EXPANDING MODULAR DESIGN:
ALL-RISE MASS TIMBER RESIDENCES IN HAWAIʻI

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For my family—thank you Amy, Kyle, Katie, and Brysen

for believing in your big brother.

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Abstract

The building construction industry is on the verge of a massive transformation of construction practices set forth by continued pressure to evolve and adapt to rising global and urban challenges. While an array of recently developed construction practices and technologies now exist, two prefabrication methods tackling these issues that are now seen as plausible alternatives of building construction are modular construction and mass timber construction. With current building methods compelled to change, questions begin to arise of what the future of construction looks like and which systems can adapt to local environments with distinct conditions.

The research provided focuses on Hawai‘i’s urban challenges and the need to adopt new methods of construction to confront the housing demand of 64,693 additional housing units by 2025, as well as meet the state’s clean energy initiative by 2045. An evaluation of prefabrication methods with emphasis on modular and mass timber construction is conducted to understand the benefits of the recent developments and determine its appropriate feasibility for urban Honolulu, Hawai‘i’s capital city with the largest housing demand. The benefits of both methods are summarized to then be implemented with a proposed residential building model expressing the local conditions that may be faced.

The resulting building design proposes to use a hybrid model that combines both modular and mass timber construction methods to resolve various issues while simultaneously taking advantage of the both prefab types’ reduced construction times and environmental benefits. The design proposal closely follows local building codes in addition to the revised 2021 IBC that identifies mass timber construction as Type IV to ground the model with real world constraints. In reaction, the development of a varying, “light” module is also proposed with the hybrid building model that implies modular construction’s increased flexibility and the potential for further exploration and applicability to other building typologies. The concluding design scheme offers a glimpse into what Honolulu’s future construction methods could be to effectively support the city’s housing needs and local environmental issues, while the collected research can be expanded upon with other emerging prefabrication methods, to continue to pursue construction practices that address the global urban issues unique to the 21st century.

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List of Abbreviations and Terms

Affordable Housing:	Housing for which the occupant(s) is/are paying no more than 30 percent of his or her income for gross housing costs, including utilities. In Hawai‘i, as of 2016 the median household income was $74,511, making housing that costs $22,353 or less per year affordable.
Area Median Income (AMI):	Area median income is a statistic generated by the U.S. Department of Housing and Urban Development (HUD) for purposes of determining the eligibility of applicants for certain federal housing programs including affordable housing.
Cross-Laminated Timber (CLT)	Cross-laminated timber is a type of mass timber produced by laminating layers of wood panels perpendicular to each other to achieve increased strength in both spans.
Design for Manufacturing and Assembly (DfMA):	DfMA or Design for Manufacturing and Assembly is Singapore’s clearly defined guidelines regarding building prefabrication in the country. It regulates and standardizes the methods of prefabrication to ease accessibility and efficiency for the country’s manufacturers and builders.
Factory Built Housing (FBH):	Defined within the Hawai‘i Building Code as any structure or portion thereof designed primarily for residential occupancy by human beings, which is either entirely prefabricated or assembled at a place other than the building site.
Global Warming Potential (GWP):	Global warming potential is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide, the time period usually being 100 years. As an example, methane heats up the atmosphere at a rate 25 times faster than CO2 so has a GWP value of 25.
Housing and Urban Development (HUD):	The U.S. Department of Housing and Urban Development regulates the codes and executes policies on housing and cities which the construction industry must follow.
Land Use Ordinance (LUO):	The Land Use Ordinance includes the zoning designation boundaries and zoning maps set forth by the Planning Department of the city; this project specifically refers to the City and County of Honolulu’s LUO.
Manufactured Home	Type of home that differs from modular homes in that the prefabricated structure rests on a chassis, a steel platform with wheels, making the home also known as a mobile home that follows HUD guidelines.
Mass Timber	A category of engineered wood used for construction that is manufactured within factories by layering wood panels together and then laminated, compressed, or glued to form solid panels of wood for floor slabs, walls, and ceilings. Popular mass timber products include CLT panels and glulam.

Modular	The term modular has been used extensively throughout the construction industry. For clarity and future use here, the term modular is an adjective referring to modular design and construction; a type of prefabrication which utilizes modules or sections of a structure to be fabricated off-site in a controlled environment, then transported and assembled on-site.
Modular Home	Type of prefabricated home that utilizes modules and differs from that of a manufactured home by resting on a permanent foundation and following IBC and federal guidelines.
Permanent Modular Construction (PMC):	Modular construction can be categorized into two overarching types, permanent and relocatable. Permanent modular construction utilizes modules and techniques that are permanently designed for a specific site and cannot be removed without extensive intervention and labor.
Prefabrication (Prefab)	Prefabrication is the informal umbrella term describing the assembly of buildings or their components at a location other than the building site. The method controls construction costs by economizing on time, wages, and materials. Prefab can encompass building components, panels, room units, or entire buildings.
Prefabricated Prefinished Volumetric Construction (PPVC):	In 2014, the government of Singapore officially defined and standardized modular construction in the State as PPVC and created an official manual for manufacturers and contractors to follow and meet declared standards.
Relocatable Building (RB):	Relocatable buildings are a type of modular construction where the structures can be moved and installed after its initial construction.

1. Introduction

1.1 Problem Statement

Hawaiʻi continues to face housing pressure brought on by the insufficient inventory of residential units that are accessible to its locals, especially for the urban residents of Honolulu where new housing options are needed most. As the time-sensitive crisis approaches a catalyst, described by the special action team report for Hawaiʻi's state legislature,[1] a focused search and adoption of efficient, rapid, and environmentally conscious construction methods are necessary to sustain the city's urban growth. Conventional means of construction are being challenged and proven obsolete in the wake of a vast array of newly developed tools, materials, and building techniques, in turn making the pursuit for appropriate methods in Hawaiʻi both exciting and daunting to evaluate and determine feasibility. The critical decision of which construction techniques are most beneficial for Oahu and its neighbor islands is paramount to the islands' future and will heavily influence the urban built form.

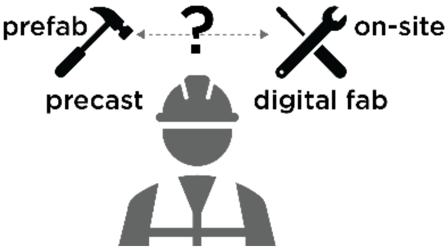

Figure 1: Construction Options Graphic

Source: Author

Two major developments in the construction industry worthy of deeper understanding are occurring in the realm of prefabrication. An umbrella term for prefabricated parts or whole segments of a building manufactured off-site and assembled for completion, prefabrication methods have been leading the construction industry's

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[1] State of Hawaiʻi, *Affordable Rental Housing Report & Ten-Year Plan," State of Hawaiʻi,* (Honolulu: Department of Business, Economic Development and Tourism, 2018), 5-16.

evolution towards more efficient and economic practices. Categorized under prefabrication, modular construction and mass timber construction are quickly gaining global attention and adoption for their widespread, inherent benefits which are being shown to outweigh the currently dominant building options. While major urban hubs begin to use these recently available choices of construction, a study of their characteristics and possible long-term effects must be conducted before widespread use throughout Hawaiʻi. Then, building upon the gathered knowledge, questions of physical form and assembly processes of modular construction and mass timber within Hawaiʻi's unique environment can begin to be explored and attempt to resolve the housing challenges bearing down on the islands.

