

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[121] Peter Cameron and Nadia DiCarlo. 2007. “Piecing together modular: Understanding the benefits and limitations of modular construction methods for multifamily development.” Thesis, Massachusetts Institute of Technology.

limit the height. Although the primary paths will be used over the secondary paths, the primary paths do not utilize highways, areas that can expect traffic and delays.

Figure 11.7 - Site circulation with primary and secondary routes.

## MODULE (Step B 2)

### Material (step B 2.1)

Steel is a material with great tensile and compressive strength which has elastic properties. It has a consistent quality giving it an advantage in the dimensional accuracy. Due to the structural behavior, large spans can be built as well. All of these properties are what make this building material very suitable to be used in modular building systems. Besides the structural system, it can also be used for space enclosure and facades. It can be folded, curved, and used for interior fit outs.[122] In fill panels can add variations to the steel modular system also because they may not

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[122] Gerald Staib, Andreas Dörrhöfer, and Markus Rosenthal. 2008. *Components and Systems: Modular Construction: Design, Structure, New Technologies*. Basel, Switzerland: Birkhauser.

be structural and can be moved into various locations. Steel modules are primarily used in tall commercial buildings that require robust structural systems. A steel framed module can be less stout in comparison to wood and concrete because of its inherent strength, which allows it to not be over structured for transportation. The level of prefabrication is another attribute related to its strength and precision, where the modules can be almost completely finished in a factory with insulation, framing, wiring, ducting, and services.[123] For this project, steel will be used because these modules are meant to be almost completely finished in the factory and also need a high level of precision for low tolerances. Structural steel will be used for load bearing elements, and light steel framing will be used for non-load bearing partition walls.

Figure 11.8 – Typical load bearing structural steel with light steel framing module. Lawson, Robert. 2007. "Building Design Using Modules." *The Steel Construction Institute* 348, (September): 1-16.

**Type** (Step B 2.2)

Load bearing frame: (Step B 2.2.1)

For this project, the type of room module that is going to be used is a structural module. The reason that a load bearing room module was chosen instead of a non-load bearing module is because this is meant to be a permanent structure. Non-load bearing structures are usually used

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[123] Ryan Smith and James Timberlake. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

when the building is not permanent or because the units are able to be changed out. The Metabolist movement that experimented with this concept failed because people liked the idea of permanent dwellings psychologically, and also because removing modules was not as easy as it sounded and modules were not ever interchanged. In Hawai‘i where the proposed design will be placed, a proposal of a non-load bearing modular tower was already proposed in 1963 by Kiyonori Kikutake called Marine City, but it was never built. The changeable modular idea sounded good in theory, but was never constructed besides a few experimental structures. Load bearing stackable modules on the other hand have been constructed all over the globe.[124]

Figure 11.9 - Unbuilt Marine City in Hawai‘i. Kikutake, Kiyonori. *Marine City.* Accessed December 7, 2017. http://architecturalmoleskine.blogspot.com/2011/10/metabolist-movement.html.

After deciding on a load bearing module for this project, the type of load bearing module that will be used is a corner supported open sided load bearing frame. According to Lawson, these modules can be partially open sided by providing corner posts, intermediate posts, and edge beams. This will create flexibility interior spaces with partition walls that can be arranged in different ways. This will also allow for larger openings to occur between modules creating larger spaces in return. This type of module can accommodate an integral corridor as well as having

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[124] Stanley Russell. 2009. “Without a hitch: New directions in prefabricated architecture.” In *Metabolism Revisited: Prefabrication and Modularity in 21st Century Urbanism*, 246-253.

balconies or other components attach to the corner posts. This is important because enabling attachable components is a vital part of creating variety.[125]

The structure in this module begins with corner posts as vertical load tranfer elements, usually as square hollow sections (SHS). Then, edge beams span between corner posts in order to transfer loads to them and provide open sides. The edge beams on the ceiling can be shallower than the floor edge beams. Combining these elements together creates the bones of the welded steel frame chassis, which is the building block of the room module.[126] [125] [127]

Figure 11.10 - Corner post supported module with intermediate posts and diagonal bracing. Arup. *Module chassis arriving at the factory for fitout.* Accessed December 7, 2017. http://doggerel.arup.com/engineering-the-factory-built-tower/.

Floor: (Step B 2.2.2)

For the floor system in this project, steel tube purlins with a metal deck will be used instead of concrete in order to lighten the module which will reduce transportation costs, craning costs, foundation construction, and transfer steel.[126] The spacing of the purlins are dictated by their size and spanning capability as well as the placement of the intermediate posts. The flooring above

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[125] Robert Lawson. 2007. “Building Design Using Modules.” *The Steel Construction Institute* 348, (September): 1-16.

[126] David Farnsworth. “Modular Tall Building Design at Atlantic Yards B2.” Council on Tall Buildings and Urban Habitat Conference Proceedings, Shanghai, China, 2014.

[127] Mark Lawson, Ray Ogden, and Chris Goodier. 2014. *Design in Modular Construction*. Boca Raton, Florida: CRC Press.

the metal decking will be cementitious particle board because it is moisture resistant and improves acoustic insulation.[128]

Roof: (Step B 2.2.3)

In the roof system, a metal deck with steel tube purlins will be used in a similar fashion as the floor system. The difference is that in combination with the edge beams, metal decking, and purlins, the roof will act as a diaphragm to transfer lateral loads to either a core or braced frame. Using the roof as a diaphragm instead of the floor allows connections between modules to be done from outside the modules, reducing steel work inside the modules.[129]

Wall: (Step B 2.2.4)

The use of intermediate posts supports the edge beam on the open side of the module. These are usually small (SHS) posts that fit within the width of a wall. The intermediate posts also provide stability to the module during transportation and therefore, additional temporary bracing for transportation and lifting aren't needed. The overall stability of the module is often provided by diagonal bracing located in the walls. Thin gage diagonal bracing will minimize steel deflections, and when combined with the edge beams, intermediate posts, and corner posts, the sides of the module will act as a vierendeel truss. The vierendeel truss sides aid when there are openings in the side and shear must be resisted without the diagonal assistance. It also will allow for longer cantilevers which will be mentioned later.[126] [127]

**Circulation** (Step B 2.3)

In order to speed up construction and avoid water tightness problems during finishing and installation, corridors for horizontal circulation can be incorporated as a part of the module or an attachable element. These integral corridors this project will use, is enabled by using long

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[128] R. Lawson, P. Grubb, J. Prewer and P. Trebilcock. 1999. *Modular Construction using Light Steel Framing: An Architect's Guide*. Silwood Park, Ascot: The Steel Construction Institute.

[129] David Farnsworth. "Modular Tall Building Design at Atlantic Yards B2." Council on Tall Buildings and Urban Habitat Conference Proceedings, Shanghai, China, 2014.

modules that can have partially open sides or modules with open ends. The integral corridor can serve as either a double loaded corridor where modules backed up to each other both utilize the corridor provide by one of the modules, or as a single loaded corridor. This eliminates the onsite construction of a corridor and limits the number of connections that have to be made.[130] In an attempt to make a fully modular structure that is prefabricated off site to the furthest degree, this is a key element of the design.

Figure 11.11 - Open sided module with integral corridor. Lawson, Mark, Ogden, Ray, and Goodier, Chris. *Design in Modular Construction.* Boca Raton, Florida: CRC Press, 2014.

**Dimensions** (Step B 2.4)

For this project, the site is on the island of Oahu in Hawai‘i and public road transportation is the determining factor of module size. According to Hawai‘i Revised Statutes, the length, width, and height cannot exceed 65’x9’x14’ respectively.[131] Permits can be issued for increases in length, width and height though. It is stated in the permit manual that vehicles with a width of over 12’ require an escort vehicle and widths of over 14’ require two escorts. Typical permits for oversized

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[130] Robert Lawson. 2007. “Building Design Using Modules.” *The Steel Construction Institute* 348, (September): 1-16.

[131] Hawaii Revised Statutes. 2016. “TITLE 17. MOTOR AND OTHER VEHICLES, 291. Traffic Violations, 291-34 Size of vehicles; width, height, and length.” Accessed November 15, 2017. https://law.justia.com/codes/hawaii/2016/title-17/chapter-291/section-291-34/.

dimensions have a length of 65’, a height of 14’, and a width of 16’, although a height on 16’ can be achieved if the path does not go through tunnels and the length can extend as far as the client wants as long as it meets turning radius requirements on roads used .[132] For this project, the dimensions will remain at or under these guidelines and will have to coordinate with the column grid at the podium for parking requirements if needed to determine the final size. This project will also take into account the size of the units in the Waiea Tower to make sure that the dimensions are either the same size or bigger to obtain an accurate comparison. The ceiling height in the units are 9’6”, 10’6”, and 11’6”, the average room width is 14’, the average living room width is approximately 16’, and the longest length from the façade to the corridor is approximately 50’ without the corridor.[133]

**Space** (Step B 2.5)

Interior partitions: (Step B 2.5.1)

Because the module is load bearing, the walls will be non-load bearing light steel framed partition walls. These walls are relatively thin at less than four inches, and have the ability to be rearranged differently making flexible spaces.[134] Light-gauge steel framed walls are the usual choice for infill walls on large scale projects and can be manufactured as panels that can be quickly erected, saving time and money. An advantage to using this wall system is that it can be finished out in a factory with insulation, wiring, ducting, and finishing surfaces.[135]

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[132] SC&RA. “Oversize/overweight permit manual Hawaii.” Permit Manual Hawaii. 2015

[133] Howard Hughes. Waiea mini book. Ward Village.

[134] Robert Lawson. 2007. “Building Design Using Modules.” *The Steel Construction Institute* 348, (September): 1-16.

[135] Ryan Smith and James Timberlake. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

Figure 11.12 - Typical light steel framing infill panel with an open side on a corner supported module. Lawson, Robert. 2007. “Building Design Using Modules.” *The Steel Construction Institute* 348, (September): 1-16.

Finishes: (Step B 2.5.2)

For the purpose of this project, a cost and spatial comparison will be made to the Waiea Tower, a building with very high-end finishes. It is known that lesser quality finishes are cheaper and I don’t want to compromise the luxurious interior, so in order to not compare finishes and have them remain constant, finishes will not be specified for this project and it can be assumed that they will be the same as in the Waiea Tower. This includes finishes such as hardwood or stone flooring and onyx or marble countertops.[136]

**Skin** (Step B 2.6)

Enclosure: (Step B 2.6.1)

The enclosure determines the visual appearance of a building and can also affect the interior space. The first thing considered is to use a non-load bearing façade so that it can be treated similar to a non-load bearing partition wall and can be arranged differently in module configurations creating variety. The next thing this project considered was the transmission of the enclosure and transparent glass was chosen in order to maintain a proper comparison to the Waiea tower. After this, the structure-enclosure-space relationship must be determined. This project will place the glass enclosure in front of the structural system when no balcony is used, or

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[136] Howard Hughes. Waiea mini book. Ward Village.

in line with the structural system when a balcony is used. The effect created will be either a seamless surface or an extrusion from the building mass.[137] For high rise buildings, the cladding is generally supported from each module according to Mills et al. This project will thus utilize this method where each module contains its own enclosure. The glass enclosure is an element that may either be installed onto a module or onto an attachable component, but in either case, it will be installed off site in a factory in order to have as much complete off site as possible and receive the economic benefits that come with lessened construction time.[138]

Figure 11.13 - Structure enclosure relationship. Smith, Ryan and Timberlake, James. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

Balcony: (Step B 2.6.2)

For this project, balconies will be used to add variation to the modular system, and due to the fact that transportation limits modules to box like shapes, the balconies will be added as components. These attachable components will be transported to the site and installed on site on the ground before being lifted into place to give the benefit of allowing variation while not disrupting the transportation limitations. The design of this structure will use cantilevered balconies on the exterior of modules by using a separate steel structure that attaches to the corner posts of

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[137] Ryan Smith and James Timberlake. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.
[138] Shonn Mills, Dave Grove, and Matthew Egan. “Breaking the Pre-fabricated Ceiling: Challenging the limits for modular High-rise.” Paper presented at the conference on Global Interchanges: Resurgence of the Skyscraper City, 2015.

modules for the cantilevered exterior space of balconies. This will create an opportunity to modify the exterior aesthetics as well adding variation from the typical box like unit space. Tension members will be tied to the corner posts with at least one location per unit, in an attempt to reduce the external steel structure. For the length of the cantilever, at least a five-foot cantilevered external structure will be used to abide by the code for ADA turn around dimensions.[139]

Figure 11.14 - Balcony external structure attachment. Lawson, Robert. 2007. "Building Design Using Modules." *The Steel Construction Institute* 348, (September): 1-16.

Figure. 11.15 - Components of structure and envelope for a balcony. Neal Panchuk, "An Exploration into Biomimicry and its Application in Digital & Parametric [Architectural] Design," Masters diss., University of Waterloo, 2006.

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[139] Mark Lawson, Ray Ogden, and Chris Goodier. 2014. *Design in Modular Construction*. Boca Raton, Florida: CRC Press.

## <u>**SERVICES**</u> (Step B 3)

### **Bathroom** (Step B 3.1)

In conventional construction, services can be one of the most time consuming on site tasks, so for this project the bathrooms will be completed and installed off site in a factory. This will be accomplished using bathroom pods, which are non-loadbearing modules that are supported directly by the floor of the room module.[140] Bathroom pods provide the most benefits when there will be multiple repetitions produced, therefore, this project is perfect for it. There may be a few different types of bathroom pods, but they will all have multiple repetitions. By installing all of the piping and high-grade finishes in a module, the quality, control, and speed are all increased. This also allows the pod to be hooked up to the services easily.[140] In order to have a floor level in the pod consistent with the floor level in the module, a recessed area can be made in the room module without the floor buildup. The pods are usually manufactured with thin wall and floors starting at approximately 2 inches.[141] The next thing to consider is the vertical service riser. Generally, a vertical service duct should be incorporated into the bathroom pod that contains the drainage, pipework, and service connections.[142] For this project the vertical service riser will be placed into the corner of the bathroom pod as in internal service void, and the bathroom pod will be placed backed up to another bathroom pod when possible so that the service riser can be utilized and accessed for both simultaneously. For this project ADA bathroom dimensions will be used as the limiting factor. ADA bathrooms require that there is a clear space with a five-foot diameter according to the ADA standards for accessible design.[143] The bathroom will contain a water closet, sink, and either a shower or bathtub to maintain the same elements as in the proposed comparison structure, the Waiea tower.

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[140] Ryan Smith and James Timberlake. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

[141] Mark Lawson, Ray Ogden, and Chris Goodier. 2014. *Design in Modular Construction*. Boca Raton, Florida: CRC Press.

[142] R. Lawson, P. Grubb, J. Prewer and P. Trebilcock. 1999. *Modular Construction using Light Steel Framing: An Architect's Guide*. Silwood Park, Ascot: The Steel Construction Institute.

[143] Department of Justice. 2010. "ADA Standards for Accessible Design." Last modified December 7,2012. https://www.ada.gov/regs2010/2010ADAStandards/2010ADAstandards.htm.

Figure 11.16 - Toilet pod used with light steel framing. Lawson, Robert. 2007. “Building Design Using Modules.” *The Steel Construction Institute* 348, (September): 1-16.

Figure 11.17 - Typical service duct in modular building. Gorgolewski, M, Grubb, P, and Lawson, R. 2001. Modular Construction using Light Steel Framing: Design of Residential Buildings. Silwood Park, Ascot: The Steel Construction Institute.

**Kitchen** (Step B 3.2)

This project will use non-load bearing kitchen pods that are inserted into modules similar to the bathroom pods. The elements that will go into them include a sink, dishwasher, oven, and refrigerator. While the form and dimensions are design dependent, there are some rules to ensure it will be code compliant for ADA. According to the ADA standards for accessible design, the kitchen counter or work surface has a maximum height of 34” above the finished floor. Pass through kitchens require openings on either side and a 40” clearance between opposing sides. U-shaped kitchens or ones with three enclosed sides require 60” of clear space between opposing sides. In any case there is a requirement that states that at least in one place the counter surface needs to be at least 30” wide.[144] The more complete a module can be before installation, the more cost and time will be saved, so a kitchen pod for these benefits.

Figure 11.18 - Accessible kitchen design standards. Department of Justice. 2010. “ADA Standards for Accessible Design.” Last modified December 7,2012. https://www.ada.gov/regs2010/2010ADAStandards/2010ADAstandards.htm.

**Vertical circulation** (Step B 3.3)

<u>Stair:</u> (Step B 3.3.1)

This project will use stair modules comprised of braced steel frames to provide vertical circulation in the core structure along with helping the overall structure deal with lateral loads. These stair modules are manufactured with a partially open top and base to connect to each other via stacking. The rigid welded frame will utilize square hollow sections similar to the corner posts of the modules in order to carry vertical loads to the ground. For the lateral loads, bracing of these modules where there aren’t opening will ensure that they are sufficiently taken care of. The module staircase that will be used for this design will be a double flight of stairs supported by half landings and full landings.[145]

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[144] Department of Justice. 2010. “ADA Standards for Accessible Design.” Last modified December 7,2012. https://www.ada.gov/regs2010/2010ADAStandards/2010ADAstandards.htm.
[145] Mark Lawson, Ray Ogden, and Chris Goodier. 2014. *Design in Modular Construction*. Boca Raton, Florida: CRC Press.

Figure 11.19 - Stair module supported with corner posts. Lawson, Mark, Ogden, Ray, and Goodier, Chris. Design in Modular Construction. Boca Raton, Florida: CRC Press, 2014.

Figure 11.20 - Modular stair system. Lawson, Robert. 2007. “Building Design Using Modules.” *The Steel Construction Institute* 348, (September): 1-16.

Elevator: (Step B 3.3.2)

In the design of this project, modular units will be used for the elevator that will be part of the larger core. Incorporated into a braced steel framed core, this project is expecting the lift modules to provide benefits of reduced construction time and helping to relieve lateral loads from the overall structure. According to Lawson et al., the time it takes to install conventional lifts usually determines when a project is handed over to a client. Modular lifts allow quick installation while also providing lateral load transfer.[146] Lawson et al., state that modular lifts permit guide rails, doors, and finishes can be installed in the factory. As for the structure, lateral bracing cannot be installed across the door elevation and therefore, a rigid frame is used here. The tolerances also increase in this type of lift construction and shims are used at the corners to minimize any misalignment. For the door openings, a standard 800 mm door is suitable for wheelchair access, so I will use this as a minimum in my project. The lift system will be broken down into four different module types: a lift pit module, a door height module, a floor zone module, and a capping module.[147]

Figure 11.21 - Modular lift units by Schindler. Lawson, R, Grubb, P, Prewer, J, and Trebilcock, P. 1999. Modular Construction using Light Steel Framing: An Architect's Guide. Silwood Park, Ascot: The Steel Construction Institute.

Figure 11.22 - Attachment of modular lifts and guide rails. Lawson, Mark, Ogden, Ray, and Goodier, Chris. Design in Modular Construction. Boca Raton, Florida: CRC Press, 2014.

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[146] R. Lawson, P. Grubb, J. Prewer and P. Trebilcock. 1999. *Modular Construction using Light Steel Framing: An Architect's Guide*. Silwood Park, Ascot: The Steel Construction Institute.

[147] Mark Lawson, Ray Ogden, and Chris Goodier. 2014. *Design in Modular Construction*. Boca Raton, Florida: CRC Press.

## STABILIZATION (Step B 4)

In the previous section on the type of module, a load-bearing module was selected. This dictates the structure and would put this structure in the category of an endoskeleton or mass structure. The endoskeleton structure is composed of a core, braced frames, and load bearing modules that conceal their structural members. This structure will be considered a hybrid though because as most elements will be constructed modularly, the plinth will be constructed conventionally. This structure will use the core and podium type of tower as the Waiea tower did, therefore constituting this hybrid of conventional and modular construction. Some of the key factors that should be taken into account in the design of a high-rise modular structure are the influence of eccentricities and construction tolerances, the application of design standards for steelwork, the mechanism of force transfer of horizontal loads to the stabilizing system, and the robustness or structural integrity of the modular system.[148]

### Lateral loads (Step B 4.1)

Core: (Step B 4.1.1)

The building core is one of the primary stabilizing elements in high-rise buildings. This will transfer and resist lateral loads as well as containing the vertical circulation such as the stairs and lifts. For the layout of this project, the structure will only use one core because it will be centralized, allowing units to access it off a single loaded corridor.[149] The structure of the core will utilize a modular steel only braced structure instead of a reinforced concrete core to reduce the number of trades on site, ensure compatible tolerances between all systems, and due to the long term deflection of a concrete core, the connections between systems would be complicated.[150] Using

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[148] Robert Lawson and Jane Richards. 2010. "Modular design for high rise buildings". *Structure and Buildings* 163, no.3 (January): 151-164.

[149] Sri Velamati. 2012. "Feasibility, benefits and challenges of modular construction in high rise development in the United States: A developer's perspective." Thesis, Massachusetts Institute of Technology.

[150] David Farnsworth. "Modular Tall Building Design at Atlantic Yards B2." Council on Tall Buildings and Urban Habitat Conference Proceedings, Shanghai, China, 2014.

modules for the core will give the benefit of having less on site work being done, reducing overall construction time and cost. It will also give flexibility where the core does not have to be placed directly in the center of the mass.[151]

Structural frames: (Step B 4.1.2)

When designing high-rise buildings over ten stories, structural frames are often used to resist lateral loads and provide stability to a group of modules. This project aims to be thirty-six floors high so it will use additional steel braced frames to resist lateral loads. The structural frames will be placed around the core in each primary direction of North, South, East, and West to provide uniform stability, while additional structural frames may be placed between modules. The braced steel framed will be installed at the same time as the modules so that they can be fitted between the module walls at each floor.[152] The benefit of this is that it relieves some of the lateral loads from the core and enables the building to be constructed as a high-rise, as well as enabling the modules to not have to tie directly back to the core. The type of braced frame that will be used is a steel concentrically braced frame and the design will be of an inverted v-brace (chevron). The reason for a concentric brace is that the diagonal bracing meets at a joint intersection allowing it to work as a vertical truss system to resist lateral forces. The reason for the chevron is that it is the typical choice in high-rise steel braced frames. Further relating to this project and according to Tarranth, the most efficient method for resisting lateral loads in ultra-tall buildings is to provide super columns at the ground level and interconnect these columns with these braced frames and vierendeel frames. This works out perfectly for this project because not only will these braced frames be used, the modules are also vierendeel trusses, so the structural stability should suffice.[153]

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[151] Tharaka Gunawardena, Tuan Duc Ngo, Priyan Mendis, and Jose Alfano. 2016. “Innovative flexible structural system using prefabricated modules.” *Journal of Architectural Engineering* 22, no.4 (May): 1-7.

[152] Mark Lawson, Ray Ogden, and Chris Goodier. 2014. *Design in Modular Construction*. Boca Raton, Florida: CRC Press.

[153] Bungale Taranath. *Structural Analysis and Design of Tall Buildings: Steel and Composite Construction*. Boca Raton, Florida: CRC Press, 2012.

Figure 11.23 - Application of steel braced frames Atlantic Yards B2. Farnsworth, David. “Modular Tall Building Design at Atlantic Yards B2.” Council on Tall Buildings and Urban Habitat Conference Proceedings, Shanghai, China, 2014.

**Vertical loads** (Step B 4.2)

Corner posts: (Step B 4.2.1)

For this project, a podium structure will be used and discussed in subsequent sections, but this means a column grid under the podium will have to be considered. It is stated that support beams should align with the walls in the modules and columns should be arranged on a grid to optimize parking. The rule used for column spacing is based upon placing columns on a multiple of modules widths, depending on how many create a unit.[154] Columns generally align with every two or three modules and the beams are designed to align with the ends of the modules as well.[155] The reason for this is to continue the vertical load paths to the ground from the corner posts of the modules to the columns supporting the podium. If there is a conflict where this cannot be designed effectively, a transfer slab or beam can be added.[156] There may be a need to incorporate parking into the podium under the tower, and if so, the spacing of the column grid will have to align with the corner posts of the modules and also with parking stalls underneath.

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[154] Mark Lawson, Ray Ogden, and Rory Bergin. 2012. “Application of modular construction in high-rise buildings.” *Journal of Architectural Engineering* 18, no.2 (June): 148-154.

[155] Robert Lawson. 2007. “Building Design Using Modules.” *The Steel Construction Institute* 348, (September): 1-16.

[156] Peter Cameron and Nadia DiCarlo. 2007. “Piecing together modular: Understanding the benefits and limitations of modular construction methods for multifamily development.” Thesis, Massachusetts Institute of Technology.

According to the Revised Ordinances of Hawaiʻi in chapter 21 article 6, off-street parking and loading, the standard parking space shall be at least 18 feet long by 8 feet 3 inches wide.[157] On the implementation of this design, this parking stall dimension along with the width of a module will determine the appropriate column grid spacing where parking is located under the tower.

Figure 11.24 - Corner supported modules supported by columns and a podium. Lawson, Robert. 2007. “Building Design Using Modules.” *The Steel Construction Institute* 348, (September): 1-16.