To understand why modular construction techniques and mass timber structures are becoming a growing trend recently, and why they should be considered feasible alternatives to conventional construction, a macro-scale perspective of current challenges directly affecting architectural practice must be assembled for inventory as the guiding principles on why it is necessary to change current construction methods in the first place. The need for housing solutions are being felt in all major urban areas around the world, with Hawaiʻi seen as one of the countless places struggling to keep up with the congested residential landscape. By 2060, two-thirds of the global anticipated population of 10 billion people will reside in cities alone. This translates to 6 billion or 2 out of every 3 people needing a space to live within the urban environment. The demand for space will require advanced efficiency in construction with no allowance for structural systems to waste the already limited space and materials on form or structure alone. With a rising urban population, the global floor area growth is expected to reach 2.48 trillion square feet as depicted in Figure 2 by the projected 2060 timeline. To put into an added perspective, this is the rough equivalent of adding another New York city to the built environment every month for 40 years. [2]

On the current timeline, throughout the continental U.S, a shortage of available and affordable housing is already being experienced with no significant approaching remedies in sight. As a contributing factor, an updated consensus has expressed the U.S's expected

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[2] Architecture 2030, https://architecture2030.org/buildings_problem_why/

population to be 400 million by 2050, an increase of 75 million within the next 32 years.[3] At 325 million current residents as of 2017, the domestic population has grown from 309 million in 2010, and from 282 million in 2000, on an average of 0.9% annual growth between 2000-2010, and a smaller 0.7% annual growth during the last eight years. Within this decade alone, the country has gained 16 million people, the majority residing in dense urban areas; as reflected in the Department of Economic and Social Affairs' report at being 82.8% of our population, significantly above the global average of having a 55% urban population.[4] The recorded and projected population growth in the country provides a crucial argument of the need to continue redefining urban spaces and promote effective, efficient residential construction methods and planning throughout the built environment.

Figure 2: Global Floor Area Growth

Source: Architecture 2030

For Hawai‘i, a 2017 gap report was published highlighting the 50th state as one of the most burdened from the affordable housing crisis.[5] The current Hawai‘i population is at 1.43 million people distinguishing Honolulu, the state's capital and largest city reaching 350,000 people while the overall island of Oahu provides residency to 953,000. As the housing crisis continues, more Hawai`i locals and Native Hawaiians suffering from inaccessible housing are being pushed out of the State and seeking refuge in other areas of

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[3] Population Division, Department of Economic and Social Affairs. 2017. Worldometers U.S. Population. Accessed June 3, 2018. http://www.worldometers.info/world-population/us-population/.

[4] Ibid.

[5] National Low-Income Housing Coalition. The Gap: A Shortage of Affordable Homes. Washington, D.C., National Low-Income Housing Coalition. 2017.

affordability.[6] The role of architecture in Hawai‘i and its urban policymakers' responsibility of providing rapidly built affordable housing will be continually questioned and challenged critically over the next thirty years as the country reaches a new milestone of overall population growth of 1.65 million in 2045, an average growth rate of 0.5 percent per year.[7] The preparation for innovative building methods and early policy adoptions allowing for efficient construction timelines set forth within these keystone years will have lasting effects on the state's housing supply and position of accessibility in comparison to the rest of the country.

Population growth in urban areas is a critical contributing factor towards the housing challenges felt globally and has directly influenced the motivations behind the progress of prefabrication and modular construction to reach faster construction times, reduce waste, and offer affordable housing options to the city's residents. However, the increasing wave of recently developed construction methods being adopted throughout the global built environment is also being pushed to meet other rising challenges unique to the 21st century. "Climate Change is the defining issue of our time and we are at a defining moment," United Nations.[8] It is estimated that there is about 30% more carbon dioxide in the atmosphere today than there was 150 years ago while ice core samples show that there is now more carbon dioxide in the atmosphere than there has been in the last 420,000 years.[9] In the era of climate change and climate crisis towards humanity, understanding carbon emissions, embodied energy, and the construction industry's role in reducing its carbon footprint is now an added layer of responsibility for architects and stakeholders of the built environment held with utmost importance. According to Architecture 2030, a nonprofit organization whose mission is to make buildings carbon neutral by 2030 and is backed by the national AIA towards the 2030 commitment, has shown that buildings make up 39% of global carbon emissions, with the urban built environment being responsible for

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[6] Bureau, United States Census. 2017. Hawaii Quick Facts. Accessed June 11, 2018. https://www.census.gov/quickfacts/fact/table/HI/PST045217#viewtop.

[7] https://files.hawaii.gov/dbedt/economic/data_reports/2045-long-range-forecast/2045-long-range-forecast.pdf

[8] https://www.un.org/en/sections/issues-depth/climate-change/

[9] CLT UK 100

75% of annual greenhouse gas emissions depicted in Figure 3 below.[10] The direct effects of building with environmental awareness and consideration is explicitly shown here.

Figure 3: Global CO2 Emissions
Source: Architecture 2030

Adding to the average carbon output by current buildings, the projected embodied carbon emissions from new construction will reach 49%, and 51% of the new construction carbon emissions will be operational carbon. This translates to half of a building's carbon emissions throughout its lifecycle is emitted before and during construction, highlighting necessary reviews of which construction materials should be used and the carbon footprint of transporting materials having a greater influence than the renovation or retrofitting of energy efficiency tools to mitigate a building's operational footprint.

Figure 4: 2020-2050 New Construction CO2 Emissions
Source: Architecture 2030

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[10] https://architecture2030.org/2030_challenges/2030-challenge/

The overwhelming challenges presently faced to speed up construction to meet rising housing demand while simultaneously reducing the building sector's carbon emissions is now getting government organization and updated policies to combat climate change and global carbon emissions. Every industry is being directly transformed and guided by government authorities, with the building industry being at the forefront of change. In 2016, at the 21st Conference of Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCC) the Paris Climate Agreement was signed into effect by 196 sovereign states. Its goals state the agreed efforts by each signed nation to reduce their carbon emissions in order to keep the global temperature below a 2-degree Celsius rise from pre-industrial levels and aim for no more than 1.5-degree Celsius increase. The support of governing bodies to reduce carbon emissions has led to greater funding towards initiatives sequestering carbon. Mass timber, a recent development of structural engineered wood that is prefabricated and then assembled on-site is an example of growing developments in the construction industry to reduce carbon and is researched further along with modular construction throughout this body of work. As the only renewable structural material and inherently being a carbon sink, mass timber has the potential to greatly combat carbon emissions. Also falling under prefabrication, it is increasingly seen as an economical asset with faster construction times and reduced waste, attributes shared with modular construction. Whether it is modular construction, mass timber, or a new development not yet known, all future buildings must use sustainable and efficient means of construction to be carbon neutral and help mitigate the greenhouse gas emissions, while still providing the primary programs of a building and supplementing global housing needs.

Meeting the needs of the 21st century's rising challenges, the urban built environment is rapidly changing, leading to the question of what does the future of construction hold and what will it look like? How do the various systems work together and do the benefits truly outweigh the costs of transitioning away from conventional means of construction? Leading the movement of increased construction efficiency and cost savings are two major developments considered to be potential alternative means of building: modular construction and mass timber. The beneficial implications of both prefab types are explored further in this research to try and understand the potential applications and how they may be adapted to Hawaiʻi. Being on an island, the state's largest city of

Honolulu will be the focal point of future residential construction in the nation. Having limited resources in space, materials, labor, and time will provide a critical framework to develop a fast-paced residential construction method at an efficient, affordable, and sustainable rate for its locals. The constraining parameters make for an ideal testing ground of prefabrication and determining whether modular construction and mass timber are future alternatives to construction or just temporary trends. In Hawaiʻi, prefabricated residential homes are already currently being offered as an alternative option to conventional ones, yet they still face challenges moving forward and becoming the main source of housing construction. With the implied benefits of off-site construction becoming more pronounced, the question of modular design being appropriate for Hawaiʻi is raised along with the materiality of mass timber. Regardless of the successful implementation of these two specific construction types, the early adoption and adaptation of a novel construction method that addresses today's defining issues will have the potential to influence the livelihood of Hawaiʻi's locals for generations to come.

1.2 Research and Design Methodology

The conducted body of work is organized into eight chapters, with the main subject focusing upon modular and mass timber prefabrication methods. The analysis of both methods is done to understand the respective fabrication processes and the positive effects of implementing its methods in design and construction in Hawaiʻi. The research first considers the global issues affecting the construction industry and then localizes it to Hawaiʻi and the challenges similarly felt within the archipelago. Once established, the second part introduces the history of prefabrication and current methods as precedent alternatives to help mitigate and resolve the issues at hand. A mixture of case studies and literature reviews are broken down within the third to sixth chapters as a deeper focus is placed on the prefabrication methods of modular construction and mass timber as the primary prefab options to be explored. This is done to begin understanding the system of fabrication and assembly behind both construction methods and weigh the benefits of each to form a possible use and relevancy in urban Honolulu.

Chapters three and four extensively review modular construction, its types, and assembly processes, ending with case studies to take in a spectrum of modular design and construction examples already built. The visible and physical aspects of previously completed modular buildings, the differences in building materials, and the history behind them are recorded to understand the design, and the systems of the prefabrication method. The research done on modular construction organizes the various informal terms and types used throughout the industry interchangeably to begin providing a coherent toolkit of which modular construction methods and prefab methods in general may be suitable for further exploration and implementation on a larger scale than typically seen.

A new layer of materiality is built upon the modular design analysis with the introduction of mass timber in part five and six. The ongoing development of mass timber is recently gaining traction in the U.S., and the implementation of the International Building Code (IBC) 2021 acknowledging mass timber as type-iv construction sheds new light on the material with standardized requirements when in use. Therefore, the research acts as an introductory summary of mass timber with its types and assembly processes to define the potential of the renewable material for future building plans, as well as provide evaluations of case studies primarily built in the Pacific Northwest.

As modular construction repeatedly faces its own challenges and limitations, the recent advocacy of mass timber as a structural material is explored to understand the potential benefits of coupling the material with modular construction and expand both prefabricated options as a hybrid option to meet Hawaiʻi’s housing needs. Chapter seven illuminates the research gathered by providing a design proposal that implements both prefab construction options and begins to express the hybrid model as a feasible precedent study for future prefabrication development in Hawaiʻi. With the anticipation of having both modular construction and mass timber becoming widely adopted throughout the construction industry, the design model follows current Hawaiʻi codes and zoning ordinances. The guidelines include selecting a site directly affected by the Transit-Oriented Development Plan, and using the updated IBC 2021 version, to allow the proposal to express the practicality of implementing these methods locally in the near future and also highlight the challenges that may be faced when choosing this route of construction.

To conclude the body of work and questions raised, the final chapter reviews the goals of the research done of understanding the various alternative construction methods currently offered in an attempt to begin asking and directing the questions of where does the future of construction lie, why is it changing, and what are the possible methods of adoption for Hawai‘i when facing its own local challenges. The research gathered on prefabrication and its various assembly systems, along with the hybrid residential model begin to frame these questions and attempts to offer possible answers with the chosen modular system being adapted to urban Honolulu. In combination with mass timber, the hybrid modular system has the potential to bring out the benefits of both methods while mitigating current limitations of the respective technologies. Final thoughts and discussion express the overarching benefits of using prefabrication methods over conventional practices to continue overcoming the 21st challenges felt throughout the islands. As a closing remark, there is potential for future prefabrication development in Honolulu using modular design as an alternative model for rapid and sustainable tropical housing development for its locals, supplemented by renewable mass timber that can be adopted and adapted to the local context of the city.

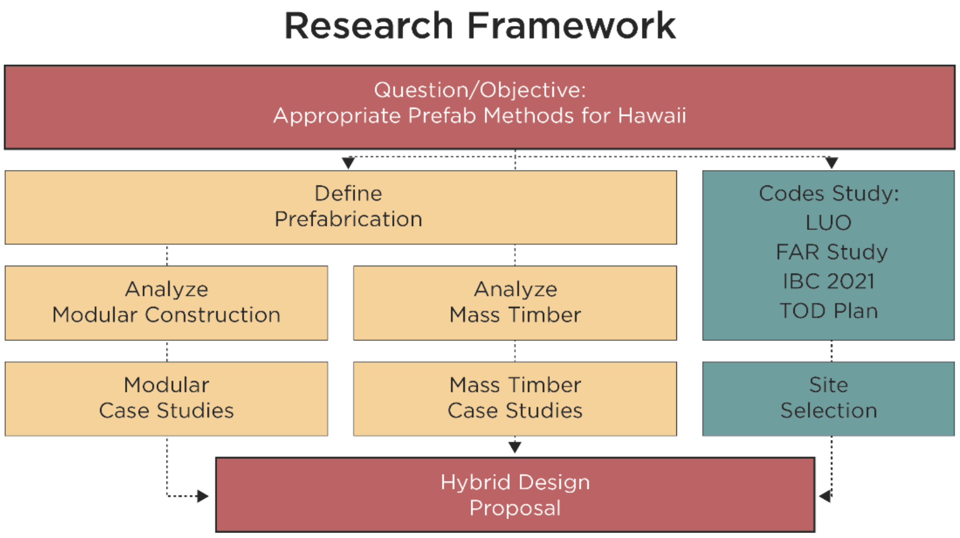

Figure 5: Research Project Framework

Source: Author

1.3 Research Objective

The unifying goal of the research completed in this body of work is to provide a housing design model in Hawaiʻi that addresses the problems of choosing an appropriate strategy from the vast array of modern construction options available. In order to meet the housing and population demands of the state, and simultaneously mitigate the climate crisis especially felt in urban areas such as Honolulu, the model focuses on the use of modular mid-rise design as a viable alternative from conventional construction methods for efficiency in materials and time. Modular design is chosen as the focus of research for its evolving construction methods and technology stemming from the history of prefabrication to produce fast-paced, efficient housing. The expansion of modular construction is attempted in the building model with the introduction of mass timber and implementing it in collaboration with modular design strategies to form a hybrid construction model using a variation of modules for Honolulu's residents that may be used throughout the state.