<u>Podium:</u> (Step B 4.2.2)

In general, for taller buildings a primary steel frame podium should be provided for modules to be stacked upon. The podium structure is usually braced to resist loads as well.[158] For this project, a podium will be used because on this site in Hawaiʻi, the ground may not be always be level to stack modules on top of. This will provide the benefit of creating a flat supported surface that modules can be readily stacked upon. It will also provide an open space for a lobby, retail or restaurants similar to how the Waiea Tower did.[159] This will further help my compassion of the two structures because they will contain the same elements. The podium will be constructed conventionally with a steel framed plinth. This was how the Atlantic Yards B2 project constructed

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[157] Revised Ordinances of Hawaii. “Off-street parking.” Chapter 21, Article 6, Section 21-6.50. Minimum Dimensions.

[158] Robert Lawson. 2007. “Building Design Using Modules.” *The Steel Construction Institute* 348, (September): 1-16.

[159] Mark Lawson, Ray Ogden, and Chris Goodier. 2014. *Design in Modular Construction*. Boca Raton, Florida: CRC Press.

their podium and by utilizing the same elements of their design, this project expects to gain similar benefits of stability and space. By using a podium, it will create the benefit of allowing programs that require large open spaces, such as lobbies restaurants or parking to occur in this space. According to ‘Chapter 217 in the Makua Area Rules’, the site chosen is in the Auahi Zone, which imposes a sixty-five foot maximum height for the street front element height of the podium so that is the podium height limitation.[160] Using this regulation, parts of the ground floor can be used for a lobby, retail, and restaurant space, while the remaining floors can be used as a parking structure.[161]

Figure 11.25 - Conventionally constructed steel podium at Atlantic Yards B2. Forest City Ratner, “Building 2 at Atlantic Yards.” Presentation to the public, November 9, 2012.

**Cantilever** (Step B 4.3)

When cantilevering modules out from the main building mass, a high load can occur in the first stud at the base of the cantilever. Therefore, a solution was found to this problem by using continuous columns from the foundation to the top at a location just before the cantilever begins. This is a system to aid in the support of the cantilevered modules, but no information is given for how far the modules can cantilever out.[162] [163] In order to see how far modules can cantilever out,

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[160] Department of Business, Economic Development and Tourism. “Makua Area Rules.” Chapter 217 of Title 15. Hawaii Administrative Rules.

[161] David Farnsworth. “Modular Tall Building Design at Atlantic Yards B2.” Council on Tall Buildings and Urban Habitat Conference Proceedings, Shanghai, China, 2014.

[162] Mark Lawson, Ray Ogden, and Chris Goodier. 2014. *Design in Modular Construction*. Boca Raton, Florida: CRC Press.

[163] Michael Hough. 2013. “World’s Tallest Modular Building.” Accessed October 30, 2017. http://modularengineer.blogspot.com/2013/06/world-tallest-modular-building_17.html.

a project that also uses a vierendeel truss, similar to the modules in this project was analyzed. In the Cantilever house by Anderson Anderson architecture, a steel framed vierendeel truss is divided into five bays, each of which are sixteen feet long. Of these, two of the bays are cantilevered, resulting in a thirty-two-foot cantilever for the eighty-foot-long structure. Thus, by using the steel-framed vierendeel truss, they were able to achieve a cantilever that is 40% of its length.[164] It is generally known that if a cantilever exceeds 33% of the total backspan, economy is lost and may lead to design difficulties. In the design of this project there will be cantilevering modules made of vierendeel trusses out off the main building mass. Therefore, continuous columns will be employed before the cantilever starts to provide the benefits of transferring loads to the ground vertically, allowing modules to cantilever at various lengths. The cantilever length will be dependent on the general cantilever rule of thumb at about thirty-three percent of the buildings back span to remain economical at most locations, but can extend out another seven percent of the backspan for the cantilever according to the evidence found in the Cantilever House by Anderson Anderson. This will be used for balcony extrusions discussed earlier also. With a module maximum module length of sixty-five feet at this projects location, this will limit the room modular cantilever to extend out no more than a maximum of twenty-one and a half feet.

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[164] Mark Anderson and Peter Anderson. 2007. *Prefab Prototypes: Site-Specific Design for Offsite Construction*. New York: Princeton Architectural Press.

Figure 11.26 - Vierendeel truss module cantilever in Cantilever house with plan. Anderson, Mark and Anderson, Peter. 2007. Prefab Prototypes: Site-Specific Design for Offsite Construction. New York: Princeton Architectural Press.

## GRID (Step B 5)

There are many grids that will be utilized for this project, due to the fact that there will be conventionally constructed columns, modules, non-load bearing partition walls, and façade components. First, the axial and modular grids need to determined because they are dependent upon each other. The axial grid will be aligned with the center of columns and the modular grid will use the axial grid, but instead of being aligned to the center it will take module wall thicknesses into account. The Waiea room dimensions were based on an average of either 14’ or 16’ widths. When the design is implemented, the column grid within multiples of 14’ or 16’, but could have 1’ variances due to braced structural frames occurring between units. It was discussed previously that the minimum parking stall dimensions are 8’ 3” wide, so if parking must be accommodated underneath the tower, a grid taking parking stall dimensions and modular dimensions must correlate. Another factor here is that according to the Revised Ordinances of Hawai‘i, columns can extend six inches into the parking stall, providing a little flexibility to these dimensions.[165] An example of this situation would be when two 16’ modules are placed side by side, a 32’ grid is made. This would allow four parking stalls adding up to 33’ to fit within this space because the columns can extend six inches into the two end parking stalls. The internal grid layout will be based upon the dimensions of the bathroom pods and kitchen pods which will vary per module configuration.

Figure 11.27 - Axial grid (left), Modular grid (right). Smith, Ryan and Timberlake, James. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

## FABRICATION (Step B 6)

**Product manufacture** (Step B 6.1)

The choice of using stocked parts or customized parts is what decides the level of customization in the product. In the previous section it was shown that with only limited customization, the value

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[165] Revised Ordinances of Hawaii. “Off-street parking.” Chapter 21, Article 6, Section 21-6.40. Arrangement of parking spaces.

of that customization was almost equal to full customization. This project will therefore use a limited amount of customization that will be stocked and able to be connected to any type of module via a standard interface. The type of customization in the product will be assembled to stock or assembled to order because you can expect to get mass production prices with mass customization qualities. Assembled to stock or order products have set designs with standards and while customers can request variation to a system, it will be a predetermined stocked variable. This decreases lead times and cost, while giving the impression of customization and flexibility. To further describe the type of product manufacturing process, this is essentially a business production strategy where certain elements of a product are customized to a certain extent and are mass produced. For example, there may be ten versions of a balcony to choose from giving a feeling of customization, but each of the ten options had ten products manufactured and stocked. Therefore, when a customer requests a certain balcony that they assume are being customized, they are actually customized stock products. This strategy requires that the basic products are already manufactured, but not yet assembled.[166] [167]

Figure 11.28 - Customized elements stocked before assembly. Smith, Ryan and Timberlake, James. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

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[166] Ryan Smith and James Timberlake. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

[167] Juliana Mikkola. 2007. “Management of Product Architecture Modularity for Mass Customization: Modeling and Theoretical Considerations.” *IEEE Transactions on Engineering Management* 54, no.1: 57-69.

Figure 11.29 - Degree of customization. Piller, Frank, Moeslein, Kathrin, and Stotko, Christof. 2004. “Does mass customization pay? An economic approach to evaluate customer integration.” *Production Planning and Control* 15, no.4: 435-444.

**Mass customization** (Step B 6.2)

For this project, soft mass customization will be used instead of hard. The first reason is because it is intended that components may be swapped or shared, while the basic body remains the same. Based on Reynolds statement, this project will have the modules contain a standard component of a chassis and other components can be modified in order to achieve variety and limit the cost. There will be a limited few module body chassis to choose from, and a slightly larger option of components that will be installed or attached. This soft mass customization chosen will depict the type of mass customization models that can be used. The models that can and will be applied are component sharing and component swapping. The component sharing model will be used when the same bathroom or kitchen pod will be used for a few different module chassis configurations. The component of the pod remains the same, but the module chassis body changes. The component swapping model will be used for attachable components that vary in form, but connect to the ends of modules the same way via a standard interface.[168] [169] According to Salvador et al., the most important thing to decide is what will be customized and how much will it be customized.[170] In this project, the first thing customizable is the space created by partition walls, and there will be a few configurations that will be used on each module chassis. Next, the bathroom and kitchen pods will be customized, but only into two or three different variations. The last customizable aspect will be the attachable component either containing extra interior space or a balcony. The attachable components of either enclosed space or balcony space will each contain around ten options each, giving the façade a dynamic variation that also allows the components to be assembled to stock for decreased customization costs. The reason the attachable components contain the most customization is because while companies like the FAB house are currently offering mass customization, it is mostly through materials and doesn't give options to manipulate geometries. This project will experiment with offering mass customization that changes the geometry of spaces.[171] There is also the fact that the façade design can be the key to preventing monotony and repetition of modular design. The façade will manipulate cantilevers, setbacks, and enclosure systems to undulate the form.[172]

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[168] Jordan Reynolds. 2014. "Modern Mass Customization – Rule 1: Modularize your People, Processes and Products." Accessed October 17, 2017. http://viewpoints.io/entry/modern-mass-customization-rule-1-modularize-your-people-processes-and-produ.

[169] Ryan Smith and James Timberlake. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

[170] Fabrizio Salvador, Cipriano Forza, and Manus Rungtusanatham. 2002. "How to mass customize: Product architectures, sourcing configurations." *Business Horizons* 45, no.4: 61-69.

[171] Branko Kolarevic. 2015. "From Mass Customisation to Design 'Democratisation'." *Architectural Design* 85, no.6: 48-53.

[172] Ahmet Dincer, Gulen Cagdas, and Haken Tong. 2014. "A computational model for mass housing design as a decision support tool." *Procedia Environmental Sciences* 22: 270-279.

Figure 11.30 - Soft mass customization procedure. Salvador, Fabrizio, Forza, Cipriano, and Rungtusanatham, Manus. 2002. “How to mass customize: Product architectures, sourcing configurations.” *Business Horizons* 45, no.4: 61-69.

An example to prove the point that by choosing these options, the mass customization will not increase costs for the purpose of this project is the building 8 Spruce Street by Frank Gehry. This project uses mass customization on the façade component in the form of ripples and leaves one side as a standard flat façade. Dennis Sheldon, the chief technological officer of Gehry Technologies, stated that in order to keep a competitive budget the one side was left flat and that the cost of the envelope system was not more expensive than a conventional curtain wall.[173]

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[173] Shaul Goldklang. 2013. “Mass-Customization in Commercial Real Estate: How the aviation industry can help us create beautiful buildings that add value.” Masters thesis, Massachusetts Institute of Technology.

Figure 11.31 - 8 Spruce Street envelope of mass customized ripples and one flat side. Goldklang, Shaul. 2013. “Mass-Customization in Commercial Real Estate: How the aviation industry can help us create beautiful buildings that add value.” Masters thesis, Massachusetts Institute of Technology.

## DELIVERY (Step B 7)

### **Transportation** (Step B 7.1)

The modules in this project will be using dimensional shipping rather than container shipping due to their large size. They will first be transported by a shipping barge which may be fully rented out and stocked with modules for this project. Then, for road shipping the modules comply with road transportation maximum limitations in Hawai‘i.  They main module body will not have to be broken down, but the attachable components may be installed when they arrive on site. These separate components will be grouped and transported together on a trailer for efficiency. Upon arrival to the site, they will be stored on a small staging ground for final attachments which will be made before being hoisted into position. Although container transportation on roads is less costly, the amount of connections that will have to be made on site as well as the amount of lifts the crane will make actually make the larger modules more economical.[174] **[175]** The figure below shows a single drop trailer that is chosen because it can accommodate module lengths of up to 66 feet and it also has a low deck of 30 inches which is important because the height of the module needs to accommodate a floor to ceiling height inside of 9 feet 6 inches. With a deck height of 30 inches and a maximum height allowed on the roads that will be takenat 16 feet, that means that the actual module height can be 13.5 feet which allows for a 12 foot interior ceiling height. This exceeds the maximum floor-to-ceiling height in Waiea and is therefore sufficient.

Figure 11.32 - Trailer options for module transport with a low and long deck. Landstar Trucking. *Landstar Trailer Options.* Accessed December 8, 2017. https://www.americasbesttrucking.com/landstar-specialized-heavy-haul.

**Craning** (Step B 7.2)

For this project, the lifting placements will be at the corner posts because these are the load bearing elements in the module. This necessitates the use of a separate lifting frame as a result though and the lifting frame will be equal to the plan dimension of the unit to not cause horizontal or shear forces during hoisting. This method used will be lifting from a pair of cross beams and is used for larger modules.[176] The next important step is to select a crane, and this depends on weight, height, mobility needed, and reach primarily. As a rule of thumb, prefabricated modules that are 95% completed and have maximum dimensions of 47.5' length by 17' width by 14.5' height, have a typical maximum weight of 16 tons. These are similar to the dimensions are

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[174] Gerald Staib, Andreas Dörrhöfer, and Markus Rosenthal. 2008. *Components and Systems: Modular Construction: Design, Structure, New Technologies*. Basel, Switzerland: Birkhauser.
[175] Ryan Smith and James Timberlake. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.
[176] M. Gorgolewski, P. Grubb, and R. Lawson. 2001. *Modular Construction using Light Steel Framing: Design of Residential Buildings*. Silwood Park, Ascot: The Steel Construction Institute.

degree of finishes that will be used for this project. Dividing this rule of thumb into tons per feet equals about .33 tons per foot of length. While the modules for this project may be up to 65’, that means that as a rule of thumb, the maximum weight of the modules will be approximately 23 tons.[177] The crane selected for this project is a tower crane because mobility of the crane is not needed, the height of high rise buildings requires a tower crane, and the reach radius and lifting capacity is generally larger. For steel framed modules a 100 ton crane is generally used because an additional force of 25% more than the weight of the module should be considered due to the dynamic forces applied when lifting. This project could use a 30 ton crane at the minimum though with the given specifications. It should be noted that an average installation rate of 6 to 8 modules per day is realistic, but 10 to 12 can be achieved.[178]

Figure 11.33 - Steel frame module lifted from rectangular frame. Lawson, Mark, Ogden, Ray, and Goodier, Chris. Design in Modular Construction. Boca Raton, Florida: CRC Press, 2014.

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[177] Kodumaja. “We build from prefab modules.” Accessed December 8, 2017. http://www.kodumaja.ee/en/Construction-method-and-technology/We-build-from-prefab-modules

[178] Mark Lawson, Ray Ogden, and Chris Goodier. 2014. *Design in Modular Construction*. Boca Raton, Florida: CRC Press.

# CHAPTER 12. DESIGN APPLICATION

Considering the advantages and disadvantages stated in the beginning of the paper, previous examples through case studies, and the fundamental and design methodology, this design application will reconstruct a portion of the Waiea tower. The purpose is to demonstrate previous methodologies, how to construct a building with a modular system economically, and how to construct a complex form in a high-rise structure using prefabricated modules. Design decisions will be shown using the principles explained earlier in the paper. This design application will demonstrate general steps that have to be taken in order to construct a prefabricated modular tower that has variations feasibly in terms of economy and structure. It will not cover the detailed technical aspects of the construction. The purpose of this chapter is also to go through the design process for a prefabricated modular high-rise to a certain extent in order to reconstruct a portion of the Waiea tower, enabling a cost and schedule comparison while retaining the qualities of Waiea. The Waiea tower has a core that separates the East half of the tower from the West side. While the West side of the tower is a typical extruded box, the East side has a curvilinear façade on the entire exterior. For this chapter, the East half of the tower will be reconstructed, keeping all of the original design features the same, such as ceiling heights and square footage. It is important to state that the purpose is to compare a modular construction method to a conventional one, so finishes, appliances, and other interior fit out elements will not be covered because these elements will remain the same. The reason is because it is not intended to compare interior design decisions, but the structure itself. The Waiea tower does have the most luxurious interiors though, so it can be assumed that the modular prefabricated system proposed will also be of the same high quality interiors, contradicting popular connotations that modular prefabricated buildings are low quality.

## SITE

This site is located adjacent to Ala Moana beach park and Kewalo Harbor in Honolulu, Hawai‘i. It is in the Kaka’ako neighborhood and this site is part of the Ward Village masterplan. The site is the location of Waiea Tower, a residential high-rise building, and this project proposal is on the same parcel. The address is 1118 Ala Moana Blvd, Honolulu, HI 96814. This proposal aims to reconstruct a portion of the Waiea tower using prefabricated modules to lower construction costs, enhance the façade curvature, and also achieve all of the same unit features without compromising important aspects such as ceiling heights, square footage, and finishes.

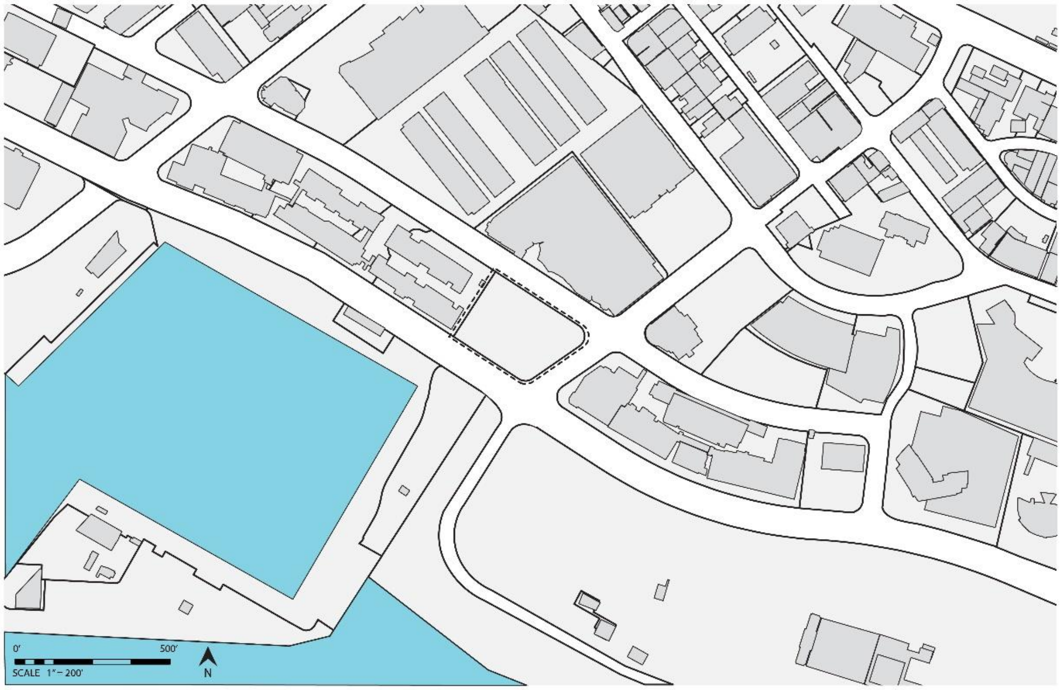

Figure 12.1 - Project site location in Kaka’ako in Honolulu, Hawai‘i.

Figure 12.2 - Tmk parcel over satellite map.

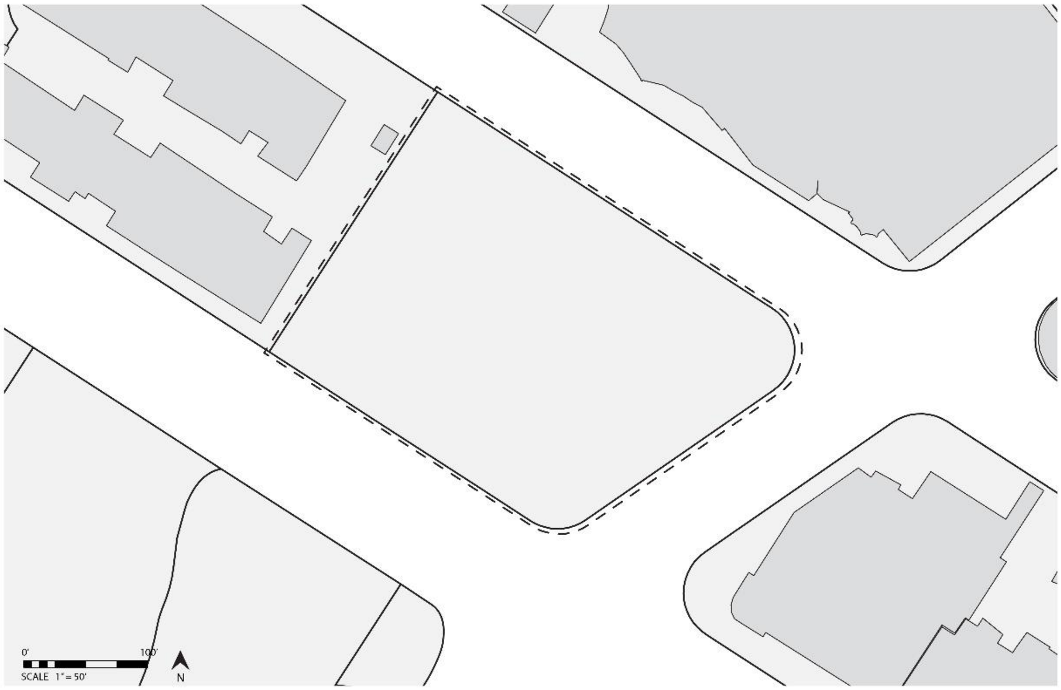

Figure 12.3 - Tmk parcel map.

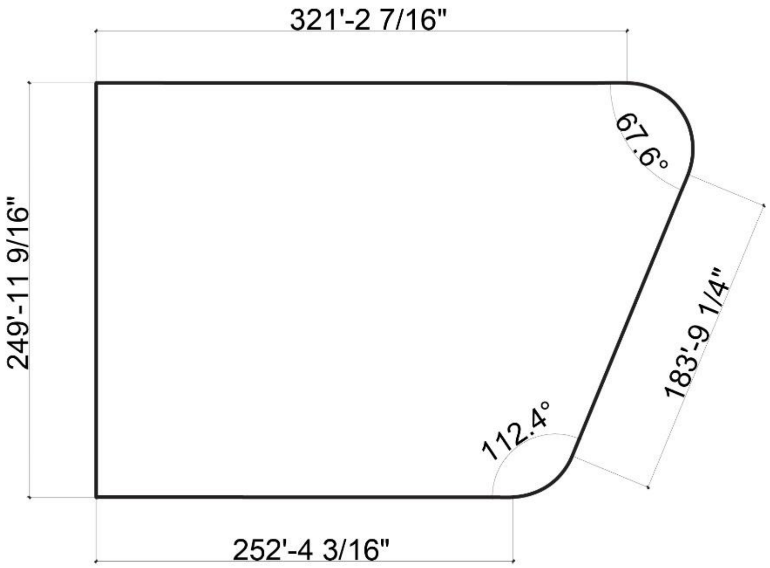

Figure 12.4 - Project site parcel dimensions.

## COMPARISON

The interest of this project is making a comparison of a steel modular structure to a conventional cast-in-place concrete structure in a building that has large units and a complex form. Using the same site, square footage, and the inspiration or concept, this study will reconstruct and compare a portion of a thirty-six story conventionally constructed concrete structure to that of a modular structure. The building that will be used for this comparison is the Waiea tower, a residential high-rise building. The building construction schedule and cost will be examined to obtain results.

Here are some important points to note that deal with the comparison. First, the podium is used for parking and is site built, so for the purpose of this comparison, the podium will not be factored into the equation. This is because the site built podium will be identical for both options. Next, the tower has an East and West component along with a core in between them connecting the two sides. For the purpose of this comparison the West side of the tower and the core will not be taken into consideration. This is because they do not have complex forms that can be optimized with modularity. The purpose of this comparison is to compare modular construction to conventional construction for complex forms to obtain results on if modular construction can become more economically feasible for luxury high-rises while also enhancing the curvature of the form. Therefore, this project will isolate the East side of the tower and disregard the podium, West tower component, and the core. To make this study an ‘apples-to-apples’ comparison, the building forms inspiration of a fishing net and a wave will remain identical although the overall appearance may change.