The final design proposal in the form of a mid-rise, mixed-use residence for urban Honolulu summarizes the gained understanding of modular construction and mass timber prefabrication methods to display the overall potential use in future housing projects relating to efficient and sustainable design in a tropical climate. The proposal ultimately allows a discussion of modular construction and mass timber as both beneficial construction methods that have the capability to evolve and adapt to Hawaiʻi's context. The exercise of using local codes and parameters also shed light on the need for collaboration with policymakers and possible review of current zonings and procedures to ensure the maximum benefits received from adopting these newly developed practices.

The overbearing question of what is the future of prefabricated construction methods as global urban challenges continue to arise, and how will it change or adapt to Hawaiʻi's unique environment is exercised here with an attempt of possible alternative forms offered as a preliminary glimpse towards construction solutions. Allowing Hawaiʻi to act as a model for contemporary housing design is an underlying goal by using rapid assembly modules and climate-conscious mass timber panels for construction. The continued research and early adoption of these novel methods may allow Hawaiʻi to offer accessible housing and act as a landmark example of the future of construction techniques.

1.4 Hawai‘i's Residential Context

1.4.1 Housing Needs

The isolated archipelago of Hawai‘i has a distinct urban form in reaction to multiple influences outside of its geographic location. Historic factors dating back to the Cook era, the rise of plantations and cash crops, and increased involvement of the military have all contributed to the current built environment across the islands, with the state's largest city of Honolulu especially reflecting the dynamic urban landscape. Residential housing, with direct and indirect reactions to all the various factors express the ongoing deprivation of housing and other urban amenities today. The demand for Housing in Hawai‘i as stated by the Department of Business, Economic Development and Tourism between 2015-2025 is projected to be: 25,847 for Honolulu, 13,949 for Maui, 5,287 for Kauai, and 19,610 for the island of Hawai‘i.[11] Honolulu being the most developed and largest city in the state, accounts for about 40% of the projected demand. The overall need of 64,693 new housing units in Hawai‘i has resulted in the implementation of Act 127 in 2016 from the State of Hawai‘i and is backed by a Special Action Team (SAT) to define a ten-year goal to combat the affordable housing crisis and provide a framework to construct 22,500 units by 2026.[12] To mitigate the intensifying housing crisis of the islands, alternative housing solutions to provide both affordable and rapid residential dwelling units must continue to be discussed, proposed, and ultimately implemented to confront the current housing availability and build upon the guidelines discussed within the State of Hawai‘i's own action plan. The period set by the special action team puts both increased pressure on lawmakers and stakeholders to address the housing issue. Moving forward, the report also grounds the need for housing in a relevant time frame that all residents of Hawai‘i can grasp, including architects and stakeholders developing the local built environment. It acts as an overarching guideline with a critical deadline attached which all involving parties of the development of Oahu should be familiar with and addressing with each project at hand.

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[11] Department of Business, Economic Development & Tourism. March 2015. Measuring Housing Demand in Hawaii, 2015-2025. Housing Analysis, Honolulu: Research and Economic Analysis Division.

[12] State of Hawai‘i, *Affordable Rental Housing Report & Ten-Year Plan," State of Hawai‘i,* (Honolulu: Department of Business, Economic Development and Tourism, 2018), 5-16.

Figure 6: Hawaii's Housing Demand

Source: Hawaii Business

Hawaii’s housing market continues to be disproportionate due to the constrained supply and increasing demand. Housing prices reached new record highs in 2014 and this new record surpassed the previous one set in 2005.[13] At an overview glance, the median household income in Hawaii in 2016 was $74,511, making it 29.3% or $16, 894 higher than the U.S. average of $57,617.[14] The archipelago ranked 6th among the 50 states and the District of Columbia where the highest had the rank of 1; California falling into rank 10 and New York being 15. Despite the higher median income nationwide, Hawai‘i’s residents suffer from a large gap of affordability when analyzing the average household rent and mortgage. In terms of mortgage rates, the median owner-occupied units’ monthly costs were $2,239, translating to a rate 50.7% or $753 higher than the U.S. average.[15]

Recorded in 2016 as well, this put Hawai‘i in 3rd place out of the 50 states with the highest cost ranked at 1. The cost of living is even worse in Hawai‘i when taking into account rental rates from 2016. The monthly gross for the renter-occupied units in Hawaii was $1,483, a total of 51.2% or $502 higher than the U.S. average, ranking the state as the highest in country. Due to the high median cost, 47.4% of residents in 2016 spent 35% or

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[13] Ibid.

[14] Department of Business, Economic Development & Tourism, “Research and Economic Analysis: How Does Hawai‘i Compare to Other States?” State of Hawai‘i, accessed October 5, 2018. http://dbedt.hawaii.gov/economic/ranks/.

[15] Ibid.

more of their household income on gross rent, again ranking Hawaiʻi the highest in the U.S.[16] The need for accessible housing in Hawaiʻi is reaching locals' tolerance threshold.

1.4.2 Environmental Issues

Hawaiʻi has recently been ranked as the most dependent state in the nation reliant on fossil fuels, largely due to electricity production.[17] To make matters worse, Hawaiʻi heavily relies on tourism for its economic livelihood and flights going to the state produce high volumes of carbon emissions. As noted by Oahu Sierra Club, the emissions from a single flight from Los Angeles to Honolulu is equal to driving 710 miles. One flight emits 0.6 metric tons of carbon dioxide or about sixty-seven gallons of gas.[18] Annually, tourists arriving from the west coast produce 2,295,385 metric tons of carbon dioxide. That's equivalent to driving 5,600,000 miles or powering 400,000 homes electricity usage for a year.[19] This only accounts for the tourists incoming from the West. When taking inventory of the annual 10 million tourists, the metric tons of carbon dioxide emitted jumps from the 2.3 million to 6.3 million. The aviation industry of Hawaiʻi accounts for 30% of petroleum use overall. In comparison, 25% of petroleum use was for electric power while 28% accounted for ground transportation.[20]

As a response to this, recording and publishing the annual carbon emissions has been implemented by officials to start becoming more open and aware of fossil fuel use and carbon emissions. More significantly, Hawaiʻi has become the first state in the U.S to adopt the Paris Climate Agreement into its own regulations and has begun taking steps to towards a carbon neutral state by 2045 using 100% clean energy. Signed into effect in 2017, Hawaiʻi's 2045 Clean Energy Initiative (HCEI) is a crucial goal with set guidelines for the state's direction to reach carbon neutrality within the next twenty-five years. As shown in Figure 7, Hawaiʻi is heavily reliant on fossil fuels. However, the growing change can start to be seen as the state begins to reduce its petroleum consumption. With the environment

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[16] "Research and Economic Analysis: How Does Hawaiʻi Compare to Other States?" State of Hawaiʻi.

[17] "Greenhouse Gas Mitigation," State of Hawaiʻi, https://dashboard.hawaii.gov/stat/goals/5xhf-begg/ezet-axai/edup-hdhb, accessed April 5, 2019.

[18] Steward Yerton, "Civil Beat: Air Travel's Carbon Footprint Takes A Big Environmental Toll In Hawaii," Sierra Club Oahu Group, https://sierracluboahu.org/civil-beat-air-travels-carbon-footprint-takes-a-big-environmental-toll-in-hawaii/, accessed October 8, 2019.

[19] Ibid.

[20] Ibid.

inherently intertwined with Hawai‘i’s locals, the building sector will also need to make significant changes to combat its carbon emissions and fossil fuel dependence.

Figure 7: Hawaii CO2 Emissions from Fossil Fuels

Source: : State of Hawaii

1.4.3 Urban Residences

Figure 8: Monster Homes

Source: Citylab

The current housing options in large part are failing Hawai‘i’s residents. The overwhelming demand for affordable housing in urban areas are leading to illegal building typologies popping up across urban Honolulu to supplement the needs with whatever means necessary. These homes, informally called monster homes, exist in the local built environment and are largely given a blind eye by local officials despite its large visible presence.[21] Monster homes is used here as one example of the complicated residential landscape in Honolulu. Current conventional methods of construction used for high-rises with its high costs cannot keep up with the demand of urban residential units or be accessible to the many locals living under the average median income. So, homeowners and renters are turning towards these oversized single-family homes usually built cheaply and maxing out site boundaries to fit multiple rooms and multiple families despite being zoned as a single-family residence. In addition, this new typology can then be considered an effect and organic reaction of the housing crisis, and the informal construction used to reach affordability expresses the need for policy changes as well as new methods of construction and zoning.

1.4.4 Prefabricated Home Options

Prefabricated homes already exist in Hawaiʻi with a range of options for consumers to choose from. Many construction companies now offer entire prefabricated homes ready to be installed on-site, with accessory dwelling units (ADU) becoming a growing market for consumers and utilization of prefabrication and modular design. Some prefabricated home options on the islands can be found with Hardware Hawaii and Tiny Pacific Houses, for example. The advocacy for prefabricated homes and structures are slowly growing in the islands but is currently limited to low-rise development.

In Hawaiʻi, prefabricated homes are explained and discussed in various degrees within the 2012 Hawaiʻi Building Code under the terms of both package homes along with factory-built homes (FBH). Package Homes are defined as manufactured homes in a factory that are ready to be installed on-site, with a minimum area of 900 sq. ft. and maximum of 1400 sq. ft., not including a carport or garage. An additional space accommodating a maximum of two cars may also be included. Factory-built homes are any structure or portion thereof designed primarily for residential occupancy by human beings, which is either entirely prefabricated or assembled at a place other than the building site.

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[21] Kathleen Wong, “On Oahu, a Debate Over Honolulu’s ‘Monster’ Homes,” Citylab, https://www.citylab.com/life/2018/12/oahu-honolulu-monster-homes-hawaii-architecture-debate/577441/, accessed December 14, 2018.

They also follow the IBC for multi-family dwellings and the International Residential Code (IRC) for one and two-family dwellings.

Following these codes, existing buildings utilizing modular construction exist in Hawai‘i despite its unconventional building methods and other factors preventing it from being the primary form of construction. In Hawai‘i, most modular buildings are built on a small-scale and often are motivated by government involvement. One existing case study is the Marine Corps Base in Kaneohe Bay, Oahu utilizing a semi-permanent modular medical facility.[22] The facility was built using thirteen 12’ x 60’ modular units, resulting in a 156’ x 60’ semi-permanent modular buildings that totaled over 9,300 square feet. The structure was built to serve the marines until a permanent structure could be constructed, and included treatment and exam rooms, waiting areas, offices, conference rooms, storage for equipment and records, personnel workstations, as well as the fixtures, furniture and equipment needed for a well-functioning and efficient clinical environment.[23] In the end, all units were prefabricated off-site and shipped from the mainland to be assembled in Hawai‘i.

Figure 9: Modular at Hawai‘i Marine Corps Medical Facility

Source: Sustainable Modular Management

Concurrent with the tiny home movement across the U.S., Hawai‘i is experiencing a wave of its own tiny homes and introduction of modular accessory dwelling units (ADU). Tiny Pacific Houses, a local tiny home provider in Hawai‘i, offers various model options

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[22] “Sustainable Modular Case Studies: Healthcare,” SMM, accessed November 27, 2018, https://www.sustainablemodular.com/case-studies/lockheed-martin-aeronautics-modular-sleeping-quarters/

[23] “Sustainable Modular Case Studies: Healthcare,” SMM.

to choose from for interested homebuyers. Legally classified as RV’s (recreational vehicles), the tiny homes offer alternative and affordable housing options to those in need. An accessory dwelling unit (ADU) is a home, built on a single-family lot, separate from the main dwelling, and includes a kitchen, bathroom, and sleeping area within the unit.[24] A main source of island ADU options comes from Hawaii ADU which promotes the option of buying the ADU modules for as low as $70,000. With the development of Ohana homes and ADU specifications, residents are now being given the opportunity to expand their property when available and supplement some of the housing demand that is drastically needed.

Figure 10: Hawaii ADU

Source: hawaiiadu.org

1.5 Future Residential Landscape

There are many opportunities for Hawaiʻi to expand its use of modular construction and prefabricated materials when appropriate, with the dense landscape of Honolulu being a primary setting for precedence. Modular construction continues to grow within the industry and the demand has significantly changed. In 2013, 60,210 new manufactured homes were sold across the United States, with California and Florida attributing thousands of them and Texas having 12,048. However, Hawaii was dead last in the nation – it only purchased four.[25] However, it is recently picking up traction and increased attention. As a type of prefabrication, modular construction is expected to take off to new heights

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[24] “Accessory Dwelling Unit Homeowners Handbook,” Hawaiiadu.org, (Honolulu: Hawaii Appleseed, 2015), 1-17.

[25] https://www.civilbeat.org/2015/01/living-hawaii-why-the-islands-need-mobile-homes-and-dont-have-them/, accessed October 10, 2018.

throughout 2018 and following years, becoming a huge player in the construction industry. The market size of modular construction is projected to grow at a CAGR of 7.1% from 2018-2023. The value of the modular construction market in 2018 is estimated at 92.18 billion US dollars and is now estimated to reach 129.67 billion US dollars by 2023.[26] The slow growth of modular construction in Hawai‘i and the continuous housing crisis provides a large area of opportunity for the prefab type to be implemented throughout the islands. Though modular construction development exists, no large-scale prefabricated options are readily available to tackle mid-rise and high-rise construction projects where the majority of housing units are needed as expressed earlier by the state legislature's special action team. Increasing costs of land, decreasing availability of space, and a limited time frame to mitigate housing demand may provide modular construction and the umbrella of prefabricated building options to be taken seriously by the state's stakeholders.

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[26] "Modular Construction Market by Type (Permanent, Relocatable), Material (Precast concrete, Steel Wood, Plastic, Others), End-use sector (Housing, Commercial, Education, Healthcare, Industrial), and Region - Global Forecast to 2023," accessed November 6, 2018, https://www.prnewswire.com/news-releases/modular-construction-market-worth-129-67-billion-by-2023-818121207.html.