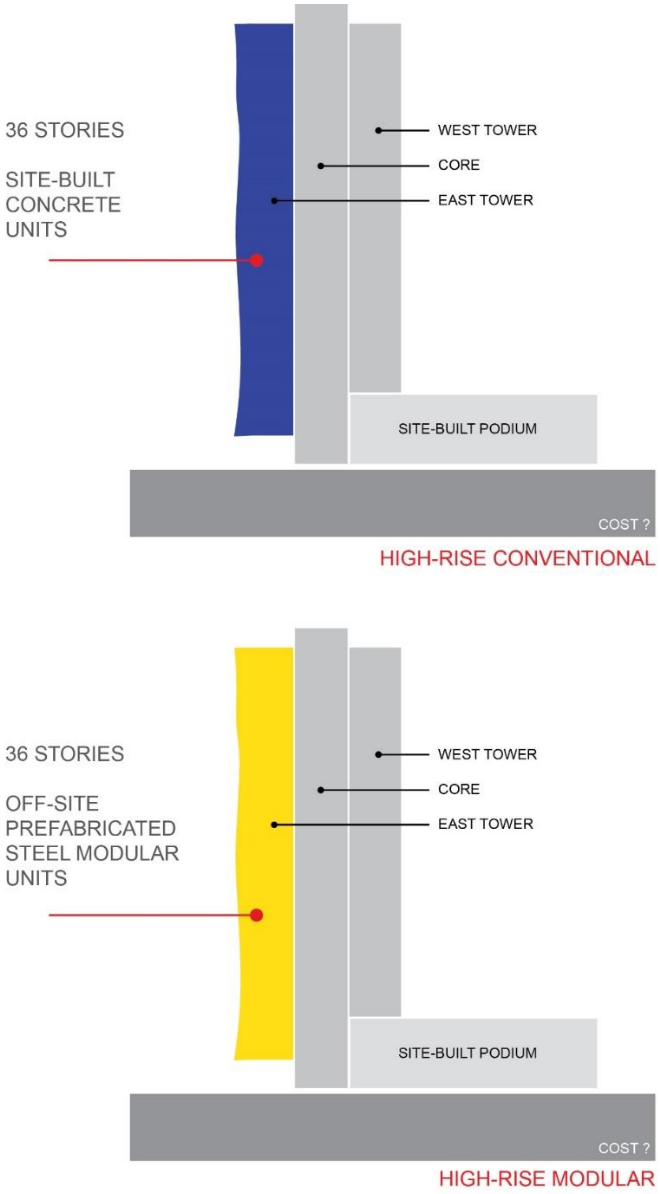

Figure 12.5 - Demonstrating the component isolation for the comparison.

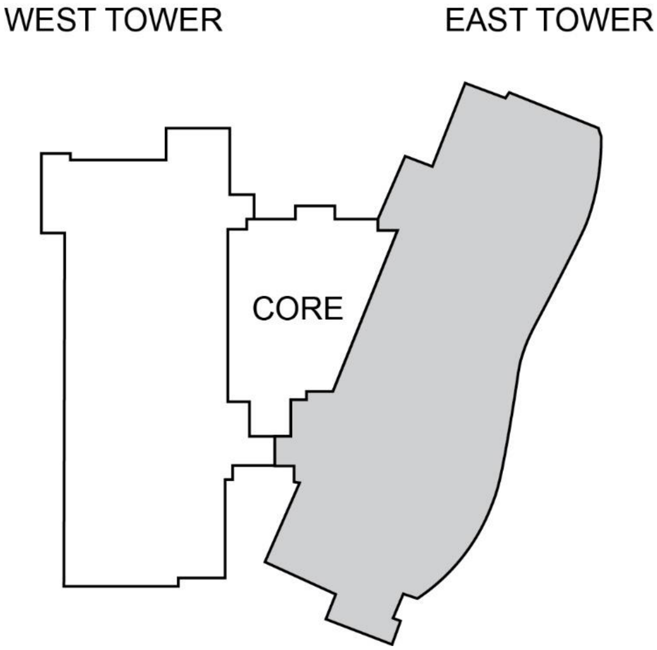

Figure 12.6 - Plan view highlighting the East tower.

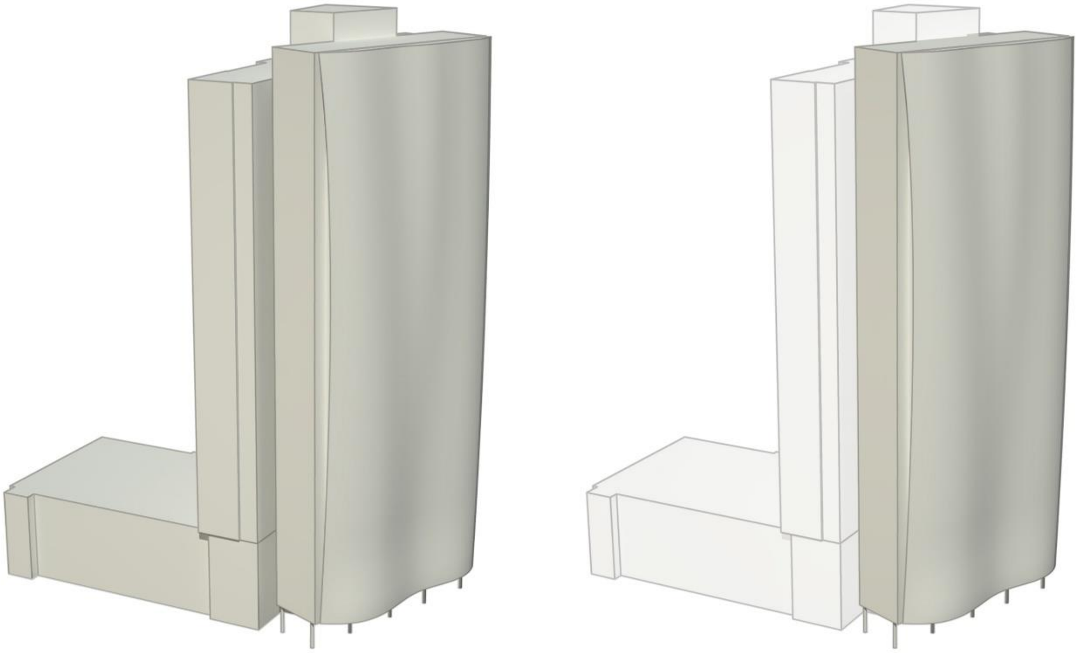

Figure 12.7 - Isolating the East tower from the podium, core, and West tower.

## PROGRAM

The program of the Waiea East tower will be represented here as a section to show how the tower is broken down by floors. For the purpose of this project, this program will remain the same. Starting at the ground, there is a porte cochere that spans floor one and two. Floor 3 contains structural and mechanical elements. Floor four is used for storage. Floor five is for guest room accomodations. Floor six is a standard residence. Floor seven contains amenities. Floor eight through thirty-one have standard residences. Floor thirty-two through thirty-four have penthouse units. Floor thirty-five and thirty-six have grand penthouse units.

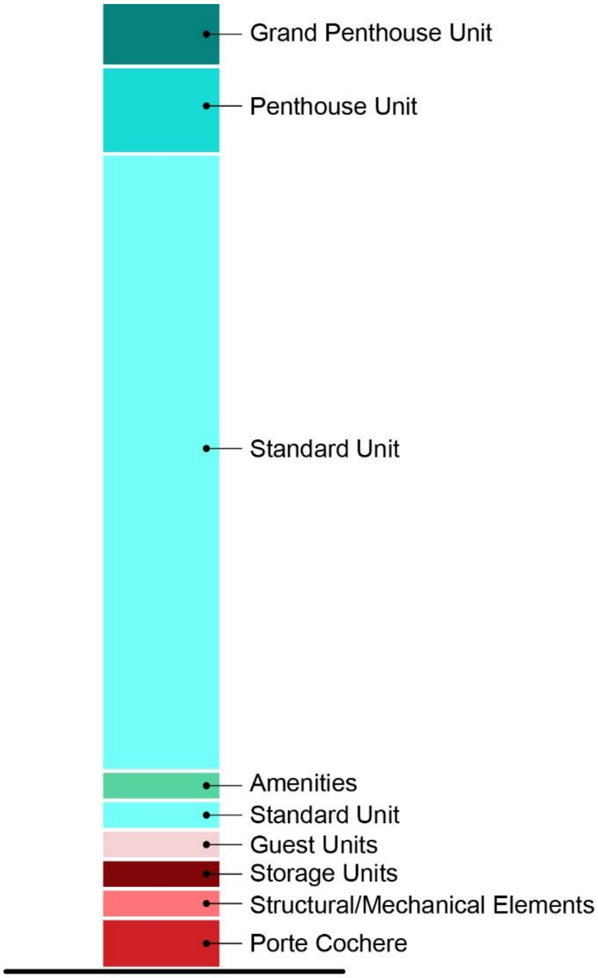

Figure 12.8 - Waiea East tower program (section view).

# ISOLATING COMPONENTS

The purpose here is show how the East tower will be decomposed into a standard rectangle component, a foyer component, a lanai component, and a façade component for modularization. The East tower is split at a point where a standard rectangle can be extacted, leaving the façade componet also isolated. The foyer and lanai components can also be extracted off of the rectangular component as well and it wil be demonstrated here.

This will begin by dividing the East tower into four components to generate a standard rectangle component, an undulating façade component, a foyer component, and a lanai component. The division will occur at 41' from the West wall because that is the point at which the new geometry begins. This allows a standard rectangle component to be extracted to enable feasible modularity. The façade, foyer, and lanai components are also split away from the rectangular component by the edges of the rectangle as the cutting planes.

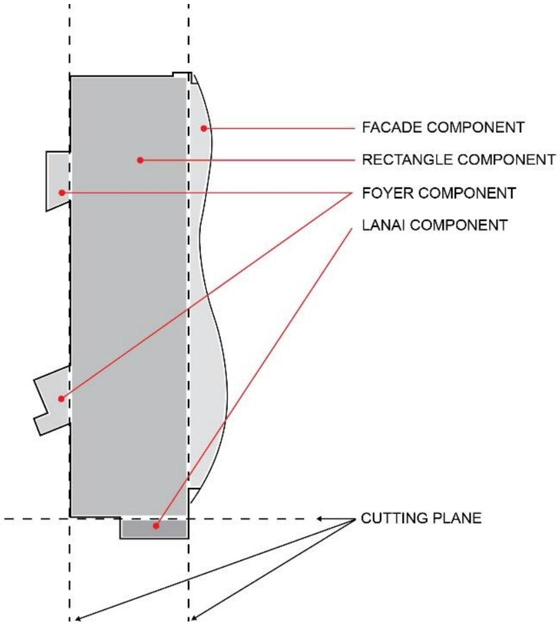

Figure 12.9 - Cutting planes dividing the mass into four components.

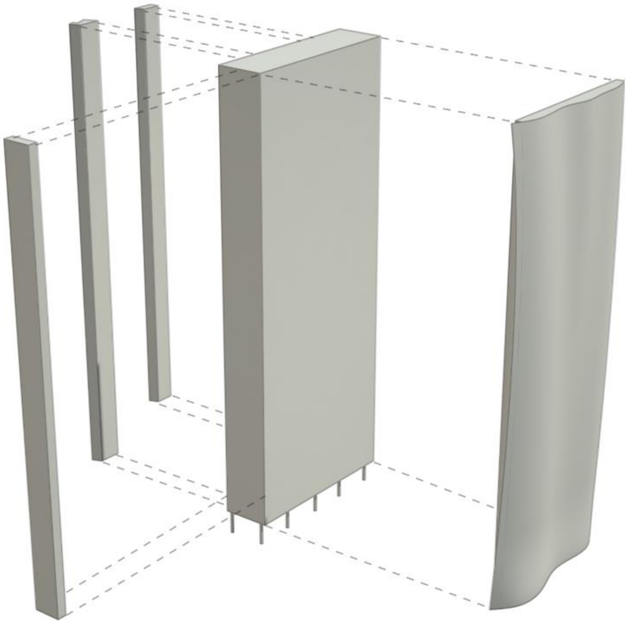

Figure 12.10 - Exploded diagram isolating components of the East tower.

## MODULARIZATION

The purpose of this section is to explain how the current East tower of the Waiea building will be enhanced and modularized using the components extracted. This section therefore examine various elements such as how to create a grid and basic building block modules, how to modularize the structure for efficiency, how to enhance the curvature of the façade, how to modularize the façade, how to create attachable components to compose the façade, how to crate modularized components to vary lengths, how to modularize the foyer component and lanai component. This will begin with the rectangular component before moving to the stabilization. Then the façade component will be explained followed by the foyer and lanai components.

### Rectangular Component

Grid and chassis module:

For the rectangular component, the first grid established is in plan view in order to divide the structure up into modules that will accurately fit within the comparable floorplan. This grid will also take structural frames between modules into consideration. The grid spacing is shown below as well as the types of modules that will compose it. After this, an elevational grid is made because the floor-to-ceiling heights vary per floor. It is shown here how the types of modules are further divided into more categories, thus making more efficient modularization. The modules created are of Module A, Module B, Structural module A, and Structural module B. Structural module A contains a structural frame and Structural module B can either be open to allow circulation, or closed with a partition to divide units. These modules are basic building block modules and are made from a vierendeel truss chassis. In later sections, units will be discussed further such as how the basic building blocks are modified for openings and enclosures.

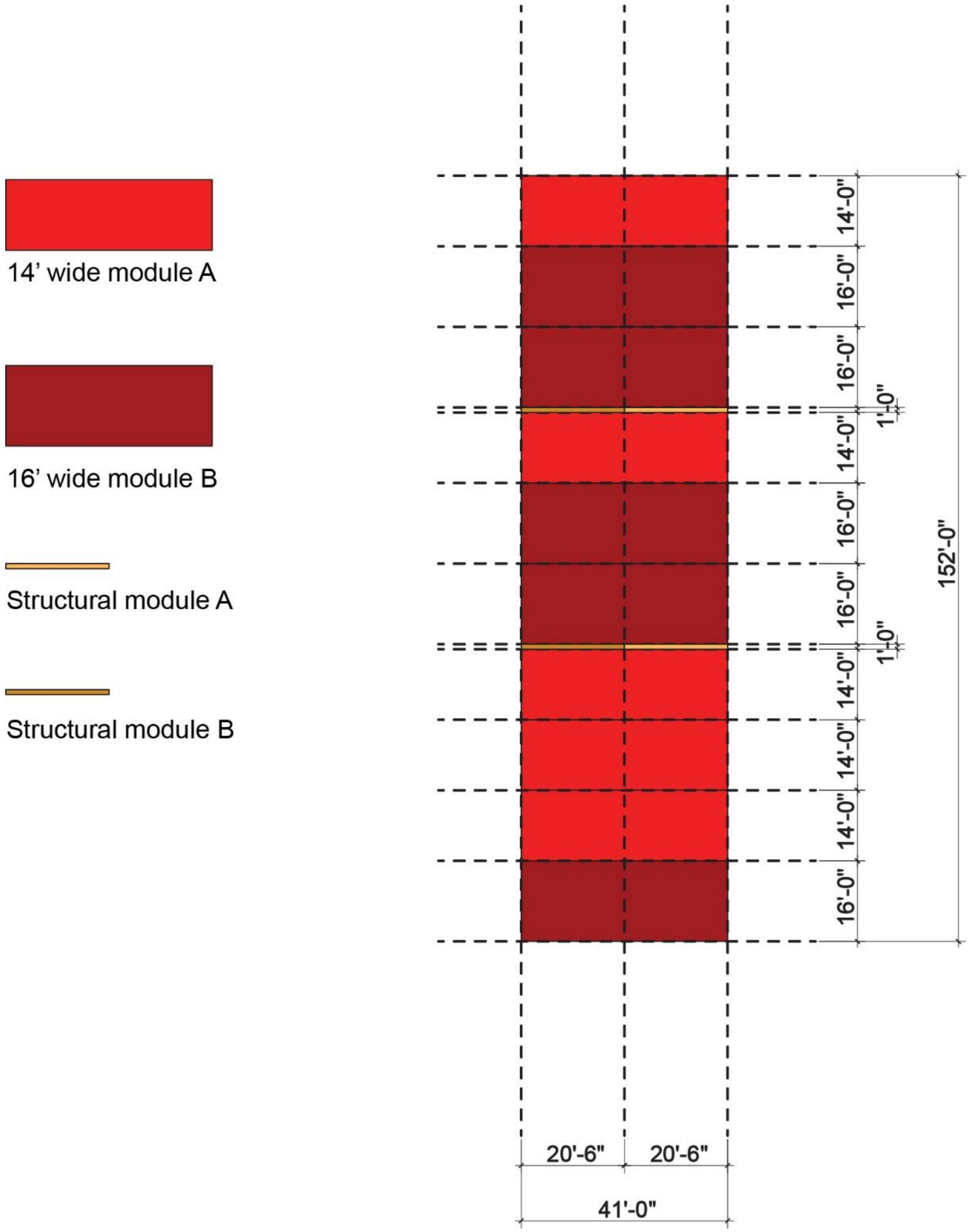

Figure 12.11 - Plan view grid for rectangular component.

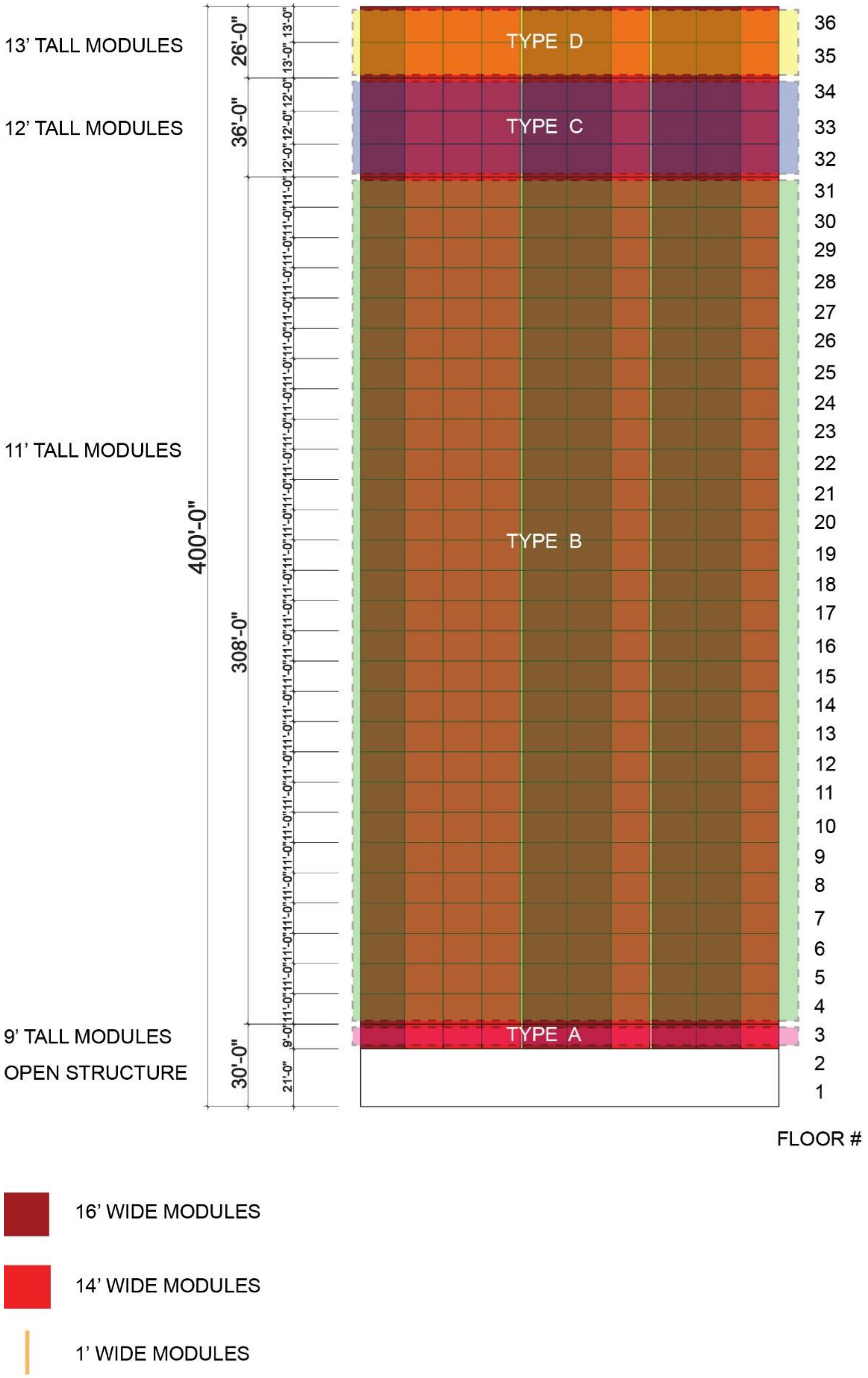

Figure 12.12 - Front elevation grid for rectangular component.

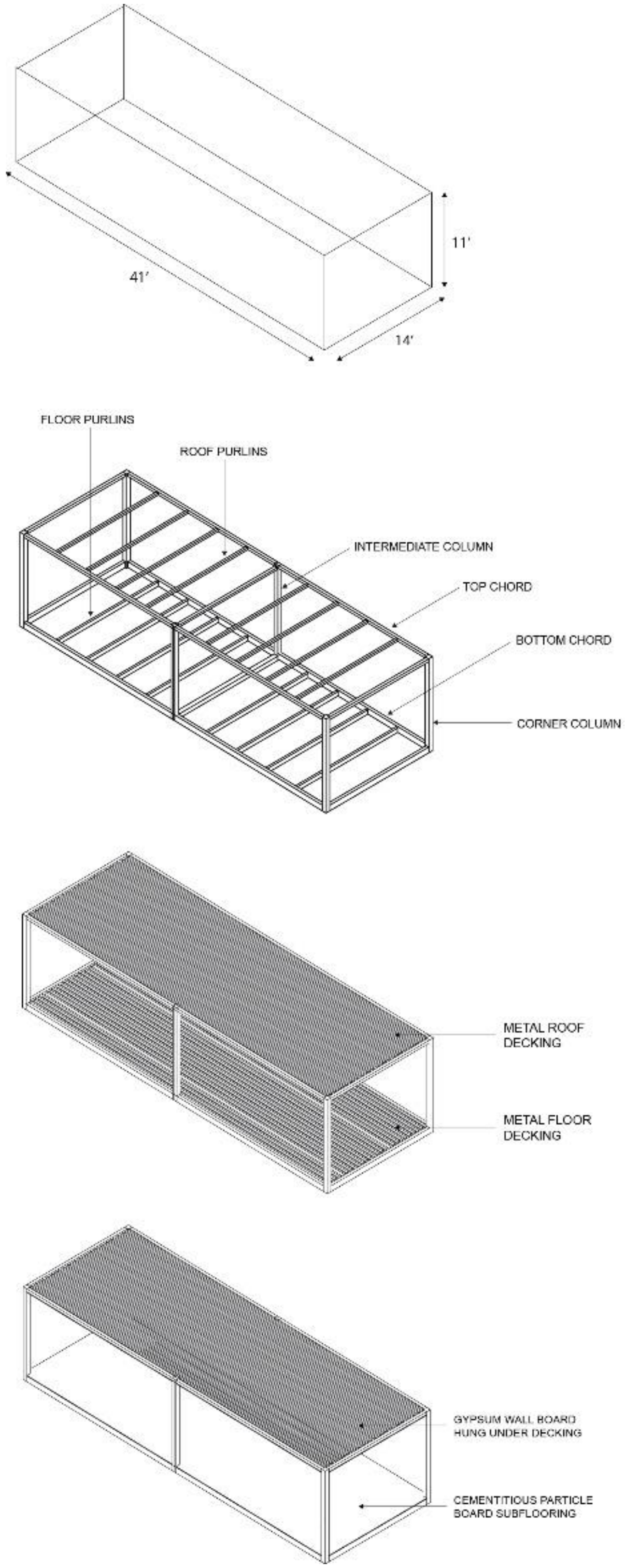

Figure 12.13 - Typical module chassis composing all base modules of product family.

Table 12.1 - Basic building block module chassis breakdown by amount (16 types of modules)

Module Chassis Table

| | Type A | Type B | Type C | Type D |
|---|---|---|---|---|
| Module A (14’ wide) | 5 | 140 | 15 | 10 |
| Module B (16’ wide) | 5 | 140 | 15 | 10 |
| Structural Module A | 2 | 56 | 6 | 4 |
| Structural Module B (open) | 2 | 0 | 6 | 4 |
| Structural Module B (closed) | 0 | 56 | 0 | 0 |

After modularizing the rectangular component of the East tower, the table above shows that there will be sixteen different base chassis modules produced.

Stabilization:

The stabilization of the East tower resides in the rectangular component, so it will be discussed here. The stabilization begins by using the established grid to create a column grid and layout first. The columns which rise from the foundation will be spaced based on a multiple of units rather than each one in order to keep the first-floor plan open. Beginning at the ground floor as well are the braced structural frames. These are lateral supporting elements and two are placed on the long side of the modules between modules that separate units, while another is placed along the back side of the modules that backs up to the core. It should be noted that there will be a braced frame placed in each direction around the core as well and the East tower will be tied back to the core, but that is not shown here. The plinth which provides a level platform for modules to be stacked upon will be demonstrated from here. Transfer beams and diagonal bracing will be located within the plinth to adequately transfer loads and support vertical load paths that aren’t continuous to the ground. The corner posts of the basic module chassis are also a part of structural stabilization as they provide the vertical load transfer. It will be demonstrated here how there will be varying plate thicknesses of the square hollow tubes so that the material weight and strength are appropriate for their location vertically.