2. Rise of Modern Prefabrication

2.1 Types of Prefab

Prefabrication (prefab) has a long-standing history in the built environment with terminologies overlapping and sometimes replacing each other throughout time and cultural exchanges. The overarching term prefabrication in an architectural context is the process and overall practice of constructing the various pieces of a structure in a factory or manufacturing facility before taking it to its on-site location for final assembly. It directly contrasts that of conventional construction practices where the majority of building and assembling the necessary raw materials are done on-site to complete the form. By understanding the distinguished methods of prefabrication and its history, a clear direction of which construction methods are most appropriate for future development and research, and more importantly, why they're beneficial in the first place, can be framed and built upon. This foundation of knowledge can then be used towards the discussion of adopting the evaluated technology into local built environments, such as Honolulu, and how the prefabrication methods can also potentially change and evolve with the urban context .

Currently in the U.S, the three major types of prefabricated structures are: panelized, which are transported in flatpacks, a component/frame type that are transported in sections, and modular construction types which are built and transported as complete modules or units. Panel construction refers to the prefabrication of flat, standardized panels which can then be assembled on-site into an overall structure. They can be part of modules or uniquely designed panels to adapt to the form of the building. Component is the use of individually prefabricated pieces or parts assembled on-site as puzzle pieces interlocking and relating to each other for final assembly. The modular construction type is then scaled up from component, focusing on the fabrication process of the whole module or unit, and how it is to be assembled with other modules using vertical joint connections and horizontal bracing between them. As such, modular construction is gaining popularity in recently built projects for its efficiency. It's important to acknowledge the term kit-of-parts, as well, in prefabrication which acts as an informal subcategory mainly synonymous with panel construction, though it may be prefabricated as larger pieces such as components. The distinguishing characteristic of kit-of-parts construction, however, is its focus on an easy and quick system for assembly of parts. The intention of being able to be disassembled and reassembled when necessary is kit-of-parts defining feature, promoting reusability for the structure and materials.

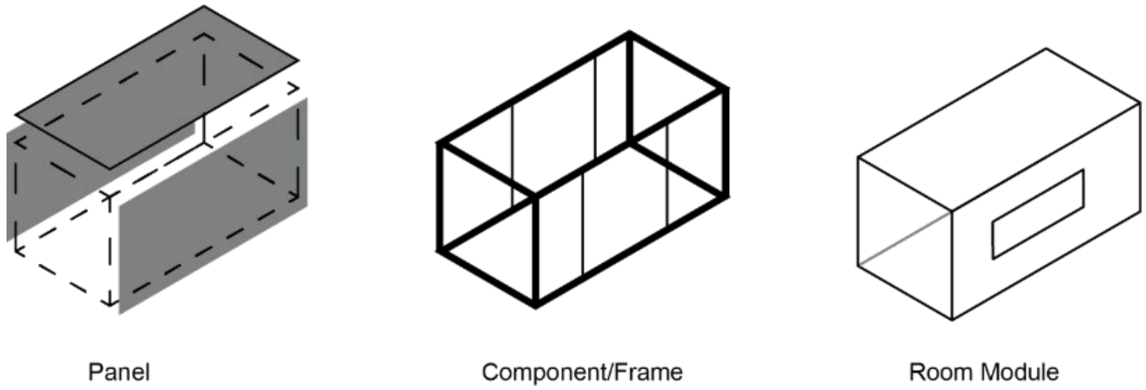
Panel
Component/Frame
Room Module

Figure 11: Main Types of Prefabrication
Source: Author

These three types of prefabrication, though distinct, are frequently used together, combining different aspects of each other to form the overall structure. For example, frame structures are often combined with systems using panels to complete a room module. Of the three types, modular construction utilizing room modules are the most prefabricated, with up to 95% completion. By comparison, panel construction systems can be up to 60% prefabricated off-site, and component systems can be 85%.[27] Overall, frame and component methods are considered the most flexible and adaptable today.[28]

2.2 Historic Overview

The use of prefabrication incorporates various parts and methods which have evolved continuously since the beginning of construction to reach its present state of innovative practices. Many precedent structures and studies have taken place reflecting the

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[27] Edition Detail, Components and Systems, Modular Construction, Design Structure, New Technologies.
[28] Gerald Staib, Andreas Dorrhofer, & Markus Rosenthal, *Edition Detail: Components and Systems, Modular Construction, Design Structure, New Technologies* (Munich: Redaktion Detail, 2008), 42.

benefits and challenges of prefabrication, with the majority of working principles remaining the same throughout time, and reminders of the constraints of prefab also being pronounced with different previously built structures. Therefore, a brief yet coherent summary of what has been done in the past is explored to gain the necessary context and build upon the already established principles guiding prefabrication as a useful and evolving construction technique.

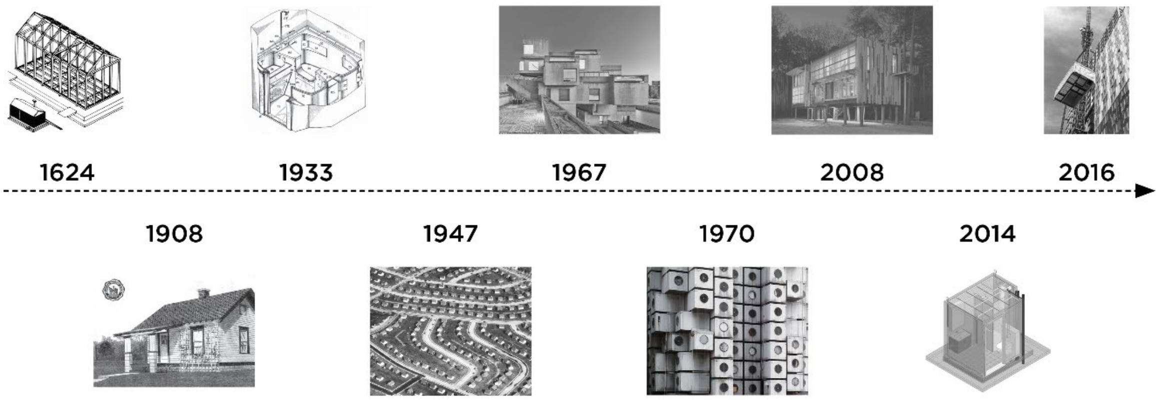

Figure 12: Prefab History Timeline
Source: Author

2.2.1 Manning Cottage

The beginning of prefabrication can date back to the 1600's with Great Britain's colonization of different areas around the world and the need for rapid housing construction once settling there. The earliest record of Britain's prefabricated components for a residential home was in 1624 for a village located in modern-day Massachusetts.[29] The structures were simple in design and material, utilizing timber frame and canvas infill or panels of lighter timber. This type of prefabricated housing model was developed further in 1830 by H. John Manning, who pushed the design further by allowing it to be easily constructed with each component capable of being carried by one person. The panels were

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[29] Ryan E. Smith, *Prefab Architecture*: *A Guide to Modular Design and Construction* (Hoboken, New Jersey: John Wiley & Sons, 2010), 6-20.

standardized with the spacing to allow ease of use and interchangeability. This case study was later known as the Manning Portable Colonial Cottage and was directed towards the emigrants of Australia.[30]

Figure 13: Manning Portable Colonial Cottage

Source: Prefab Architecture

The popular use of the Manning Cottage helped lead to the implementation of the balloon frame in the U.S. A well-known example of the use of the balloon frame is in St. Mary's church by Augustine Taylor in 1833 near Chicago. The balloon frame used studs instead of posts allowing for a quick construction, gaining popularity throughout Chicago up until the Great Chicago Fire in 1871.[31]

2.2.2 Cast Iron

British construction jumpstarted other materials into prefabrication as well, including iron. Material components such as windows, door frames, and other details were fabricated off-site and standardized before being assembled on-site. This implementation of iron prefabrication was influenced by England's bridge building and the trend of prefabricating bridge parts off-site then transporting them for construction.[32] The construction of bridges led to cast iron construction, which together with iron prefab, influenced and foreshadowed the steel movement later in the U.S.[33]

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[30] Prefab Architecture.
[31] Ibid.
[32] Ibid.
[33] Ibid.

2.2.3 Kit Homes

Popular use of kit homes began in the 1900’s. Between 1908 and 1940, Sears, Roebuck and Co. – sold more than 70,000 prefabricated homes. The homes were shipped via railroad boxcar and came in dozens of different layouts. They even had groundbreaking amenities like indoor plumbing.[34] The only thing that wasn’t included was plaster and brick for finishing the walls. Popularity continued to grow as homeowners excitedly bought the “house kits” up until 1942 when Sears, Roebuck and Co. stopped selling them.

Figure 14: Sears Kit Home

Source: https://www.apartmenttherapy.com/a-brief-history-of-sears-catalog-homes-233077

2.2.4 Postwar Housing

After World War II, a Chicago businessman fashioned his home of the future from wartime technologies and an old airplane factory, creating a line of ceramic-and-steel prefabs called Lustron Homes that are still used by hundreds of homeowners nationwide.[35] With built-in shelves and pre-installed appliances, these dwellings, ranging from about 700 to 1,140 square feet, were symbols of modern living, delivered as a kit of more than 3,000 pieces on the backs of specially outfitted trucks. However, the plant quickly closed in 1950 due to rising steel prices set upon by the Korean War.[36] In addition to the method of production being problematic, Lustron homes were cold, both visually and in temperature. Employing little insulation, the metal house would heat up in the summer and freeze in the winter.[37]

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[34] https://www.protohomes.com/blog/prefab-vs-modular-manufactured-systems-built/

[35] https://www.curbed.com/2016/10/10/13227810/prefab-lustron-house-prefabricated-home-building

[36] https://www.curbed.com/2016/10/10/13227810/prefab-lustron-house-prefabricated-home-building

[37] Prefab Architecture.

This was also the era of Levittown, Pennsylvania accomplished by William Levitt. Instead of retrofitting wartime factories and using expensive steel, Levitt systematized the onsite construction process, organizing crews and maximizing material efficiencies to reduce costs and make housing affordable for everyone. A developer by trade, Levitt created entire subdivisions of housing, though the homes were known to be unremarkable, very similar, and in many ways foreshadowed the model of the cookie cutter suburbs in the United States. The era of postwar housing reflects upon the prefabrication methods used before the war as well as adding onto the technology and borrowing lessons learned from the automobile assembly line. It's a nod to the factory setting and other industries utilizing prefabrication that share the expanse and experimental phases of prefab.

Figure 15: Lustron Home & Levittown

Source: https://madison.com/wsj/news/local/proposed-demolition-puts-renewed-focus-on-all-metal-lustron homes/ article_d0d9fed6-6cea-56f5-911f-d4c61cff7794.html

2.2.5 Precast Concrete

Modern precast concrete started in 1905, when the first precast concrete paneled buildings were created in Liverpool, England by engineer John Alexander Brodie.[38] Since then, precast concrete has expanded across the globe and has become a staple of modern construction. Moshe Safdie's Habitat 67 marks a milestone in precast concrete by the form and using entire precast units to then be assembled on-site. Still viewed as a landmark building today, Habitat 67 offers many lessons to be learned, with the greatest challenge of

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[38] https://delzottoproducts.com/2014/12/10/precast-concrete-history-lesson/

the effective prefabricated building design being how well and easily available it is to replicate for current modular construction buildings.

Figure 16: Habitat 67

Source: https://sharpmagazine.com/2016/11/24/moshe-safdie-habitat-67-montreal/

Another landmark for prefabrication and precast concrete technology is the Nakagin Capsule Tower by Kisho Kurokawa. Unfortunately, it is under threat of demolition due to continuous disrepair and voting from the building's residents advocating to replace the structure with a larger, modern one. Currently it is seeking crowdfunding to save the concrete modular building.

Figure 17: Nakagin Capsule Tower

Source: https://failedarchitecture.com/nakagin-capsule-tower-shimbashi-tokyo/

Both buildings are remarkable structures pushing the boundaries of prefab architecture as well as precast concrete. They share big ideas ahead of the time though it is important to note the inefficiencies and setbacks of both structures on technical notes of maintenance and cost due to the unique structures for Habitat 67 and the unrealized replaceable plug-in units of the capsule tower with updated modules.

2.2.6 PBU: Prefabricated Bathroom Unit

Figure 18: Fuller's Dymaxion House PBU to modern PBU

Source: Prefab Architecture

The prefabricated bathroom unit (PBU) has been an ongoing component of prefabrication beginning with Buckminster Fuller’s Dymaxion House which was conceived in the 1920’s and finally built in 1945.[39] It reflects Fuller’s own exploration and experimental solutions to mass-producible affordable housing. With it, prefabricated “rooms” of a house gained larger presence in the construction industry and the PBU was a primary example. Unfortunately, only one prototype of Fuller’s Dymaxion (Dynamic-Maximum-Tension) House was fully assembled, due in part to lack of compromise.[40] Yet it remains today as a pivotal moment in prefabrication history and helped further future developments and the modern PBU used commercially worldwide.

The Loblolly House built in 2006 is an evolution of Fuller’s original prototype, taking prefabricated parts to a higher level. The house uses integrated assemblies of parts fabricated off site to make for an efficient ease of construction assembly structure. Floor, ceiling, and pre-built modules, including the bathroom units and MEP blocks were lifted and fitted into place. From the platform up, the house was assembled in less than six weeks.[41] It explicitly shows the benefits of prefabrication and how developed off-site construction has become, while also revealing the delicate balancing act between

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[39] https://www.bfi.org/about-fuller/big-ideas/dymaxion-world/dymaxion-house

[40] https://www.archdaily.com/401528/ad-classics-the-dymaxion-house-buckminster-fuller

[41] https://kierantimberlake.com/pages/view/20/loblolly-house/parent:3

standardization and customization of parts to remain affordable and still be site and form-specific.