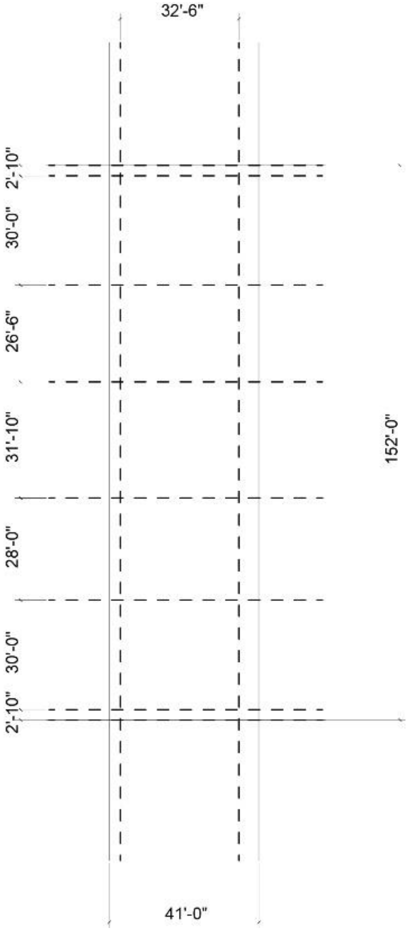

Figure 12.14 - Example of the Waiea East tower grid.

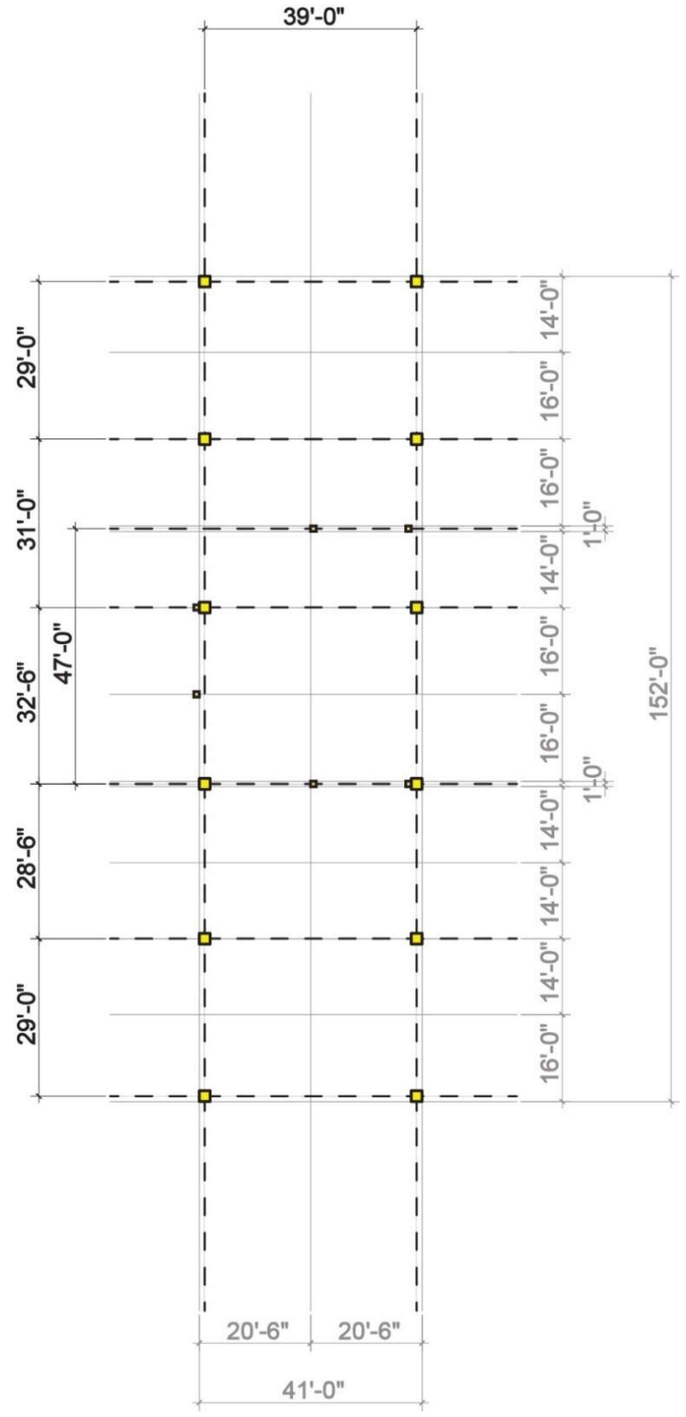

Figure 12.15 - This projects column grid overlayed on modular grid.

This demonstrates how the grid for the existing tower is used and modified for modularity. It shows the column grid for the plinth overlayed onto the modular grid spaced at every other module.

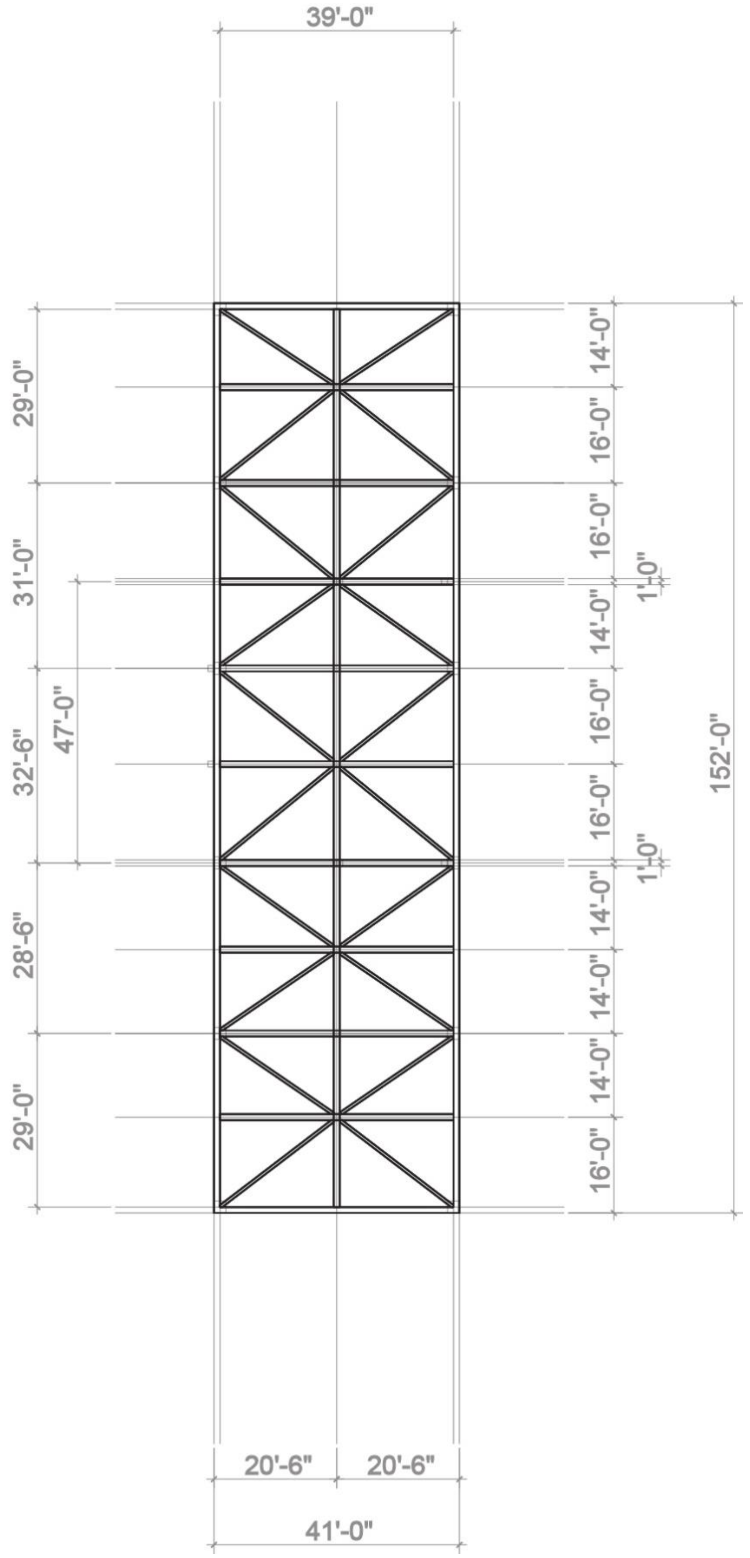

Figure 12.16 - Plinth (platform) transfer beams and diagonal bracing overlayed on modular gid.

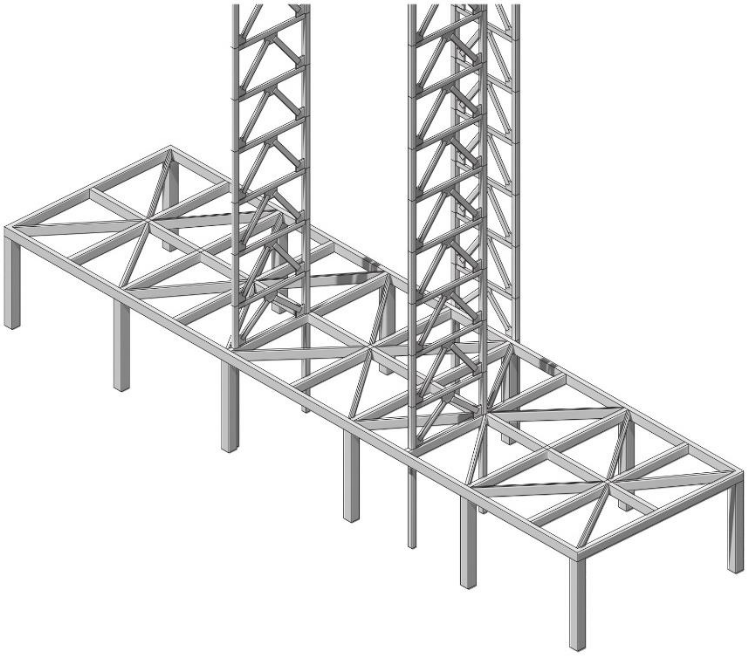

Figure 12.17 - Columns, plinth, and structural frames.

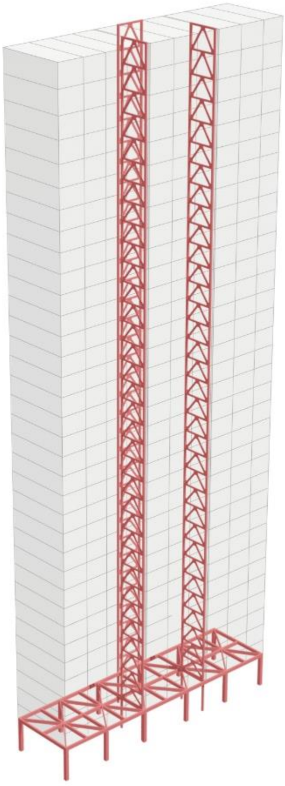

Figure 12.18 - Structural endoskeleton supporting base chassis modules.

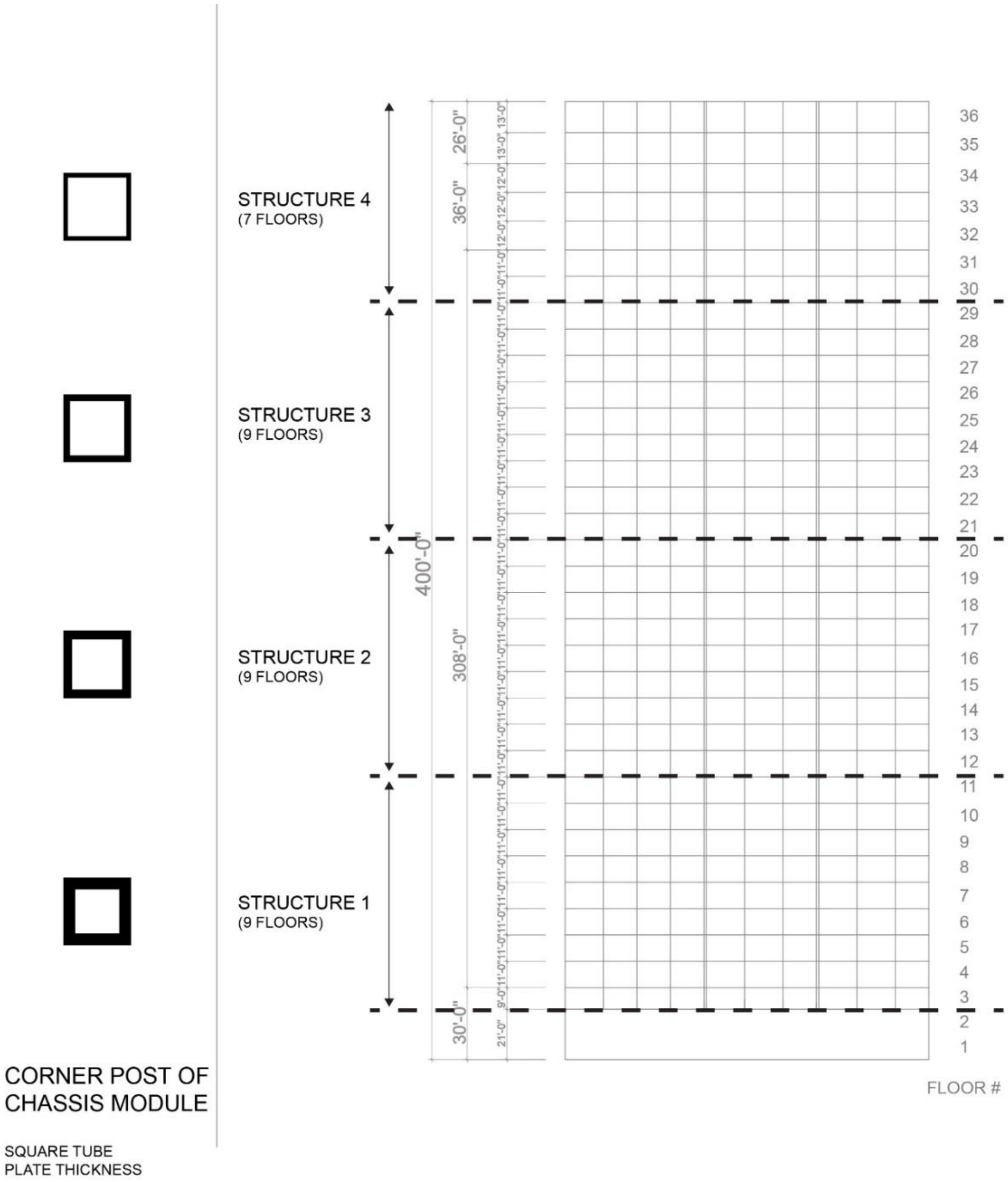

Figure 12.19 - Square tube corner post in chassis module varies plate thickness decreasing with height.

In the base chassis modules, it was shown that there were sixteen different types of modules. The figure above is showing how the corner posts of those modules will be separated into four categories of plate thicknesses before installed into those modules to maximize economic efficiency in materiality.

### Façade Component

Façade curve enhancement:

The façade of the Waiea tower undulates in and out and varies from floor to floor and unit to unit. After examining the building floor plans, it was found that 'unit A' from floors 8-31 had the highest degree of curvature and extruded the farthest away from the structure. Further examinnig 'unit A', it is shown that the floor plan can be seperated into a standard box element and the curvilenear façade element. The standard box portion extends out 41' from the West wall and is common throughout the entire structure. The façade element at its maximum extends out 13' 6.25" from the initilal 41'. What this project will do to enhance the curvature is to examine how far the facade currently extends away from the standard box element and see how far a modular system will allow it to extend along with adding additional curvature sectionally. Although the façade will undulate further forward than the current position, it will also undulate further back to ensure that the overall square footage per floor remains the same. The individual units on a floor may deviate slightly from the current square footage, but the overall floor square footage and building square footage will remain the same.

According to previous sections about cantilever lengths, the vierendeel truss module can cantilever 40% of the module length while providing a column at 60% of the module length. For this project, the standard box element length of the Waiea tower of 41' will be used. With a vierendeel truss module and a column at 60% of the entire length at 41', this equates out to allowing a 16' 4.8" cantilever for the remaining 40%. Therefore, the enhancement of the façade curvature for this project will allow the cross section curves to increase and extend out an additional 2' 10.5" at the maximum and is shown below.

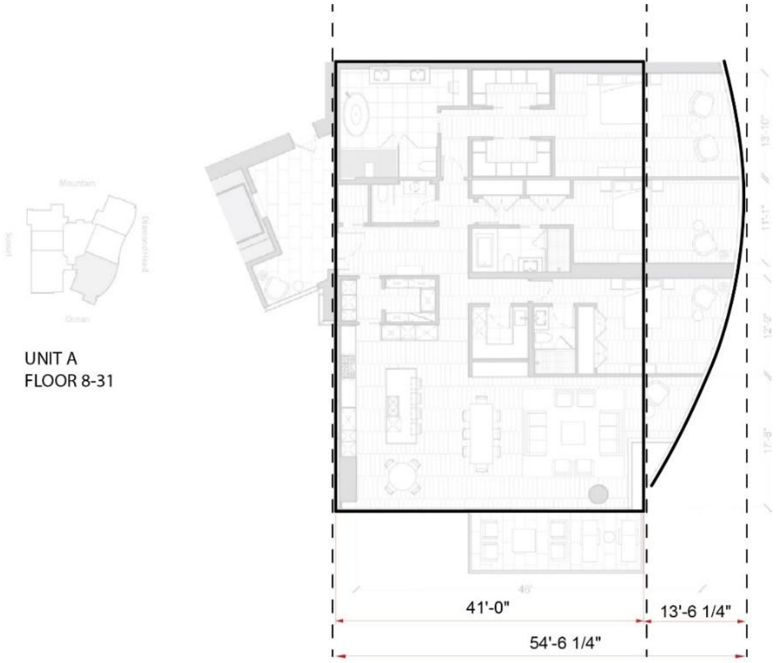

Figure 12.20 - Unit A on floor 8-31 division into box and façade element showing lengths. Hughes, Howard. *Waiea mini book.* Ward Village.

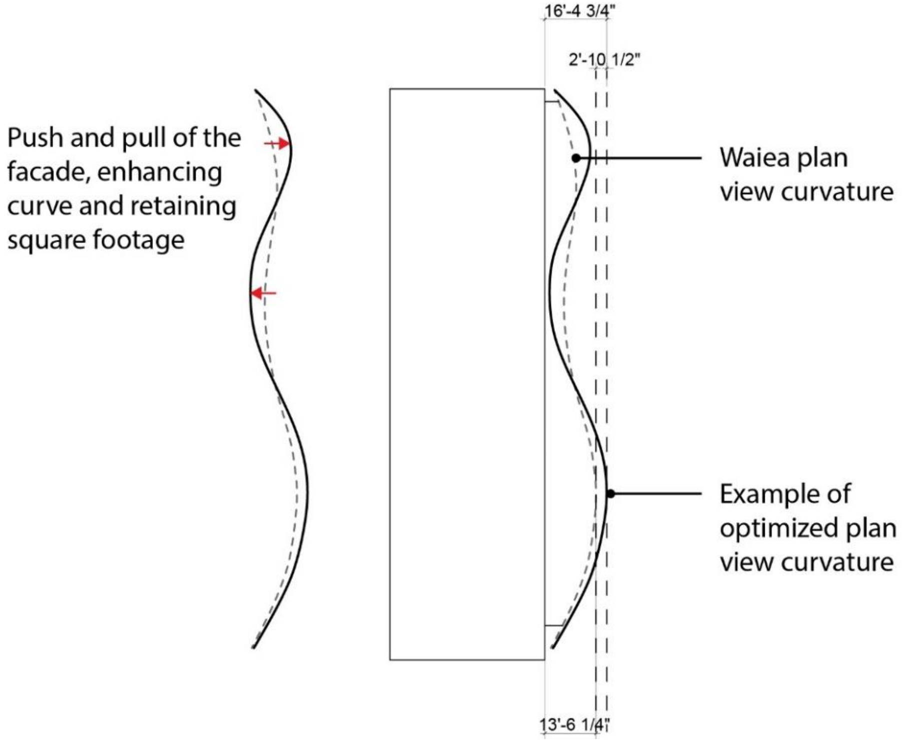

Figure 12.21 - Enhancing cross section curvature (plan view) from cantilevering modules.

Grid and modularization:

Looking at the façade component of the East tower from the (East) front elevation, it has been shown that there are differentiating module heights and therefore, will need a grid to start the modularization and optimization of this component. The grid will inform the design by finding how often the curvature can be rearranged and how often it can be repeated for efficiency. After this, the façade component will be enhanced using newly deriven curvature and generating façade modules for efficiency. This will be demonstrtaed in a table that allows one to see how often each floor of the façade component will be repeated. Once the façade component is enhanced and modularized, the next step is isolating a chassis element and an attachable façade element. The purpose of this is to create varying, but repeatable elements that can be mass customized and produced for lower costs and increased efficiency using rules stated previously. The chassis element that will be extracted will be welded to the existing chassis in the factory to extend the vierendeel truss. The attachable façade element will be connected to the corner posts of each individual module. Further explaining the concept and connections are the figures below.

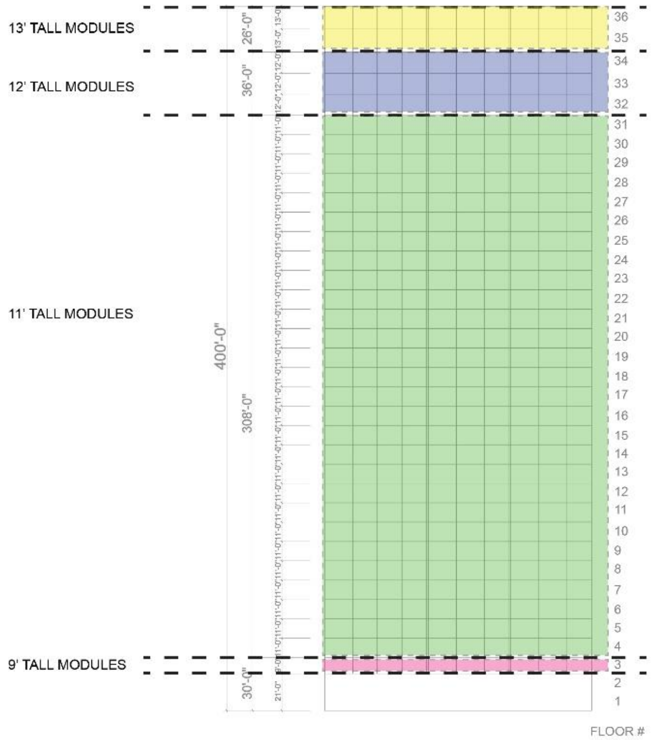

Figure 12.22 - Grid division by module heights.

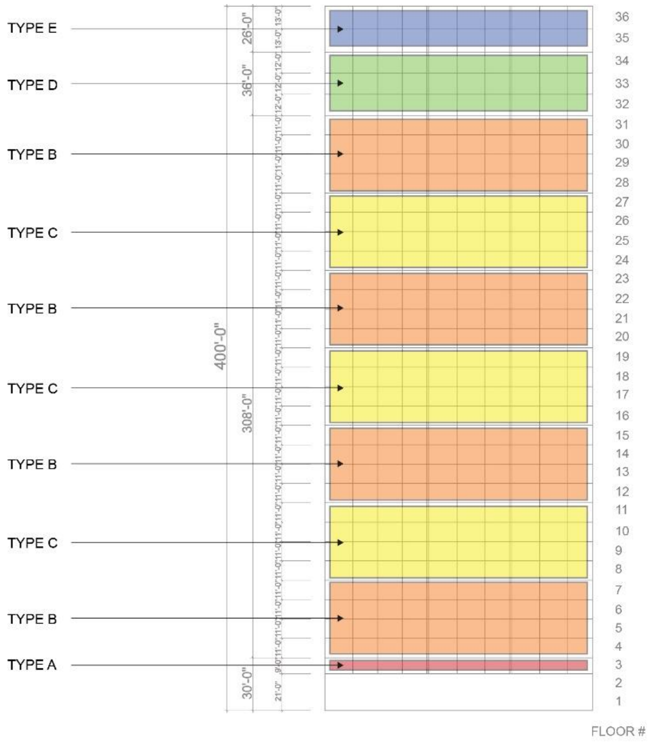

Figure 12.23 - Facade component types (Type A – 9', Type B &C – 11', Type D – 12', Type E – 13').

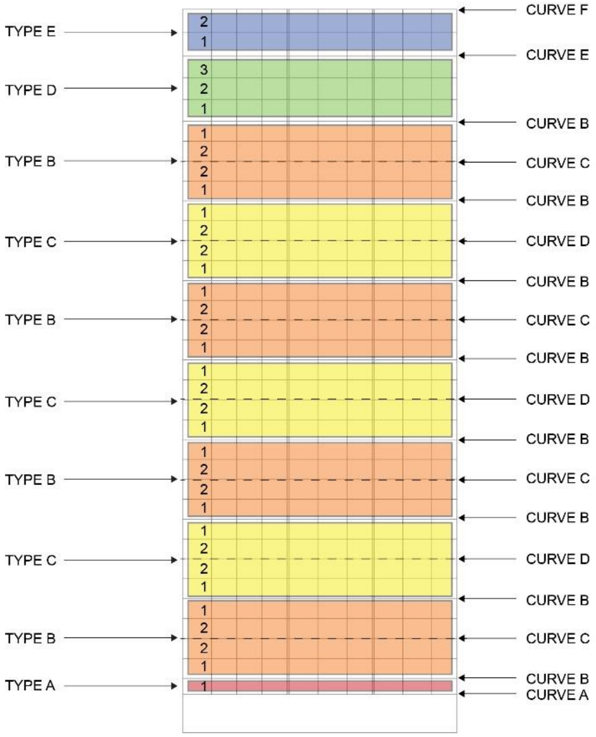

Figure 12.24 - Façade component types by floor showing curvature repetition.

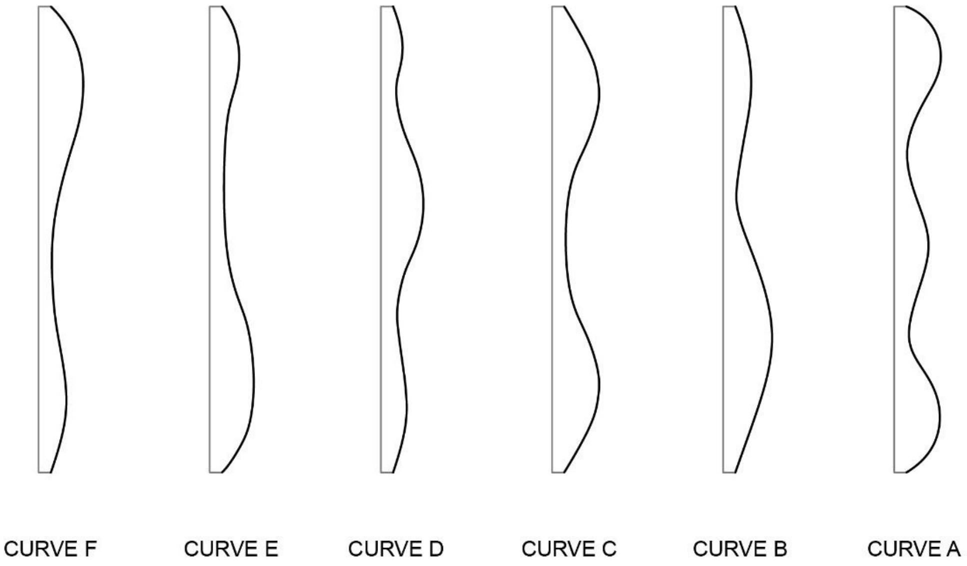

Figure 12.25 - Six different curves used to create façade components.

Compared to the Waiea East tower which has 34 floors, each with different facades, this design will have 10 varying floor plan facades interchanged. By using mass customization methods mentioned earlier, this will provide mass production costs with variation.

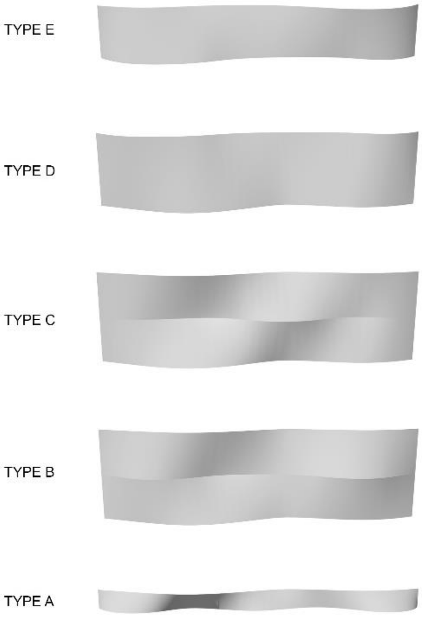

Figure 12.26 - Types of façade components.

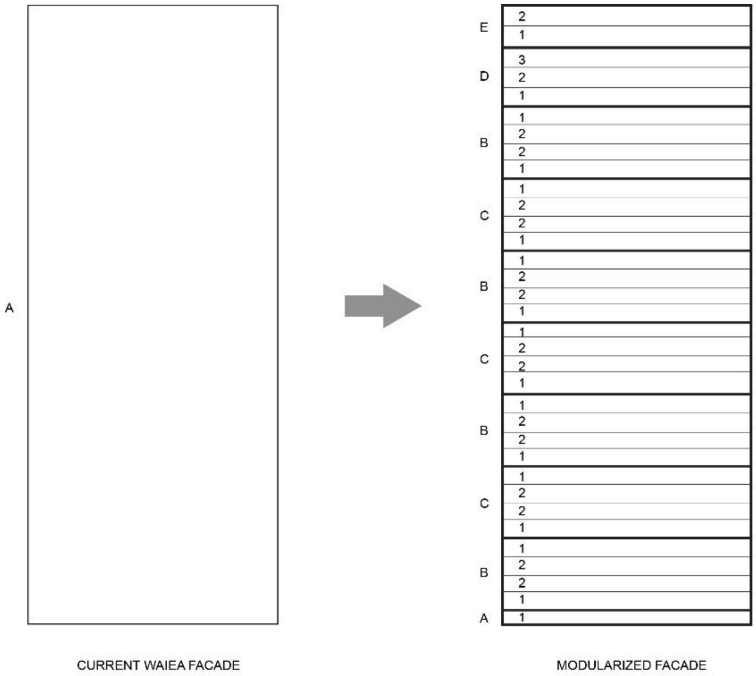

Figure 12.27 - Comparisson of current Waiea façade to modularized enhanced version.

Figure 12.28 - Comparisson of current Waiea façade to this projects.

Table 12.2 - Facade component type broken down by floor level (10 different facde floor plans)

**Facade Component by Floor**

| | Type A | Type B | Type C | Type D | Type E |
|---|---|---|---|---|---|
| #1 | 1 | 8 | 6 | 1 | 1 |
| #2 | 0 | 8 | 6 | 1 | 1 |
| #3 | 0 | 0 | 0 | 1 | 0 |

This table shows that there will be ten different facades produced that extend across the entire East façade and will be repeated up to eight times. Using ten rather than thirty-four different façade floor plans results in a 70.6% decrease in the number of customized pieces while still retaining the same conceptual goal and aesthetic desired. These are spaced out and made into a less monotonous repetition that has a hidden pattern because the pattern starts one way, then has repetition, and then ends a different way. This helps give variety while following the rules of thumb stated in the graphs below. The graphs below show that the reason there are ten varying floor plate facades rather than thirty-four is because the sweet spot for balancing the cost versus the value of customization lies at about one third of produced products. The assemble to stock or assemble to order rests at about one third of the graphs distance and it was chosen because it corelates perfectly with the one third marking of balancing cost vs. customization. The expected result is that using this amount of customization will provide this project with the perfect amount of customization that will please customers want for variation as well as the developers want for maximizing profit. It will also balance the appropriate amount of lead time with that of the flexibility.

Figure 12.29 - Optimal level of customization balancing cost and value. Kumar, Ashok. *Optimal level of customization.* 2005. “Mass Customization: Metrics and Modularity.” *The International Journal of Flexible Manufacturing Systems* 16, no.4: 308.

Figure 12.30 – Type of customization with respect to customization, flexibility, cost, and lead time. Smith, Ryan and Timberlake, James. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

Now the façade component will be isolated into a chassis element and an attachable façade element. The chassis element extracted, extends out three feet and is standard throughout the entire façade component. This is to create a standard product family translating into less customization and more mass production. The attachable façade element will have a standard interface to enable swappable component families. This means that although the attachable facades are different, they attach to the chassis element the same way. The examples below show floor 4 of the tower floor plan using 'curve B' because it is the most common curvature throughtout the façade. It extracts the two elements of the chassis and attachable component.

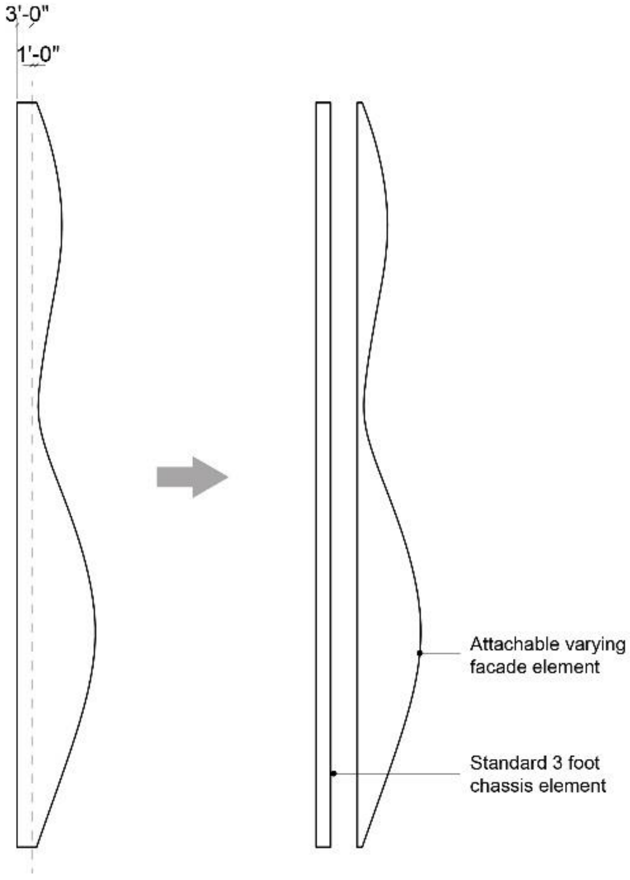

Figure 12.31 - Extracting and isolating a standard chassis and attachable element.

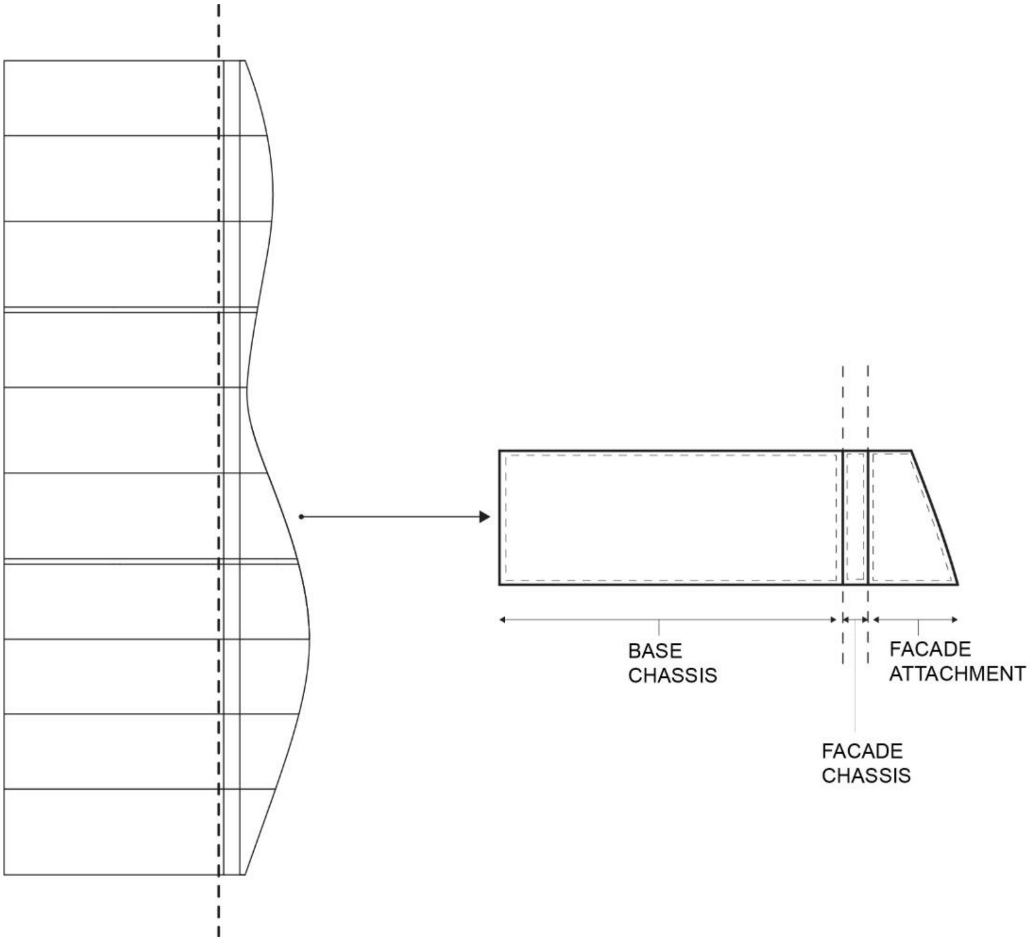

Figure 12.32 - Isolating the base chassis, façade chassis, and façade attachment of a module.

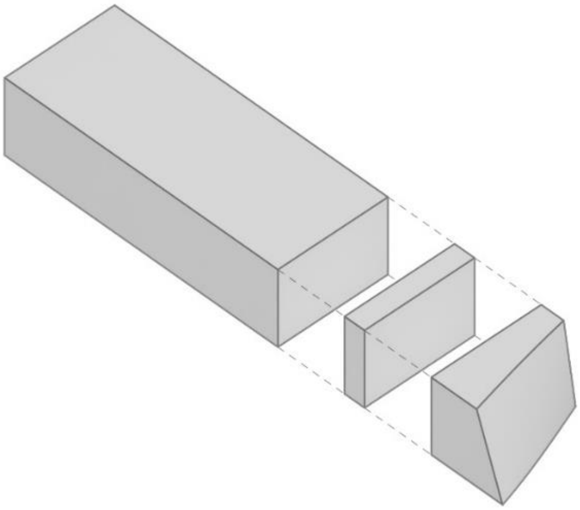

Figure 12.33 - Exploded diagram of modules base chassis, façade chassis, and façade Attachment.

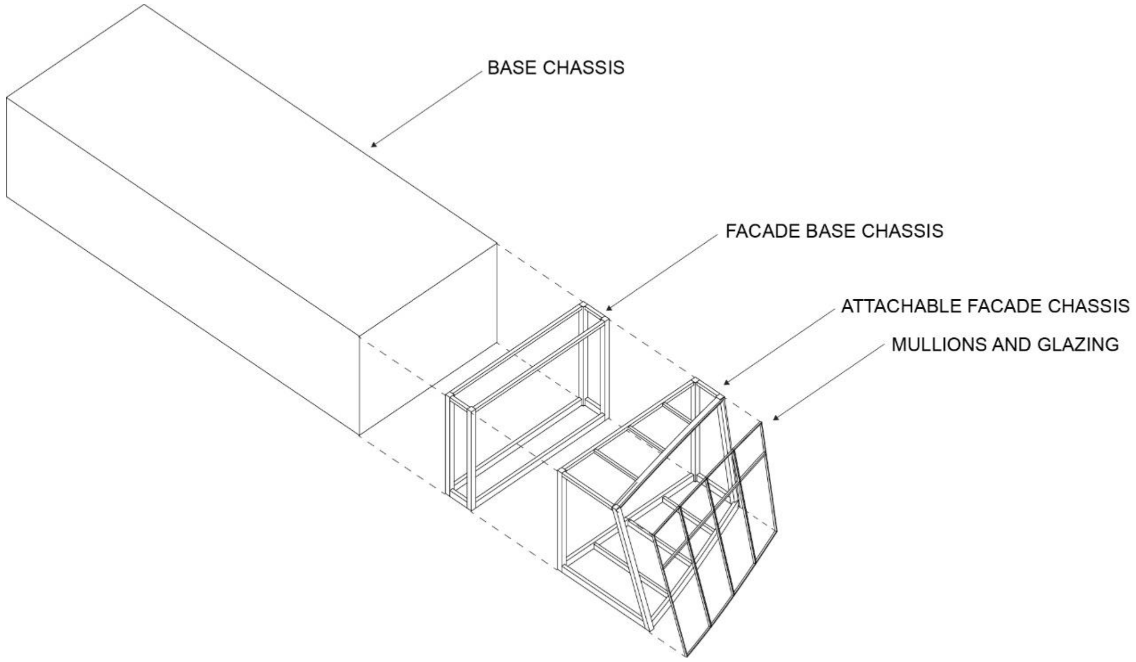

Figure 12.34 - Typical façade component structure and sequence of attachment.

### Foyer Component

For the foyer component, the plan view is displayed first to demonstrate where the two separate foyer components are located. This uses a grid previously established for the modules and the components will attach to the corner posts of modules. The foyer components are constructed of a chassis, similar to the modules, and with no columns supporting them from underneath, they will attach to the modules on site by being welded directly onto to the vierendeel truss frame and cantilevering off of the modules West side. They will not exceed the maximum cantilever which is 16’ 4.75” and have a maximum cantilever of 15’. Looking at the North elevation, it can be shown that there are differentiating module heights previously established, which will result in three different types of foyer components. Thus, there will be Type A, Type B, and Type C foyer components as well as having Module 1 and Module 2.

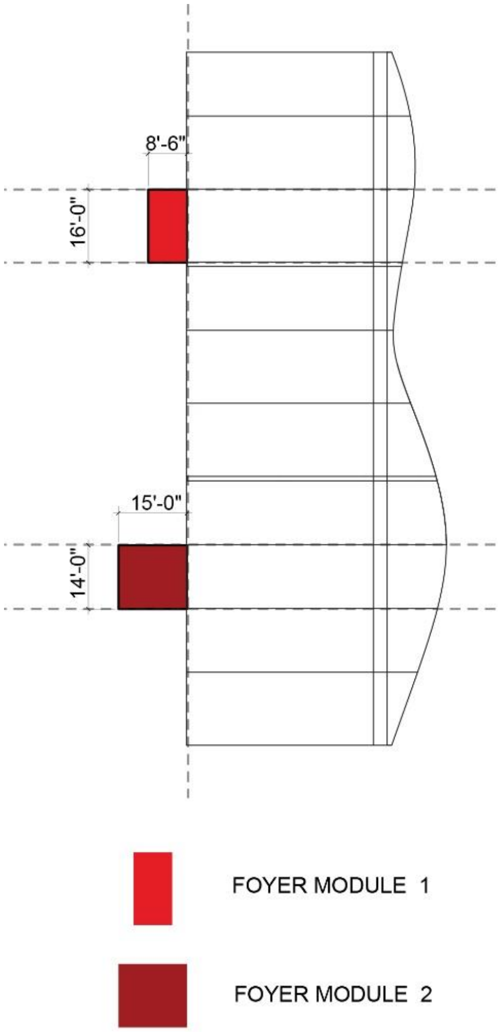

Figure 12.35 - Plan of level 4 showing foyer grid and foyer modules.

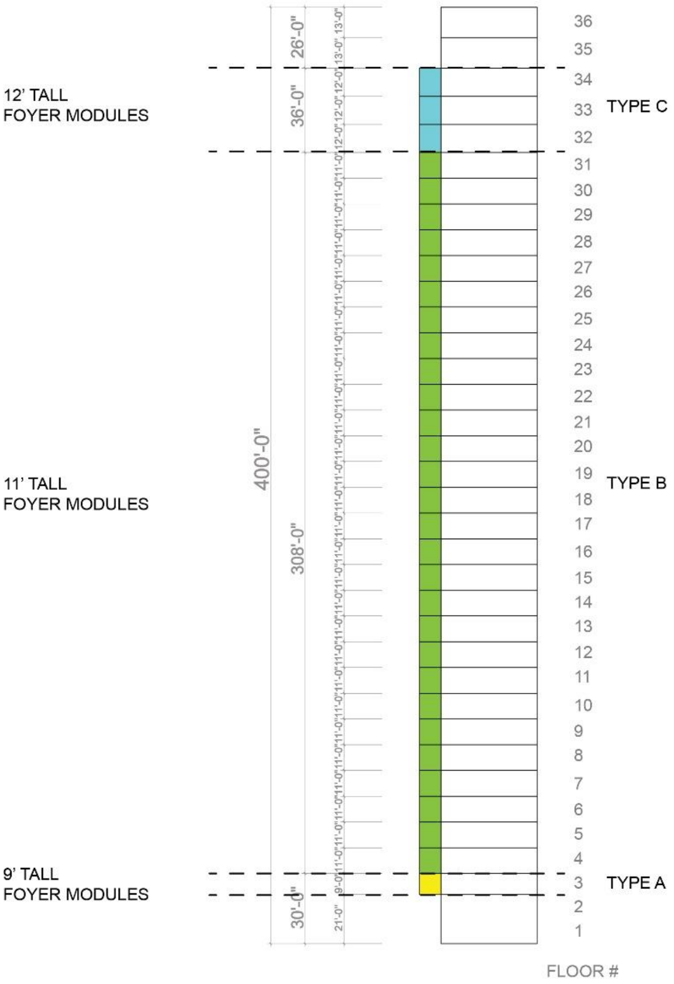

Figure 12.36 - North elevation grid for foyer component types.

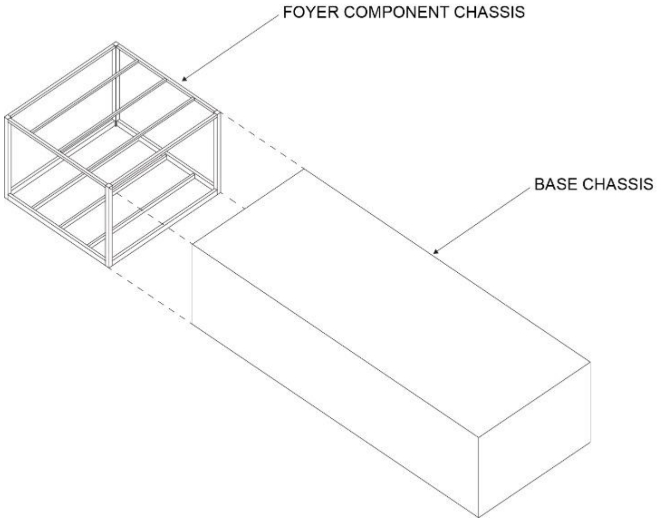

Figure 12.37 - Typical foyer component structure and attachment location.

Table 12.3 - Foyer component breakdown (6 different types of foyer modules)

Foyer Component Table

| | Type A | Type B | Type C |
|---|---|---|---|
| Module 1 | 2 | 28 | 6 |
| Module 2 | 2 | 28 | 6 |

**Lanai Component**

For the lanai component, the plan view is displayed first to show where the component is located. This attachment uses the grid previously established for the modules to separate via the same cutting plane and connects to the corner post and intermediate post of the module. This component is attached on site similar to the foyer module. The lanai component is constructed of a steel frame, and will be attached by a cantilevering system that bolts the balcony frame onto the bottom of the vierendeel truss posts and also has tension members ties to the center of the corner and intermediate posts. Although the module heights vary per floor, these lanai components are able to be standard throughout because they do not extend floor to floor. Therefore, an elevation view and a table are not needed because all of the 34 floors are the same beginning at floor 3. Therefore, there will be 34 identical lanai components produced.

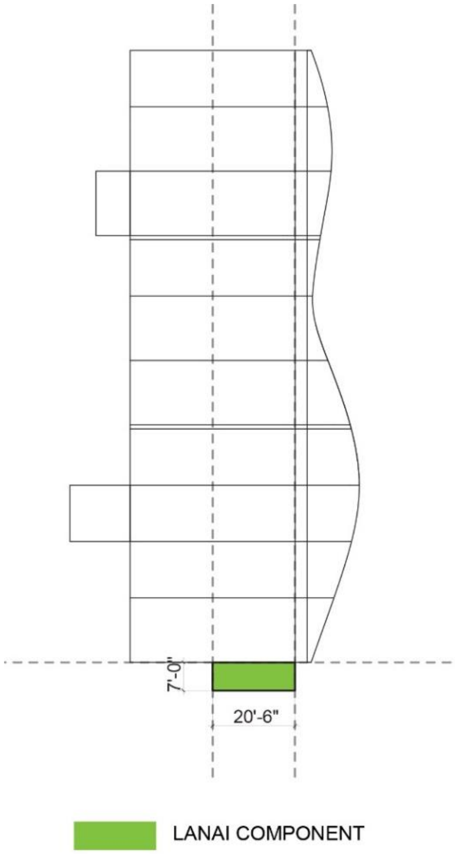

Figure 12.38 - Plan showing lanai grid and placement.

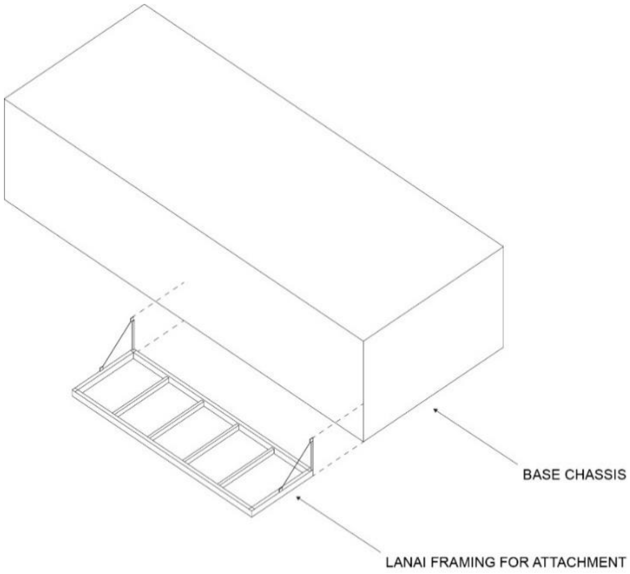

Figure 12.39 - Lanai component structure and attachment location.

## APPLIED DESIGN

### Typical Floor Plate

This represents the typical floor plate and floor plan of this projects prefabricated East tower that occurs on most floors. The purpose is to show one level of the tower and how it is broken down into spaces, units, and modules as an example of the overall building. The figure below shows the level 12 floor plate, then the units (A, B, and C) that compose it, and a space diagram separating interior and exterior space. From here the modular breakdown of the floor plate at level 12 is demonstrated which repeats at each floor. This is to demonstrate the amount of modules that compose one floor and the relationship to each other.

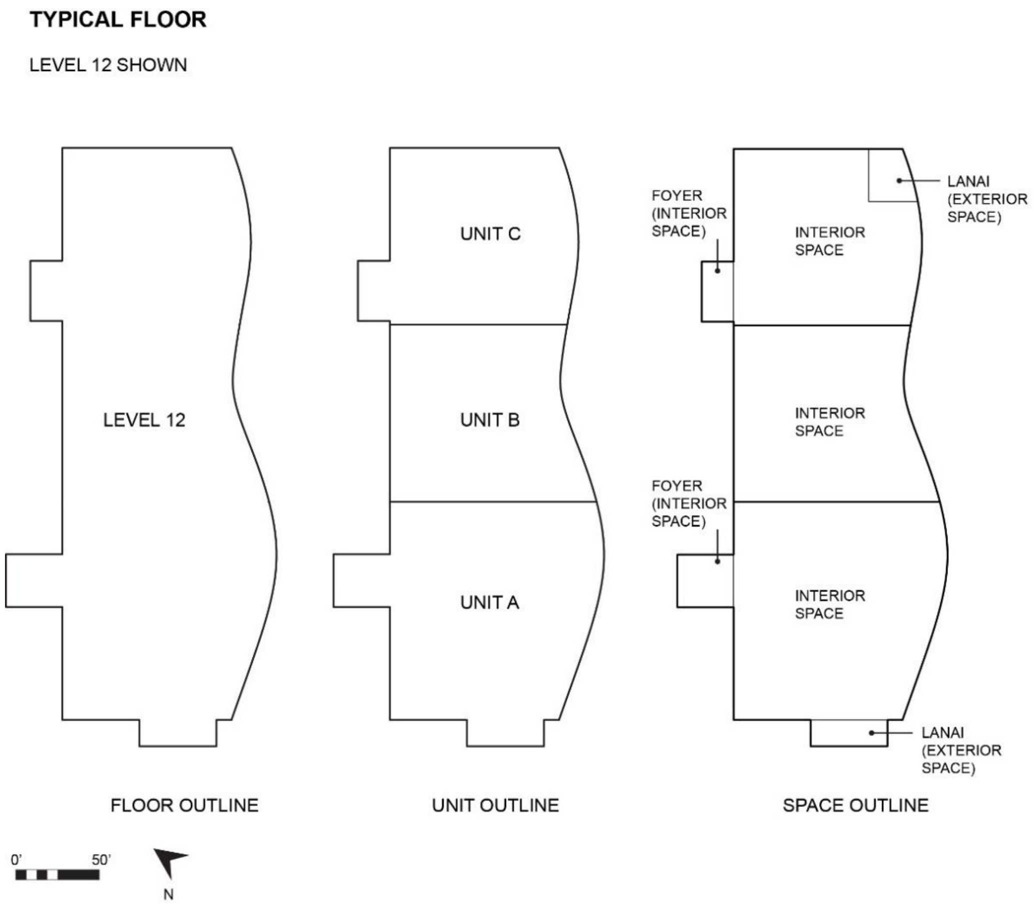

Figure 12.40 - Typical floor level in this projects tower.

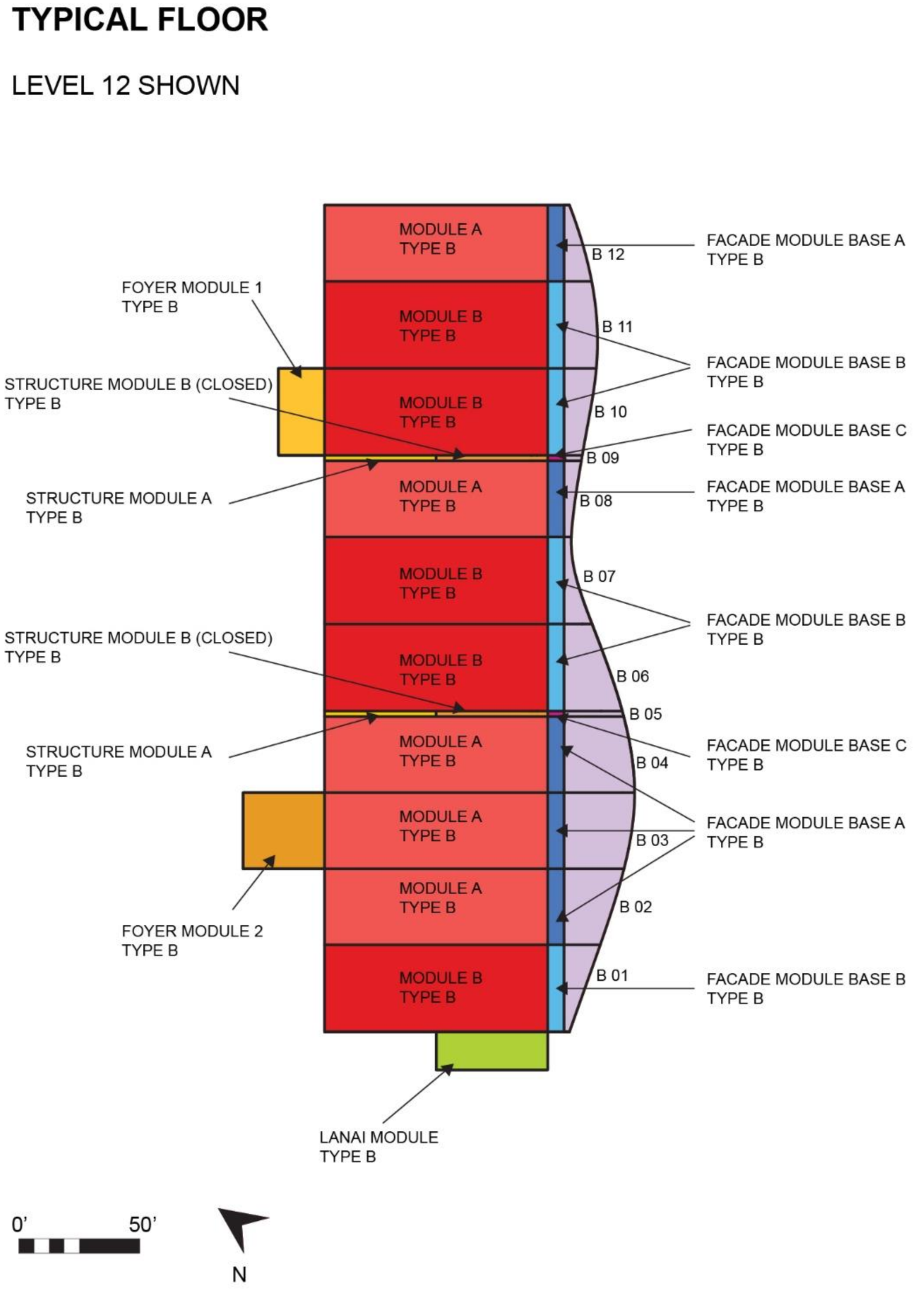

Figure 12.41 - Typical floor level broken down into modules that compose it.

**Typical Unit Breakdown**

In this section, one unit is extracted from the typical floor plate which others can use as directions and an example of how any unit in the tower will be constructed. The purpose is to give a general idea of how any unit will come together, demonstrating the amount of chassis modules that compose one unit along with the number of completed modules that arrive on site that will be connected on site. Shown first in the figure below is the floor plate of level 12 and unit A that will be extracted and used as an example for the entire towers unit composition.

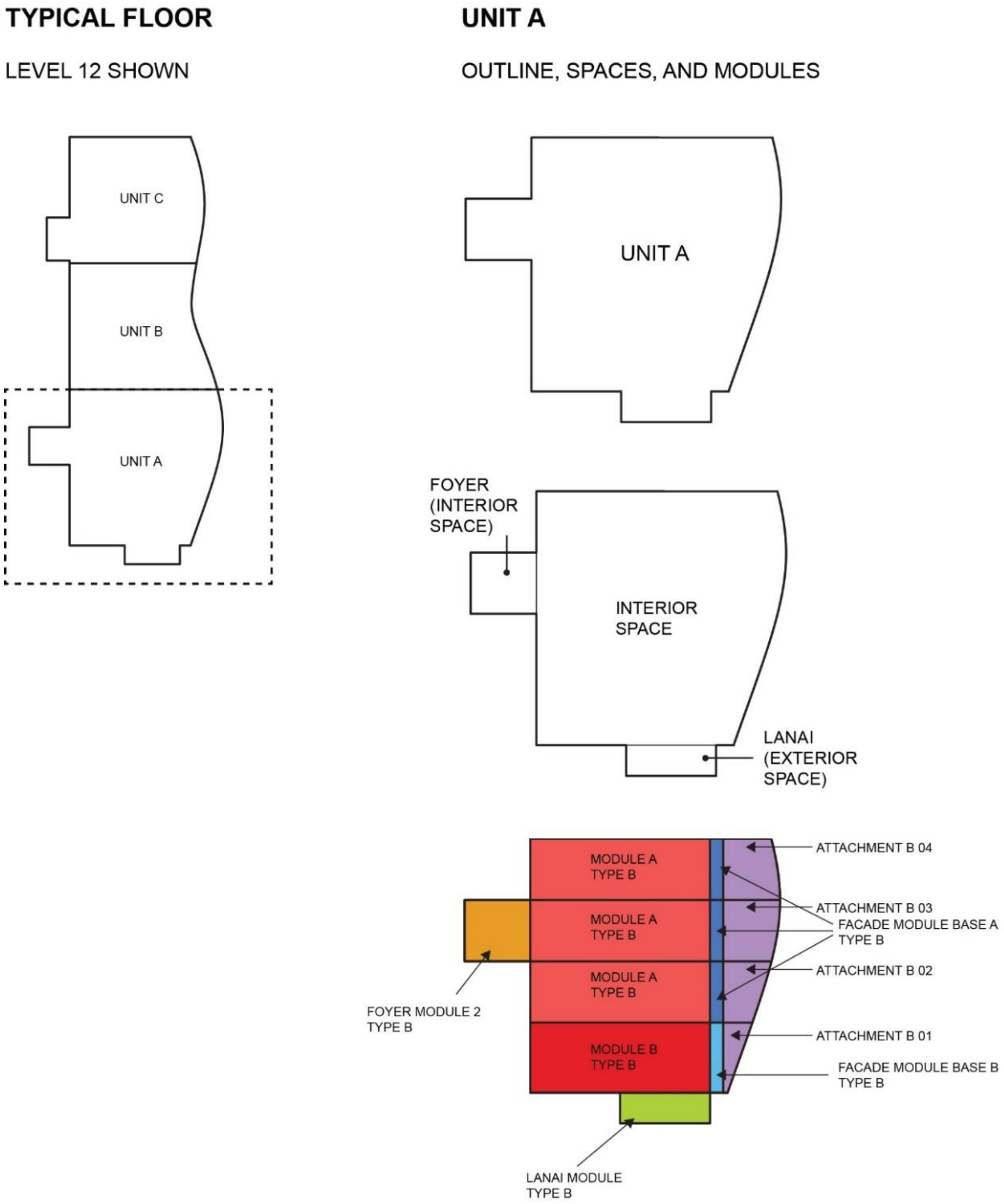

Figure 12.42 - Level 12 Unit A outline with spaces and modular composition layout.

The purpose of the drawing below is to show the dimensions of Unit A after modularization (breaking the original unit down into modules). It shows that while some walls are moved from the original plan due to the constraints of either 14’ or 16’ modules, the minimum dimensions to comply with code are still met. This demonstrates the exterior grid dimensions of the modules as well as the interior dimensions with interior partition walls.

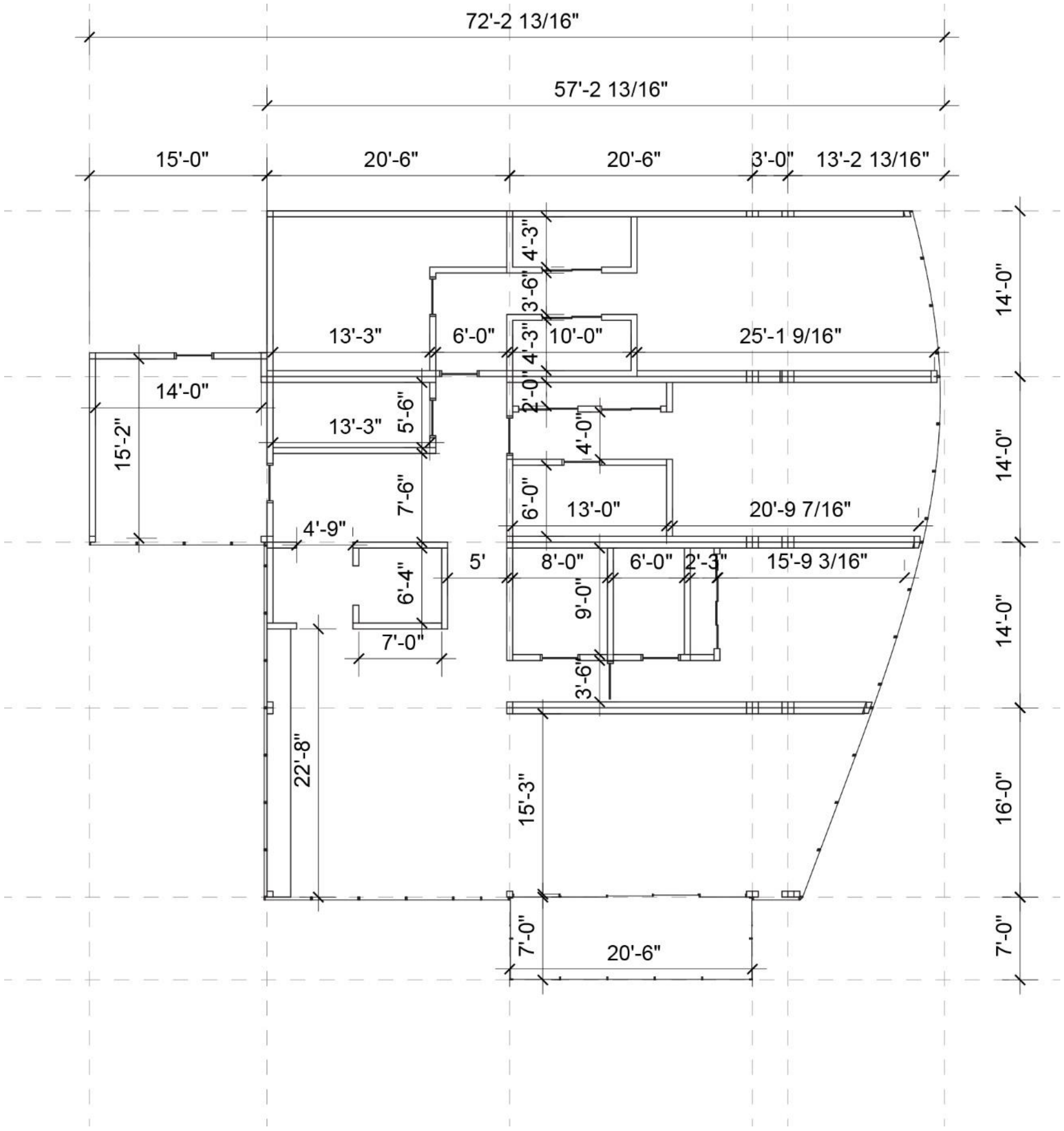

Figure 12.43 - Plan of Unit A showing dimensions.

The image below shows this projects new plan of Unit A created with its programed spaces and the original Waiea plan of the same unit for comparison. It demonstrates that even though separate modules are used to construct the unit, the same spatial features are achieved.

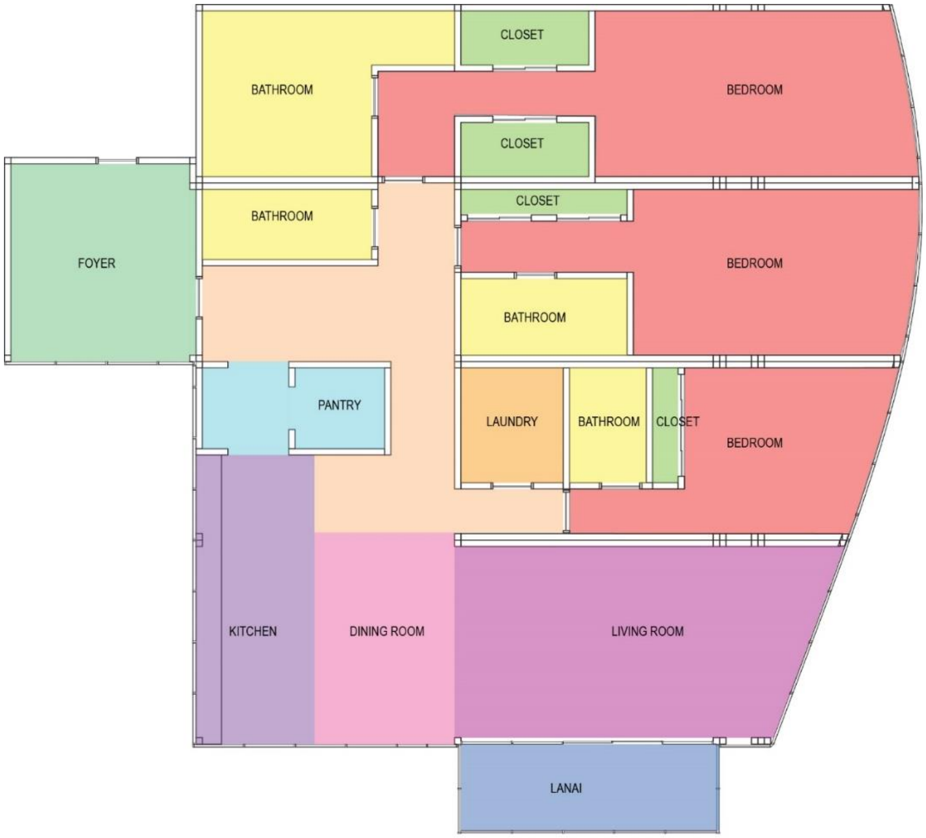

Figure 12.44 – This projects plan of Unit A with program spaces showing rooms.

Figure 12.45 - Original Waiea Floor plan for Unit A. Hughes, Howard. *Waiea mini book.* Ward Village.

The purpose of the image below is to show the interior space of Unit A. It demonstrates the interior infill walls placement and the exterior enclosure provided by walls and glazing. This image shows that large open spaces can be provided by using a prefabricated modular system that utilizes the corner post chassis with open sides or ends. This is the final image of Unit A once all of the modules and components are attached.

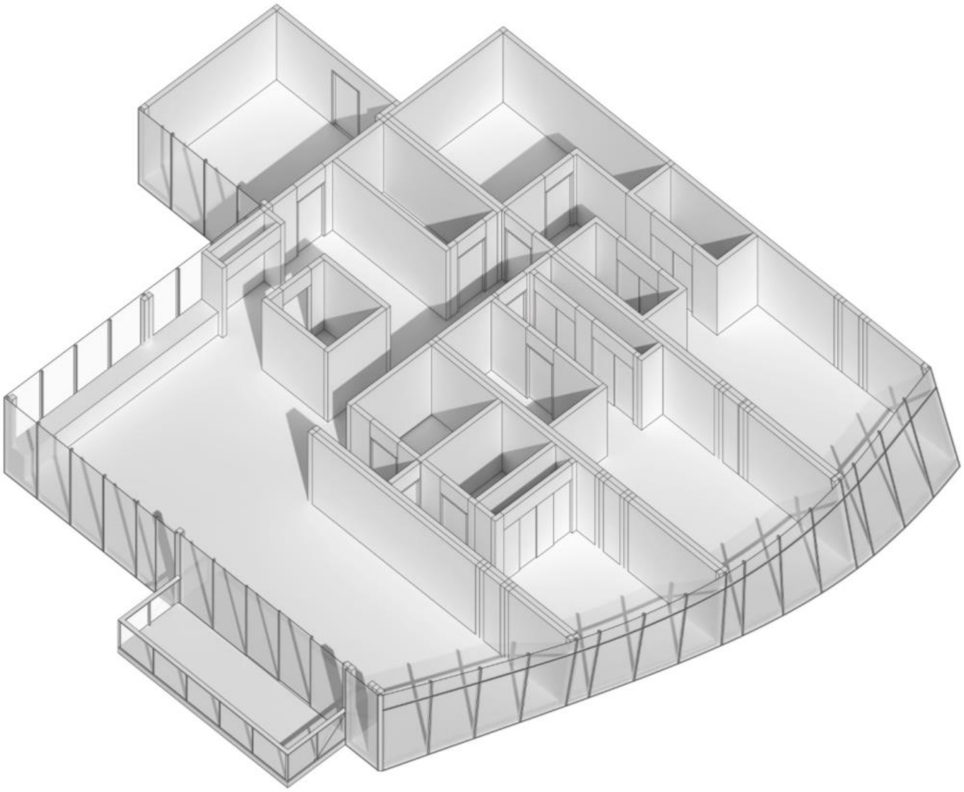

Figure 12.46 - Unit A cut by a transverse section showing interior space.

The next figures show all of the module component chassis elements and how they come together to create Unit A.

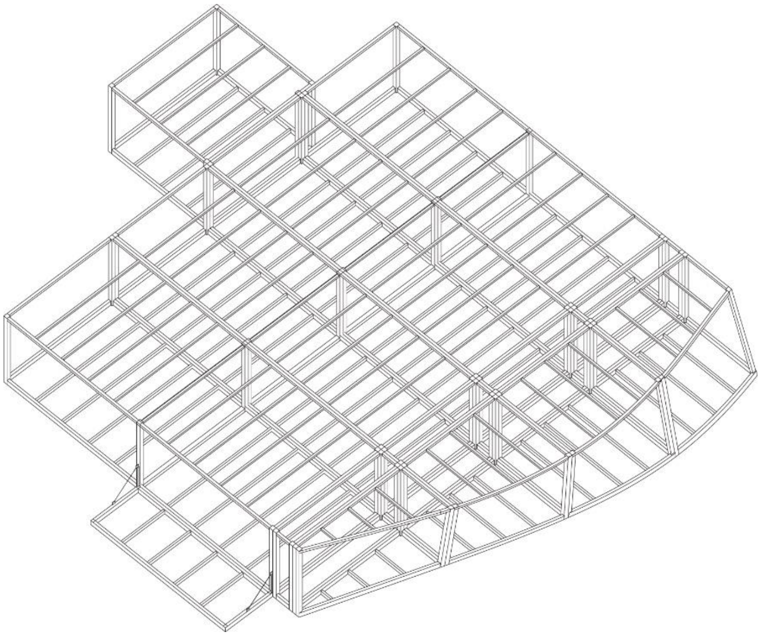

Figure 12.47 - Steel chassis framing structure of Unit A.

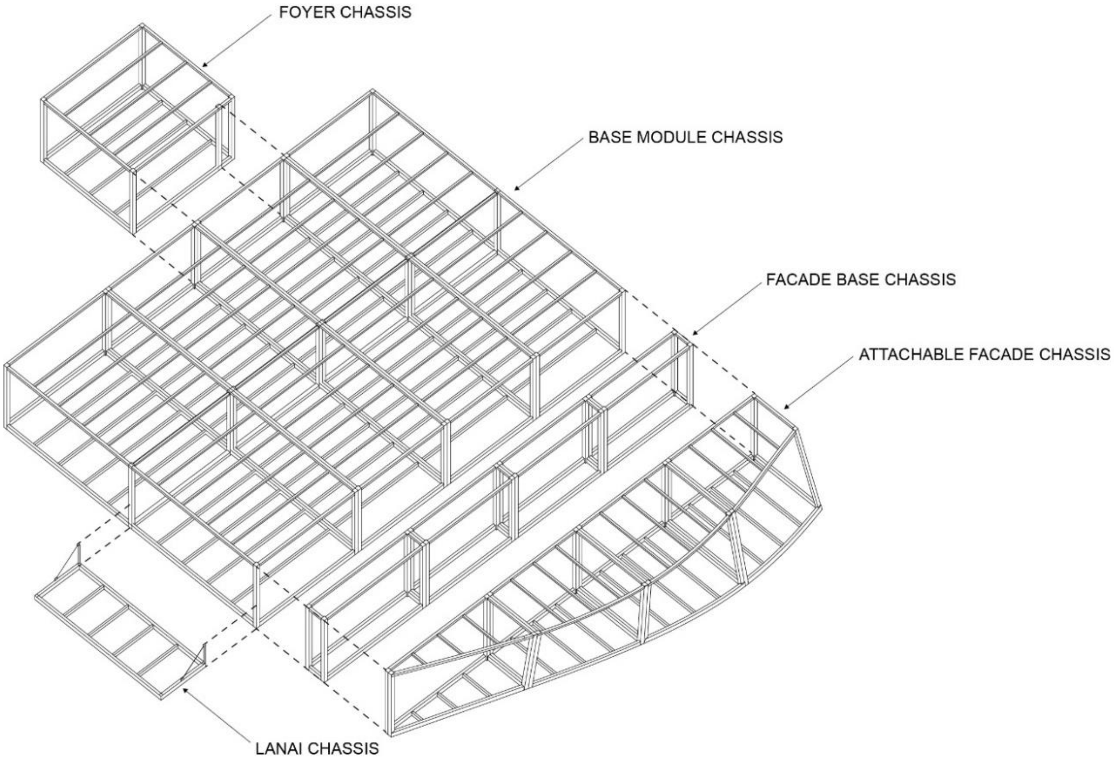

Figure 12.48 - Exploded chassis framing structure of Unit A.

The drawing below shows Unit A decomposed into the 6 modules that are used to construct it. There are four main modules that are connected side by side with some of them having open sides and others fully enclosed. The longest module is about 57’ 3”. The other two modules are the lanai and foyer components. After the modules arrive on site and before they are hoisted into position and set, if the module needs to be attached to either the foyer or lanai component it will be done on site, on the ground before being lifted. This creates less connections that must be made once lifted, as well as having less modules lifted which creates economic incentives.

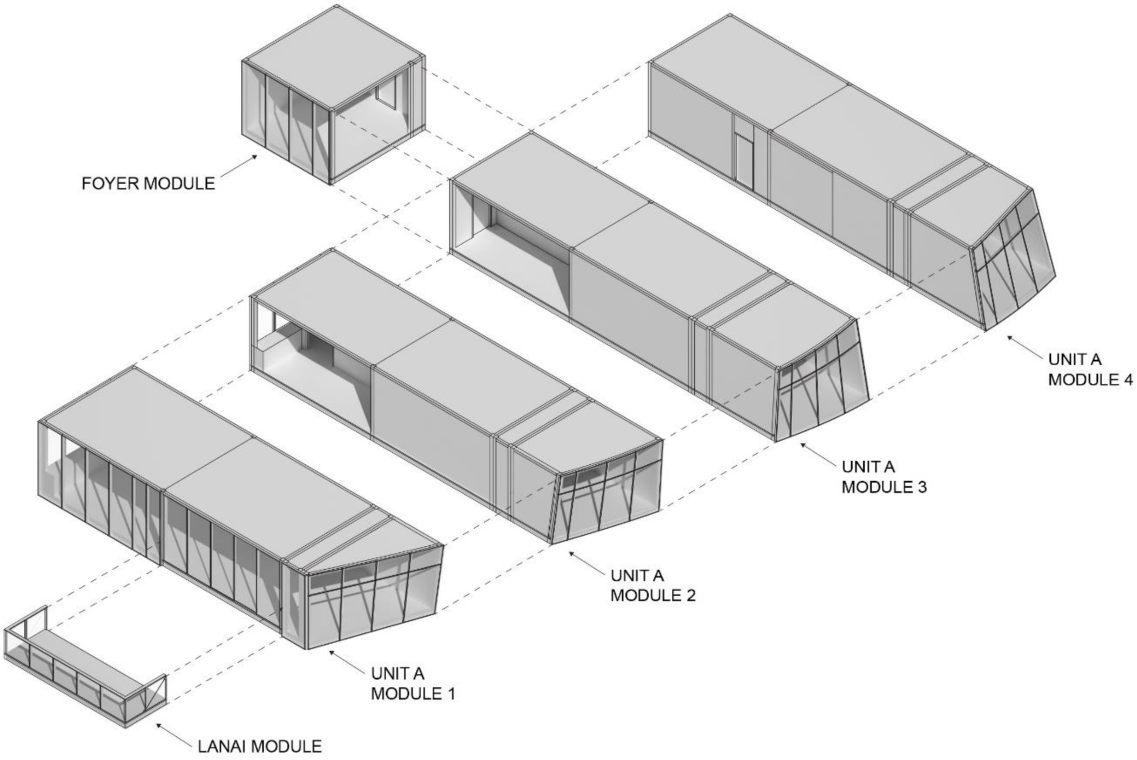

Figure 12.49 - Unit A modules exploded (demonstrating modules transported to site to be attached).

Below shows Module 4 of unit A in a further exploded diagram. This is meant to show how the module comes together in a general sense. It starts with the module chassis, and after the floor and roof are attached, the partition walls are infilled along with the bathroom and kitchen pod. It is then finished with final enclosing walls, glazing elements, and finishes.

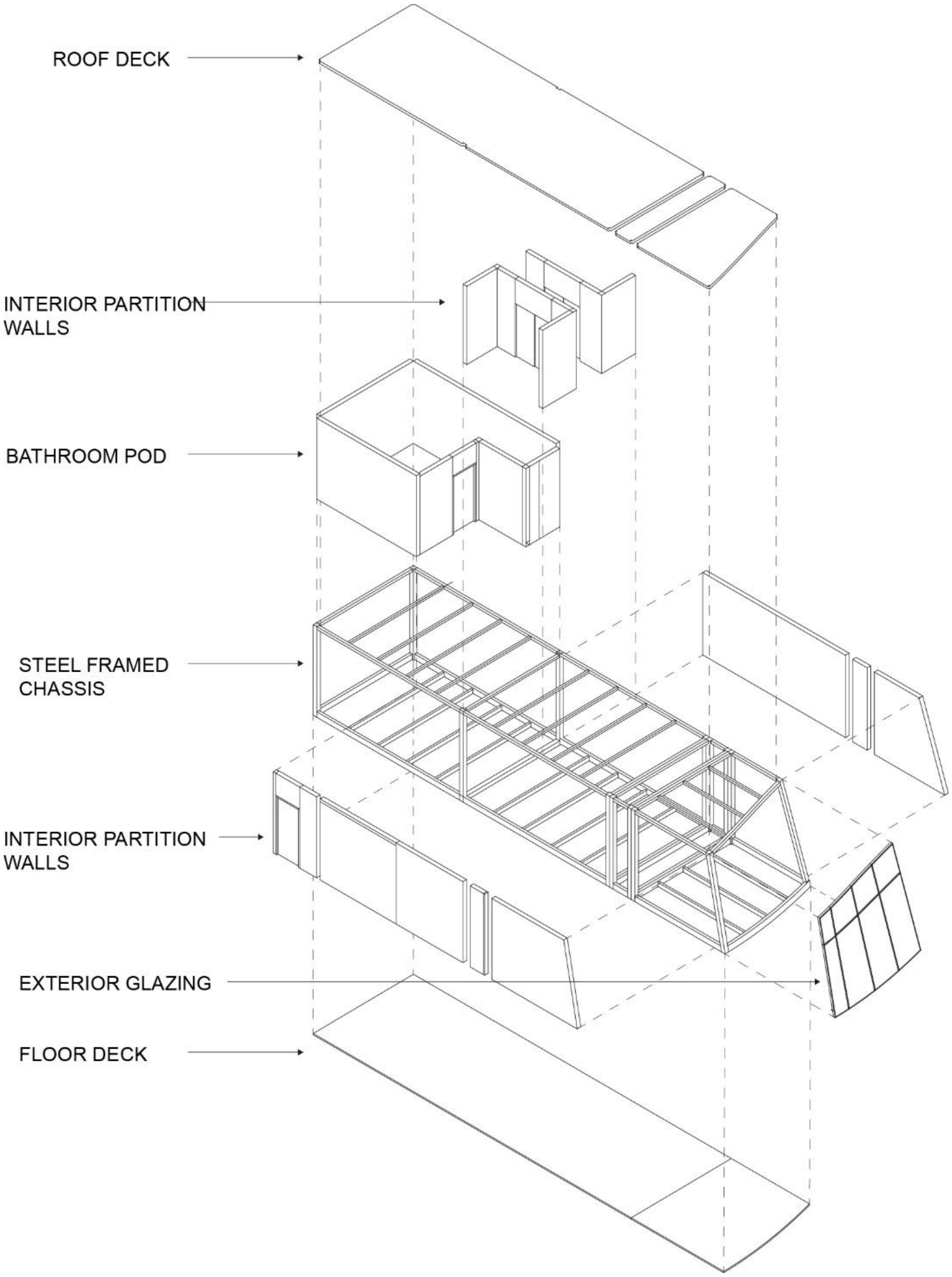

Figure 12.50 - Unit A module 4 exploded diagram.

The purpose of this isometric section below is to show that the standard 11 foot tall module has a 9 foot 6 inch finished floor to ceiling height, the same as the Waiea tower. The floor has a total depth of ten inches and the roof has a total depth of eight inches. Together the floor and roof have a combined depth of eighteen inches which allows the interior space to be 9 feet 6 inches.

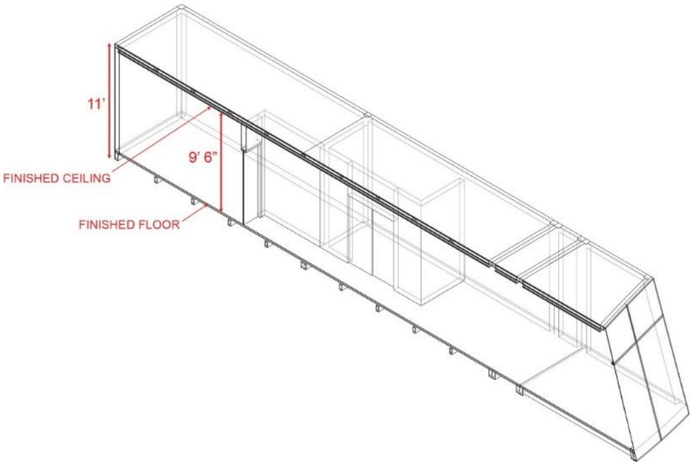

Figure 12.51 - Unit A module 4 section showing exterior height and interior floor-to-ceiling height.

The final exterior renderings shown below are an example of what this construction system can accomplish and demonstrate this projects design of the Waiea East tower using all of the above mentioned guidelines for a prefabricated modular high-rise structure with a customized geometry. This demonstrates that prefabricated modular buildings can break away from the rigid box while producing high quality design.

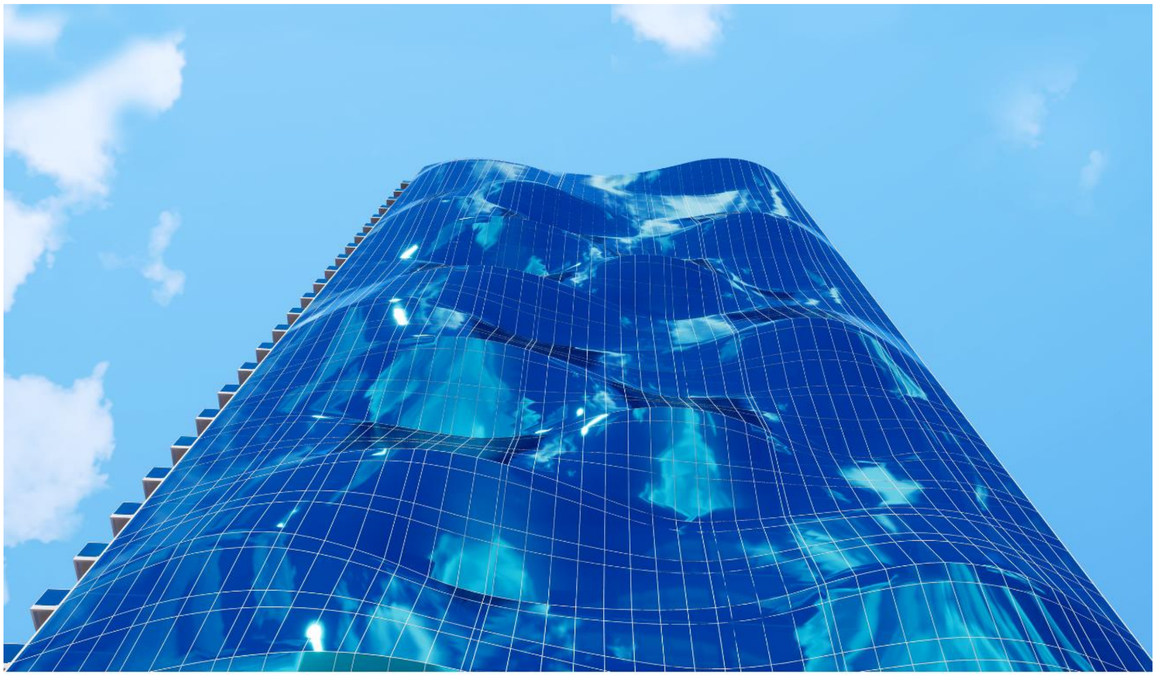

Figure 12.52 - Rendering of the enhanced undulating exterior façade.

Figure 12.53 - Renderings of this projects enhanced prefabricated modularized East tower of Waiea.

# CHAPTER 13. DESIGN ANALYSIS - COMPARISON

Looking at the advantages and disadvantages of prefabricated and modular construction presented in previous sections, the driving point that makes these types of construction more economical is the overall speed that can be achieved. This time saved relates directly to overall cost savings because saving time saves money. Therefore, this section will first focus on demonstrating the schedule of prefabricated modular construction and the predicted schedule of this project compared to the Waiea towers schedule. From here, this section will show how the time that is saved is quantified out to savings in overall labor costs and overhead costs that occur over time. It will culminate with the overall savings predicted if the entire Waiea tower was constructed with a prefabricated modular system in the same fashion that the East tower was in the previous chapter. This will help reinforce and prove this projects point that a prefabricated modular high-rise structure in Honolulu, Hawaiʻi will cost less than the conventionally constructed concrete high-rise while also allowing design freedom with customized geometrical forms.

## SCHEDULE

In project management for construction, the schedule is a list of a project's activities, milestones, and deliverables with a start date and completion date. A schedule informs how the project is planned and managed and can be represented in terms of a timetable with activities and the amount of time allotted for that activity. The savings in time on a prefabricated modular projects schedule comes directly from the ability it has to simultaneously construct in the factory and on-site. This will begin by examining the Waiea towers start and completion date. Then it will theoretically map this in terms of standard construction on top of a timetable to find out what takes place when, and the duration of that activity. From here this section will determine how much time in the overall schedule can be saved by using modular prefabricated construction. After this, the amount of time savings will be subtracted from the Waiea tower and mapped on a timeline in terms of a new prefabricated modular schedule. The savings will be quantified after this with respect to the time savings to give predictions on the monetary savings that will occur.

- Starting with the timeline of the Waiea tower, the construction schedule started in middle of 2014, in June, and ended at the end of 2016 in December. This means that all together the construction schedule was 19 months long.[179] Then, by using construction scheduling guidelines presented in the Atlantic Yards B2 project for a conventional building, activities of the Waiea Tower are assigned to the timeline. It showed that the foundation and excavation take approximately 1/3 of the schedule, the superstructure, interior, and exterior take approximately 2/3 of the schedule, followed by the closeout taking approximately 1/5 of the schedule.[180] This is demonstrated in the figure below.

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[179] Honolulu Star Advisor. 2017. "Tower." Accessed February 22, 2018. https://www.pressreader.com/usa/honolulu-star-advertiser/20171122/281956018089195

[180] Forest City Ratner, "Building 2 at Atlantic Yards." Presentation to the public, November 9, 2012.

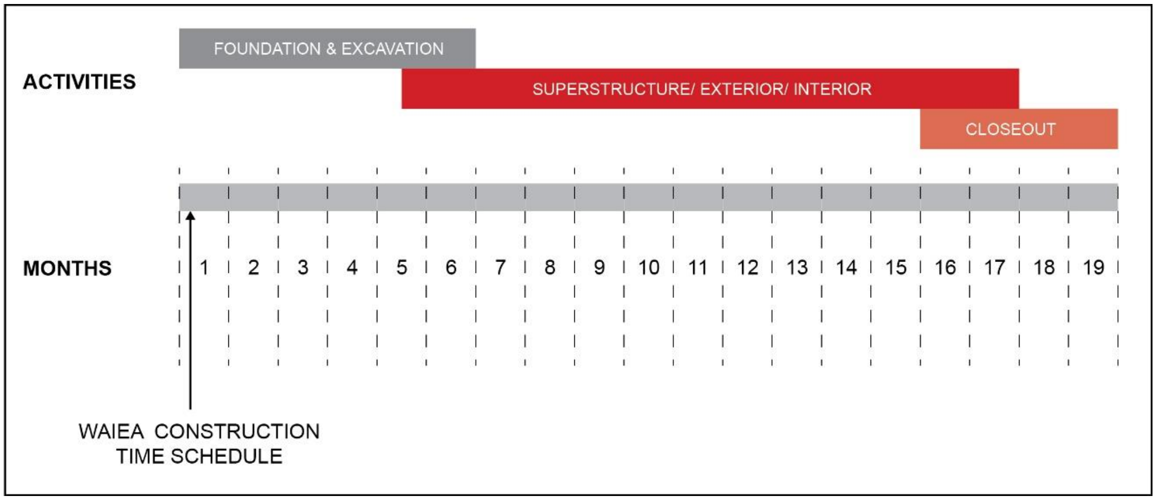

Figure 13.1 - Predicted construction schedule of Waiea tower.

- Now it will be determined how much time in the overall schedule can be saved by using modular prefabricated construction. According to the Modular Building Institute, because the construction of modular buildings occurs at the same time other activities such as foundation work and conventionally built elements, projects can be completed 30% to 50% faster than traditional construction and is shown in the figure below.[181] A case study looked at earlier in this project, Victoria Hall in Wolverhampton, is a twenty-five story prefabricated modular high rise building that predicted that it reduced the overall construction period by over 50% relative to site intensive building according to Lawson et al.[182] It is also stated by Smith et al., that Amy Marks from Kullman has fabricated a few of Kieran Timberlakes prefabricated modular projects and on average is seeing a 50% time reduction from their contractors for off-site methods over on site methods for steel and concrete commercial buildings.[183] This is also shown in the figure below along with another schedule comparison below that of a conventional to modular medium sized hotel that explains that by using an eight week lead-in time for ordering the varying

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[181] Modular Building Institute. n.d. “What is modular construction?” Accessed February 22, 2018. http://www.modular.org/HtmlPage.aspx?name=why_modular

[182] Mark Lawson, Ray Ogden, and Rory Bergin. 2012. “Application of modular construction in high-rise buildings.” *Journal of Architectural Engineering* 18, no.2 (June): 148-154.

[183] Ryan Smith and James Timberlake. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

prefabricated modules, the project time can be reduced by over 50%. Lead time can be extended back another month for prototyping depending on the degree of modularization and customization desired.[184] After speaking with Hawaiʻi Modular Space and examining these numbers, this project in Hawaiʻi will use the mean percentage of a 40% overall time savings to calculate how much time can be saved for this project. This is to make sure the quantification isn't over or under estimated.

Figure 13.2 - MBI schedule comparison (conventional to prefabricated modular construction). Modular Building Institute. n.d. "What is modular construction?" Accessed February 22, 2018. http://www.modular.org/HtmlPage.aspx?name=why_modular.

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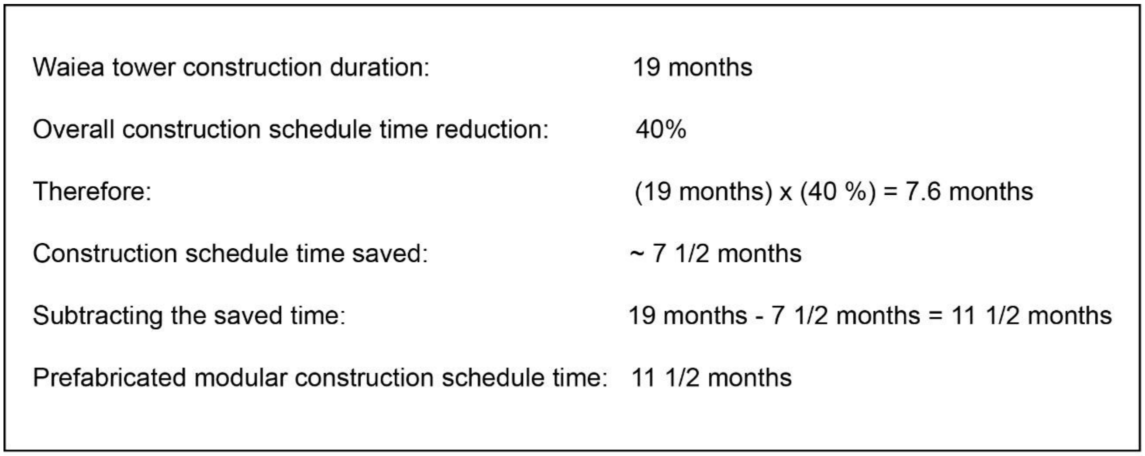
[184] R. Lawson, P. Grubb, J. Prewer and P. Trebilcock. 1999. *Modular Construction using Light Steel Framing: An Architect's Guide*. Silwood Park, Ascot: The Steel Construction Institute.

Figure 13.3 - Kullman Building Systems comparing similar projects using conventional and prefabricated modular systems in terms of schedule. Smith, Ryan and Timberlake, James. 2010. Prefab Architecture: A Guide to Modular Design and Construction. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

Figure 13.4 - Comparison of conventional to modular construction in a typical medium size hotel. Lawson, R, Grubb, P, Prewer, J, and Trebilcock, P. 1999. *Modular Construction using Light Steel Framing: An Architect's Guide.* Silwood Park, Ascot: The Steel Construction Institute.

- Shown in the figure below is the explanation and equation derived from the above-mentioned facts to find out how much time will be saved and the time of the predicted schedule for this projects prefabricated modular design.



| | |
|---|---|
| Waiea tower construction duration: | 19 months |
| Overall construction schedule time reduction: | 40% |
| Therefore: | (19 months) x (40 %) = 7.6 months |
| Construction schedule time saved: | ~ 7 1/2 months |
| Subtracting the saved time: | 19 months - 7 1/2 months = 11 1/2 months |
| Prefabricated modular construction schedule time: | 11 1/2 months |

Figure 13.5 - Expected construction schedule time savings from conventional concrete construction to prefabricated modular construction for Waiea in Honolulu, HI.

- Now, the overall time savings will be graphed in order to show how the types of construction compare graphically. This will show how simultaneous activities in modular construction overlap to create this savings. The first graph will show the conventionally constructed Waiea tower schedule, but with overlapping elements of foundation/excavation and superstructure/exterior/interior to show that even if the mass customization of the façade attachment components takes the same amount of time as the conventionally constructed customized façade, that it will still save on the overall time. This would represent the minimum amount of time savings. After this, the guidelines presented in the Atlantic Yards B2 project will be applied to this project to show how much time this project is predicted to take if the mass customized elements can be manufactured as the same rate as the base chassis modules. The guidelines state that on-site foundation, plinth, and excavation will take approximately 1/3 of the schedule time, the fabrication of modules will take approximately 1/3 of the schedule time, the module erection will take approximately 1/3 of the schedule time, and the closeout will take approximately 1/7 of the time.[180] This also includes the two month lead time for the customized components before the site work starts along with another two months of lead time once the site work begins, giving ample time for the customized geometrical formwork to be figured out and produced. This is then applied to this project to enable the comparison.

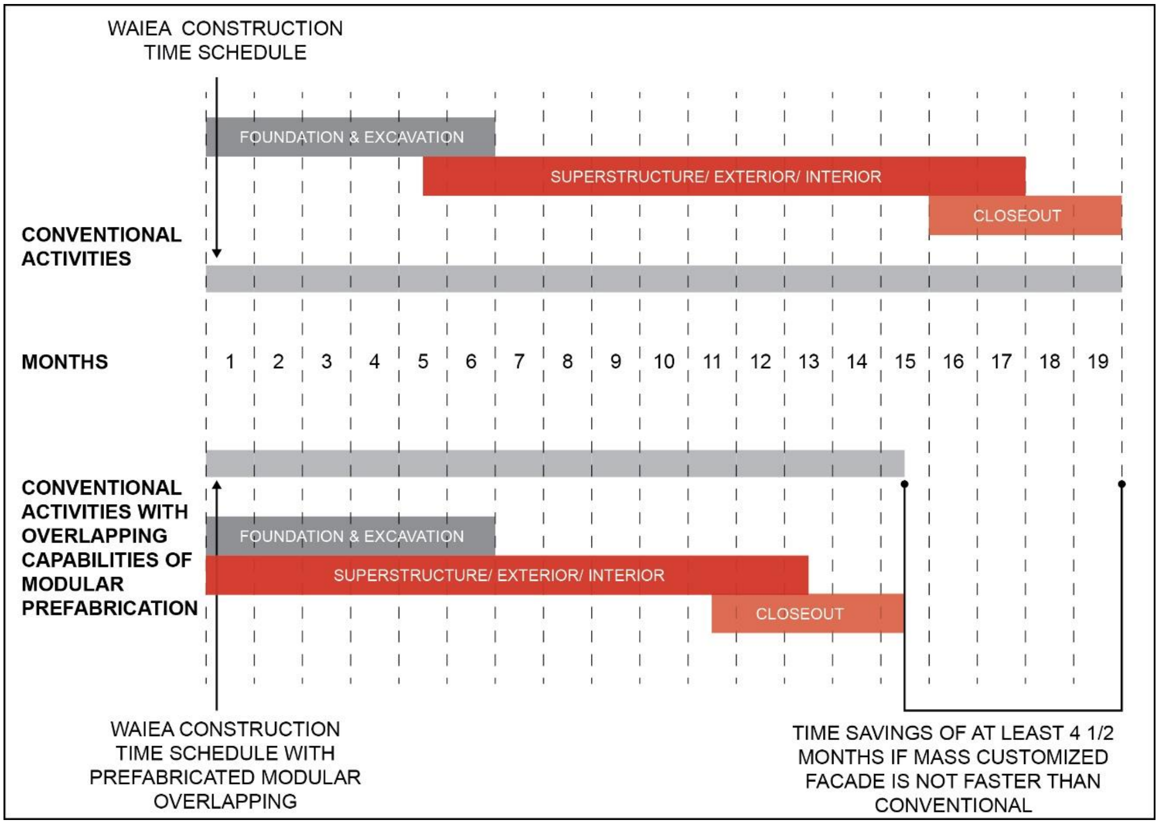


Figure 13.6 - Comparing the conventionally constructed Waiea tower schedule to the same conventionally constructed Waiea tower with overlapping time qualities seen in prefabricated modular construction (minimum savings).

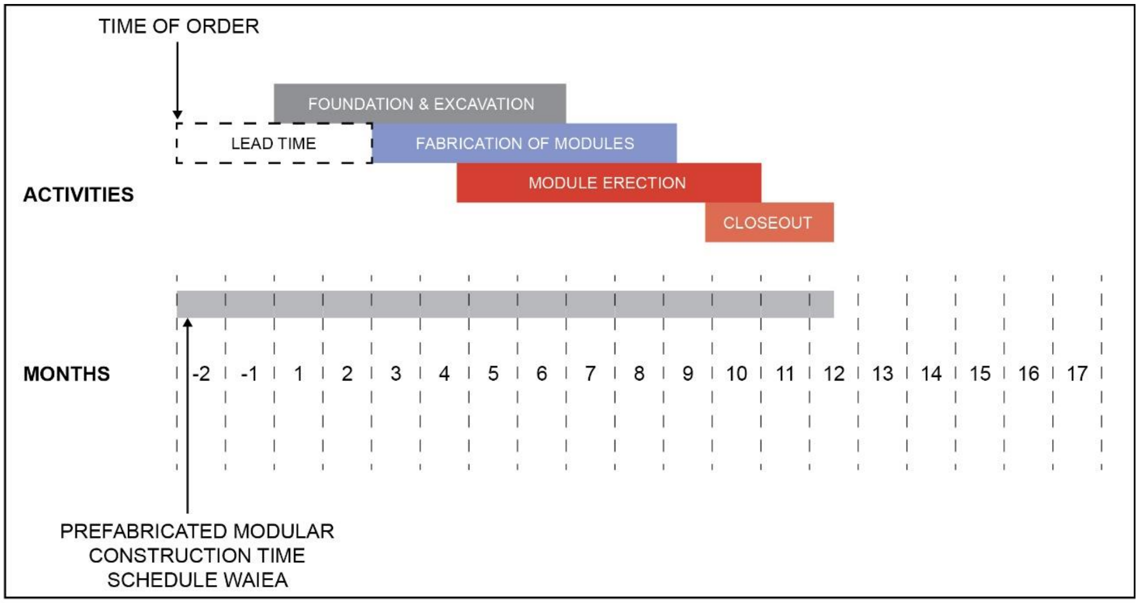


Figure 13.7 - Estimated schedule for this project including lead time.

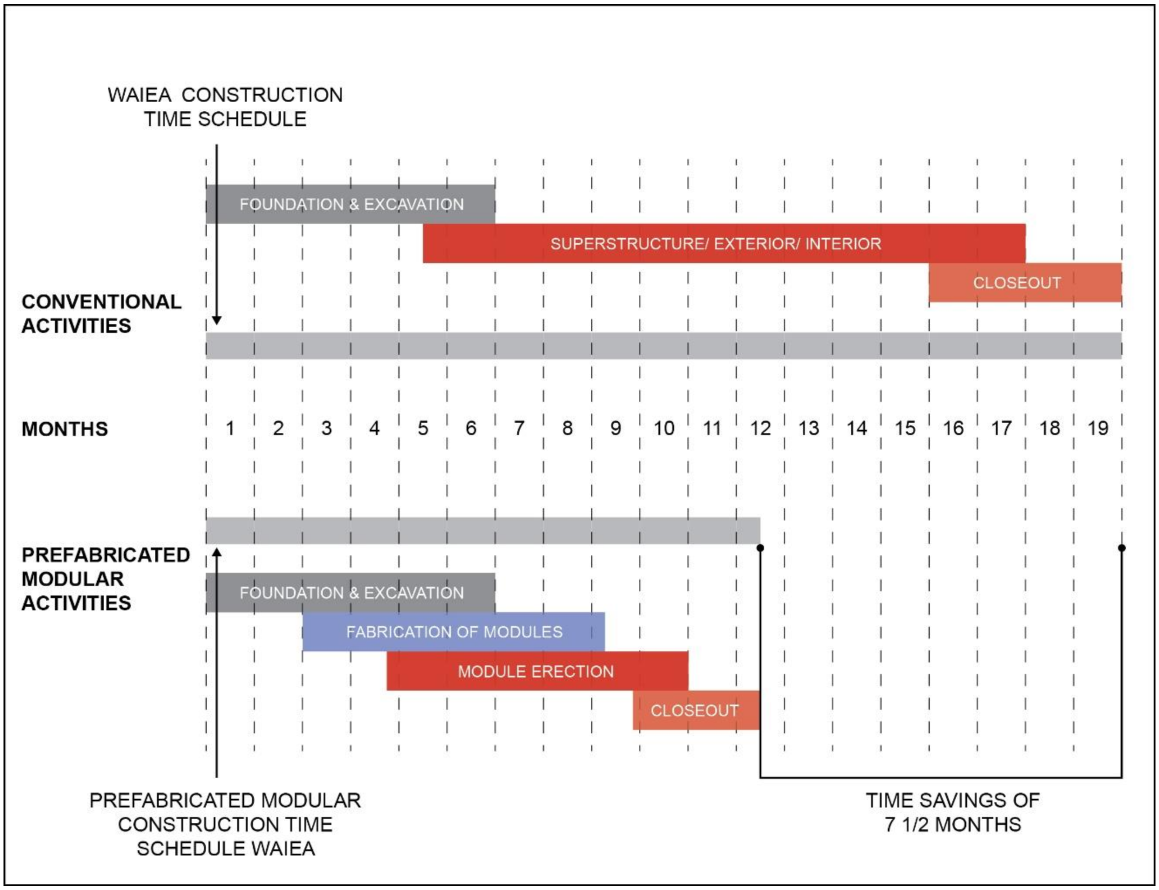


Figure 13.8 - Comparing construction schedule of conventionally constructed Waiea tower this project’s proposal of a prefabricated modular Waiea tower (maximum savings).

## QUANTIFYING SAVINGS

The three main cost saving factors from using prefabricated modules though comes from material, labor, and time.[185] The savings on material and labor though can also fall into the category of time. The time that is saved from using a prefabricated modular system can be quantified out to savings in many various aspects. This would Examples include overall labor costs that occur per day, overhead costs that occur over time, allowing occupants to move into units at an earlier date generating revenue sooner, and creating less waste to save on material costs. It is stated by Lawson et al., that that the total cost savings because of the speed of construction alone can be from 5% to 10% of the total building cost.[186] The prominent cost savings features from using prefabricated modular construction are shown below (a-e).[187] Points of overhead costs and labor costs will covered next, along with the overall savings predicted by using a prefabricated modular construction system over conventional construction systems.

Cost Savings Factors

a) Reduced interest based on construction loans resulting from the time reduction.

b) Buildings can be occupied quicker therefore generating revenue sooner

c) The materials used in the manufacturing of modules (steel) vs conventional building material (concrete), as well as less waste which also has value.

c) Reduced labor costs because time saved means less man hours on site, non-union labor wages in a prefabricated module factory is cheaper than union labor wages on site, and due to increased job safety, there are lower insurance premiums.

e) Reduced overhead costs due to time saving during construction

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[185] Ryan Smith and James Timberlake. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

[186] R. Lawson, P. Grubb, J. Prewer and P. Trebilcock. 1999. *Modular Construction using Light Steel Framing: An Architect's Guide*. Silwood Park, Ascot: The Steel Construction Institute.

[187] Sri Velamati. 2012. "Feasibility, benefits and challenges of modular construction in high rise development in the United States: A developer's perspective." Thesis, Massachusetts Institute of Technology.

### Overhead

What will be explained here is the overhead costs and how generating savings here can affect the cost overall. First, overhead costs can be defined as the operating expenses of a building with charges that cannot be attributed exclusively to a single project or service and is a ratio of a firm's additional cost burden to its bill-able cost. Total overhead costs in the United States usually do not exceed 15% of the annual construction volume, but is a significant amount. The overhead expenses can be categorized into two categories of direct and indirect overhead charges and is shown below.[188]

- Direct overhead costs are those incurred helping to construct a project. They relate specifically to a project and can be added to the project cost. These comprise the expenses of managing the project at the site and can be called project overhead costs. A list of various factors is presented below.[189]

  -project's insurance
  -financing
  -supervision
  -temporary construction
  -equipment rentals and costs
  -temporary offices
  -utilities for the job

- Indirect costs are those incurred by the contractor running the business, but cannot be charged to a specific project. They represent the cost of doing business and fixed expenses that must be paid on a regular basis whether or not the company is

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[188] Mohammad Humoud Al-Shari. 1997. "Overhead costs in building construction in Saudi Arabia." Master thesis, King Fahd University of Petroleum and Minerals.

[189] Ryan Smith and James Timberlake. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

constructing something. These can be called company overhead costs. A list of various factors is presented below.[190]

- -head office expenses
- -head office staff wages
- -warehouse, workshops, and camps
- -automobile expenses
- -insurance
- -taxes and social security
- -retirement
- -fees

According to Lawson et al., site overhead is reduced to at least a proportion of the overall construction schedule. This means that the typical 15% overhead cost of the build cost associated with conventional construction is expected to be reduced to 7-8% with a predicted time savings of thirty to fifty percent.[191] This project is based off of a forty percent schedule savings, so the median of seven and a half percent will be used as the overhead predicted cost savings. Below is an example showing the predicted savings of the Waiea Tower if the entire tower were constructed with a prefabricated modular system by using these metrics and the current information online that states that the final agreed upon cost of the Waiea Tower was initially 275 million dollars, but later increased to 303 million dollars and then 417 million dollars according to the most recent financial report by Howard Hughes. The 417 million dollars includes market and other non-construction related activities, so for the purpose of this the project the 303 million dollar final price will be used to be on the conservative side.[192]

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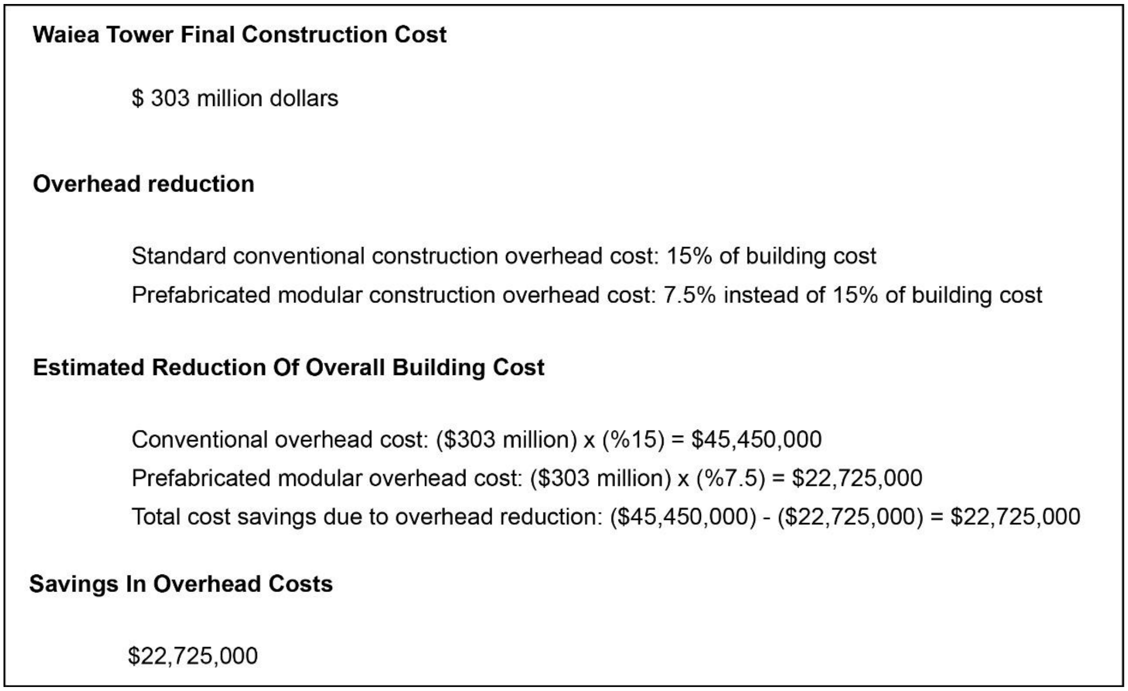
[190] Ryan Smith and James Timberlake. 2010. *Prefab Architecture: A Guide to Modular Design and Construction*. Hoboken, New Jersey: John Wiley & Sons, Incorporated.

[191] Mark Lawson, Ray Ogden, and Chris Goodier. 2014. *Design in Modular Construction*. Boca Raton, Florida: CRC Press.

[192] Honolulu Star Advisor. 2017. “Tower.” *Press Reader*, November 22, 2017.

Figure 13.9 - Comparing cost breakdowns of site intensive construction to modular construction. Lawson, Mark, Ogden, Ray, and Goodier, Chris. *Design in Modular Construction.* Boca Raton, Florida: CRC Press, 2014.



**Waiea Tower Final Construction Cost**

$ 303 million dollars

**Overhead reduction**

Standard conventional construction overhead cost: 15% of building cost
Prefabricated modular construction overhead cost: 7.5% instead of 15% of building cost

**Estimated Reduction Of Overall Building Cost**

Conventional overhead cost: ($303 million) x (%15) = $45,450,000
Prefabricated modular overhead cost: ($303 million) x (%7.5) = $22,725,000
Total cost savings due to overhead reduction: ($45,450,000) - ($22,725,000) = $22,725,000

**Savings In Overhead Costs**

$22,725,000

Figure 13.10 - Overhead cost savings due to time savings by switching from conventional to modular construction.

**Labor**

The overall savings in time relates directly to monetary savings in reduced labor times. There is also the factor that on-site labor in Hawaiʻi or other big cities will be of higher union wages, while the off-site factory labor of the modules on the United States West coast smaller cities is of lower non-union wages. This alone is a factor that reduces the overall cost of labor.[193] Research titled *Modular Prefabricated Residential construction: Constraints and Opportunities*, pointed out that even if union labor is used, it is still at a cheaper wage in off-site construction. An example is given of the Atlantic Yards B2 project. It states that in this project, a union carpenter on site was charging 85$ an hour, but at the off-site factory where the modules were produced, the wage of the same union carpenter was around 35$ an hour. This shows that even if a union worker was used in an off-site factory to fabricate the modules instead of a non-union worker, the wages will still be significantly cheaper.[194]

With the conventional method of construction used in the Waiea tower, there needed to be 19 months of labor wages. For the prefabricated modular proposal, there would need to be 11 ½ months of labor wages. This equates out to savings 7 ½ months of labor wages. While the amount of workers on site cannot be quantified, as well as the exact wages of the workers for union and non-union, a formula shown below can demonstrate how this can be quantified to show that there will in fact be economic savings because of this factor.

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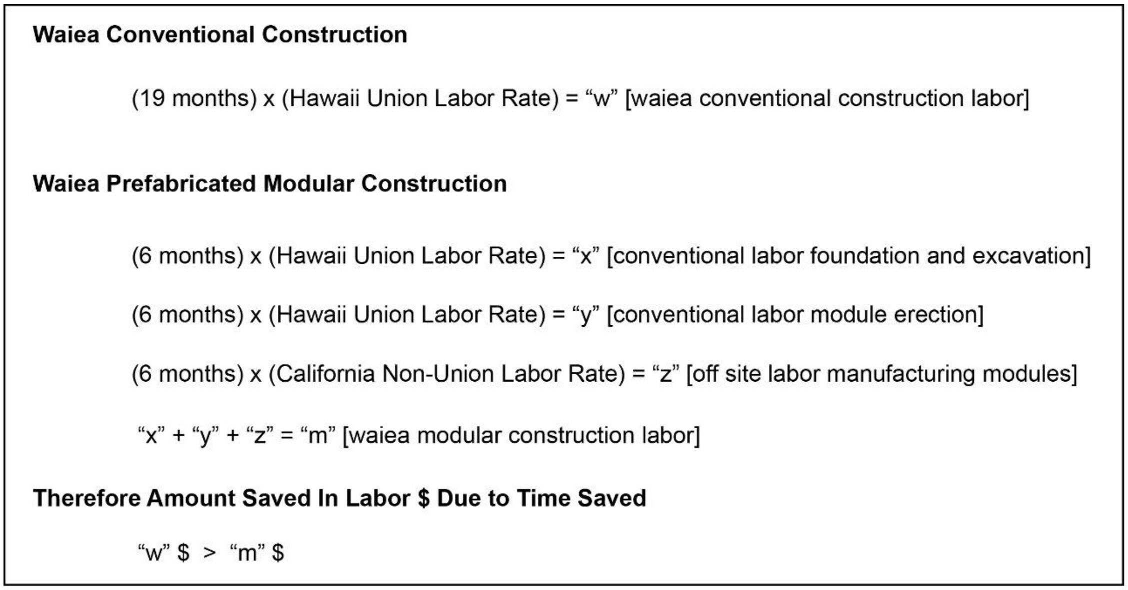
[193] Peter Cameron and Nadia DiCarlo. 2007. “Piecing together modular: Understanding the benefits and limitations of modular construction methods for multifamily development.” Thesis, Massachusetts Institute of Technology.

[194] Naomi Javanifard, Debra Markert, Kristen Strobel, and Jason Yap. 2012. “Modular Prefabricated Residential construction: Constraints and Opportunities.” Technical Report (Skanska Innovation Grant), University of Washington.



**Waiea Conventional Construction**

(19 months) x (Hawaii Union Labor Rate) = “w” [waiea conventional construction labor]

**Waiea Prefabricated Modular Construction**

(6 months) x (Hawaii Union Labor Rate) = “x” [conventional labor foundation and excavation]

(6 months) x (Hawaii Union Labor Rate) = “y” [conventional labor module erection]

(6 months) x (California Non-Union Labor Rate) = “z” [off site labor manufacturing modules]

“x” + “y” + “z” = “m” [waiea modular construction labor]

**Therefore Amount Saved In Labor $ Due to Time Saved**

“w” $ > “m” $

Figure 13.11 - Labor savings formula comparing conventional to modular construction.

**Overall savings**

After looking at some factors of cost savings presented previously, a conclusion can be drawn that the final overall cost of modular construction is cheaper relative to site intensive construction. With so many various factors though it can be hard to quantify the total savings by using prefabricated modular construction rather than site intensive, but Lawson et at., has created a chart that gives the most accurate approximation. This rule of thumb chart shown below gives the total savings as a proportion of the total building cost by using prefabricated modular construction relative to site intensive. It factors the overhead charges mentioned earlier into the site preliminaries savings and the labor charges mentioned earlier into the speed of construction savings. The snagging reduction represents savings due to risk reduction and the consultant fees accounts for the design fees.[195]

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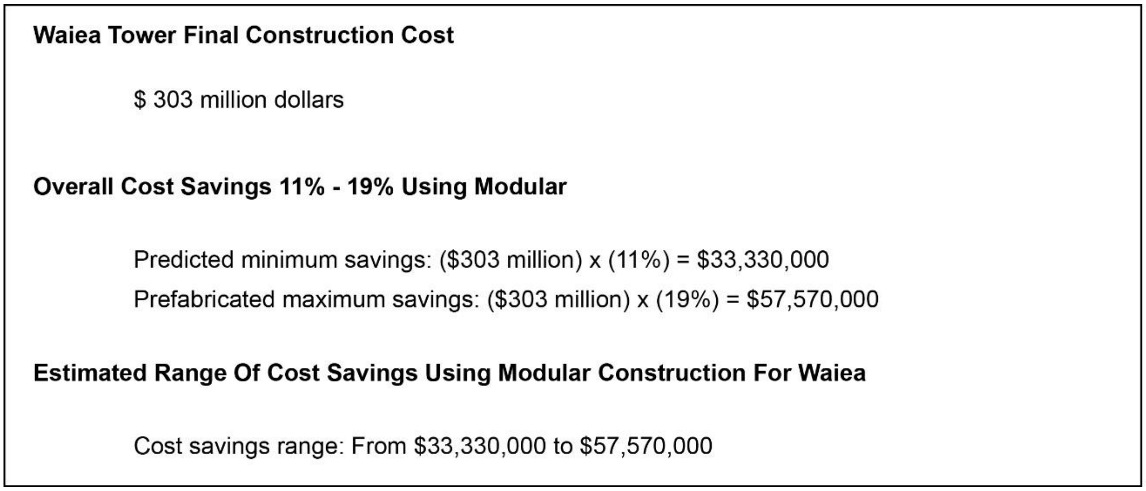
[195] Mark Lawson, Ray Ogden, and Chris Goodier. 2014. *Design in Modular Construction*. Boca Raton, Florida: CRC Press.

Figure 13.12 - Savings of using modular systems relative to site-intensive construction. Lawson, Mark, Ogden, Ray, and Goodier, Chris. *Design in Modular Construction.* Boca Raton, Florida: CRC Press, 2014.

This 11% to 19% total cost reduction shown above will be the approximation (rule of thumb) for cost savings in this project because it is stated that this chart is meant to compare similar overall builds of site-intensive to modular construction. Demonstrated below is the predicted and expected amount of overall cost savings in this projects modular version of the entire Waiea tower using the above figure as the reference.



**Waiea Tower Final Construction Cost**

$ 303 million dollars

**Overall Cost Savings 11% - 19% Using Modular**

Predicted minimum savings: ($303 million) x (11%) = $33,330,000
Prefabricated maximum savings: ($303 million) x (19%) = $57,570,000

**Estimated Range Of Cost Savings Using Modular Construction For Waiea**

Cost savings range: From $33,330,000 to $57,570,000

Figure 13.13 - Estimated total cost savings in this project by using prefabricated modular construction in the Waiea tower instead of conventional on site construction.

Thus, the overall cost savings by using prefabricated modular systems versus site intensive systems for this project is estimated to be in the range from a minimum of $33,330,000 to a maximum of $57,570,000 based upon the information above. This effectively reduces the price of the $303 million dollar Waiea tower to a range from a minimum of $269,670,000 to a maximum of $245,430,000.

## CONCLUSION

In conclusion, this research demonstrates that while there are challenges of building prefabricated modular high-rise structures with customized geometries, if the right design decisions are made, then it will be buildable in terms of structure and more economically feasible than using standard conventional construction. One of the reasons that this type of construction is not used more often is due to the architect not incorporating it into the design. This research aims to provide designers with the current advantages and disadvantages, case study examples, design methodology, and a cost comparison, so that they can be more aware of these factors, as well as being sure that the structure will be buildable and economically feasible. Furthermore, an example of the redesign of the East tower of Waiea using prefabricated modules is shown as an example of implementing the design methodology. It demonstrates the decisions made, how the tower was modularized, and the predicted overall cost savings by using a prefabricated modular system in comparison to conventional construction. It is proven that the prefabricated modular system used reduces the cost of the structure and provides design freedom for further design flexibility through customized components.

Thus, in response to the research questions, this research shows that prefabricated modular design does not have to be limited by the rigid box form. It also shows that customized geometrical forms can be made more economically feasible by using mass customized components of a prefabricated modular construction system. Prefabricated modular construction can in fact be used for high-rise structures and the important steps involved in the design decisions are outlined in this research. In response to the research objectives, first, the economic incentives mostly deal with the overall time saved which equates out to cost savings, but there is also the incentive to achieve greater design freedom. Next, the method of design decisions is outlined for future use on similar structures and is demonstrated as steps and as an example. Finally, it was shown that prefabricated modular designs are not limited to low quality, low-rise structures and have the ability to achieve high-quality high-rise structures. Therefore, the hypothesis of this research is proven correct, that states that a conventionally constructed high-rise high-quality building with a customized geometrical form can be reconstructed using a prefabricated modular system while retaining the overall qualities and properties and reducing the overall building cost. Using prefabricated modular construction for a high-rise structure with customized geometrical forms in Hawai‘i is shown to be buildable and feasible by using the design decisions outlines in this research.

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