Figure 19: Loblolly House
Source: https://kierantimberlake.com/pages/view/20/loblolly-house/parent:3

2.2.7 Mobile and Manufactured Homes

A manufactured home is a type of prefab structure designed to minimize cost and waste. It consists of a steel frame on which the portions of a house can be built. Underneath the structure is an axle so wheels can be placed directly on the home for transportation.[42] The popularity of mobile homes have significantly declined despite its affordability. However, a new generation of prefabricated homes using modular construction are growing in use and presence. Modular homes are building off of its predecessors of manufactured homes and prefabricated components to be both affordable and aesthetic for newly awaiting residents.

2.3 Continuing Milestones

Prefabrication methods continue to evolve and develop new components that can be used in construction. Since prefabrication is such a broad term enveloping product design and manufacture off-site in a controlled environment, smaller components used in housing can be applied to the term, while prefabricated home relies on the latter word to narrow down the categories it relates to. Emerging prefabricated pieces or components are

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[42] Prefab Architecture.

also becoming popular in the construction industry for many of the same reasons as prefabricated homes. Due to the smaller scale of components such as SIP's or structurally insulated panels, they can be used with ease for many projects without extra planning and care needed for other larger prefabricated components including modular rooms and units. The future of prefabrication is limitless with the advancement of manufacturing tools, in particular reference to large scale 3D-printing homes, and other products like smaller, "smarter bricks" or lighter and stronger aerated concrete. These technologies can be layered with prefabrication techniques and are only beginning to be incorporated into the building industry, giving high hopes to the next generation of construction.

3. Clarity of Modular

3.1 What does it mean?

Moving deeper into the 21st century has revealed ongoing methods strengthening the practice of prefabrication and modular design. The word modular has been expansively used and dissolved into multiple definitions and subcategories. In recent years, modular homes have become a trend in the design and construction industry, though it is important to distinguish modular design and construction as not only a trend, but another step in the evolution of prefabrication. When viewed from the broader lens of prefabrication, the momentum of modular construction and assembly can be digested as the inevitable future of all large-scale construction projects for its efficiency in a time-sensitive global development. Modular construction is defined as a method of prefabricating materials as either components or whole units off-site to then assemble as a structure on-site.[43] The Modular Building Institute (MBI), founded in 1983 as an international non-profit trade organization, states its own definition of modular construction as, "an off-site project delivery method used to construct code-compliant buildings in a quality-controlled setting in less time and with less materials waste."[44] Other definitions of the term have been expanded upon with differences in smaller details such as the definition of module as a whole unit or piece of a larger unit. The overarching theme across all construction platforms, though, is that modular construction is a form of prefabrication for higher efficiency in construction and assembly. Modular construction's connection to prefabrication has also caused some confusion in the construction industry, where the term prefabrication or prefab has been used interchangeably with the term modular and modular construction due to its fabrication off-site, and not having a widely-used industry standard definition which the MBI hopes to distinguish.[45] In reaction, the definition of modular is focused here to emphasize its distinct features and relationship to prefab in order to move

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[43] Smith, *Prefab Architecture*, 159-161.

[44] "What is Modular Construction?" Modular Building Institute, accessed October 5, 2018, http://www.modular.org/HtmlPage.aspx?name=why_modular.

[45] Smith, Prefab Architecture, 159-161.

forward and allow the construction method to be built upon and potentially become the primary construction process in all fields of architecture and construction.

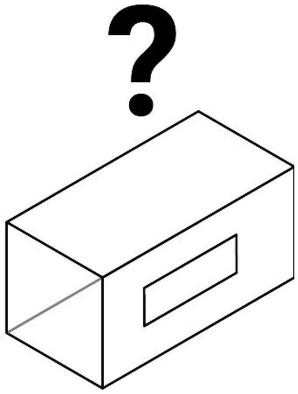

Figure 20: Modular Construction
Source: Real Projectives

Modular construction, then, is a type of prefabrication or subcategory, as stated before which utilizes modules or sections of a structure built in facilities or off-site to be transported for assembly and completion on-site, becoming its defining feature from prefab. The modules can be connected through a variety of configurations and placements, with its standardized module allowing for fast, efficient, and precise construction. Modular construction has gained popularity in recent years with the introduction of modular homes, though the modern term can be traced back to as early as 1790, in relation to the word "module," used two hundred years earlier, and is more notably expressed in Vitruvius' "The Ten Books on Architecture," originally written between 30-50 BC and translated multiple times with a heavily referenced English version dating from 1914.[46] The word, module, is used by Vitruvius in chapter two, "The Fundamental Principles of Architecture," as a physical section of a structure that becomes standardized as a base unit of measurement and scale in relation to the overall structure.[47] Reflecting upon the use of modular construction in modern design, the fundamental principles of modular construction and use

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[46] Morris Hicky Morgan, *Vitruvius: The Ten Books on Architecture,* (Cambridge, Harvard University Press, 1914),

[47] Ibid.

of modules as standard units has not changed throughout time and reveals the many advantages of modular construction based around standardization.

3.2 Benefits of Modular

The recent and continuous trend of modular design is a result of the many benefits of the construction method which has both immediate and long-term consequences. The primary positive impacts of modular construction can be derived from two characteristics of modular construction: off-site fabrication and standardization.[48] From the two, numerous benefits of modular construction can be argued and advocated for as a result. Off-site fabrication allows for efficient construction in a controlled environment. Environmental benefits such as improved air quality and less material waste also translates to economic benefits with cheaper labor cost and less overall use of material.[49]

Figure 21: Modular Benefits and Schedule

Source: MBI

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[48] MBI.

[49] Ibid.

MBI translates the benefits of modular construction into three categories, “Greener, Faster, Smarter.”[50] Many modular buildings can be disassembled and relocated, refurbished, and recycled upon demand, adding to the already apparent environmental benefits of modular construction. According to a National Association of Home Builders (NAHB) study, an estimated 8,000 lb. of waste is created from the construction of a typical 2,000-square-foot home.[51] Using modular construction greatly reduces this waste production as well. Modular construction is also known as being faster due its off-site construction. Since the modules are built off-site in a factory or other approved facility, site and foundation work can begin at the same time as the prefabrication, resulting in a significantly reduced construction work schedule by as much as 30-50% compared to conventional methods.[52] In the case of modular homes being constructed in California’s Napa Valley by Factory_OS, 1,300-square-feet structures are being assembled in a mere four hours—from foundation to turning the lights on.[53] Off-site construction and fabrication leads to less weather disruptions which also promotes faster work schedules and reduces risks of other injuries and unforeseen circumstances. The “smarter” category builds upon the safety factor of modular construction, again benefitting from off-site construction as the cause due to creating a safe work environment, reducing risk of injury or accidents, while using quality materials in a controlled facility to meet all specifications as would be required in conventional construction methods. The catalyst of the technology is that as in conventional methods, the exterior form and aesthetics is not limited to the module, a prejudged misconception. Modular construction can host limitless design opportunities that allow it to be indistinguishable from other built structures when compared as a final design product, a proven argument through various case studies that breaks its preconceived stereotypes.[54]

Inherent benefits of modular design and construction also include the limited risk of weather delays because 60 - 90% of the construction is completed inside a factory. This also means that businesses and services around the site are not affected by the

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[50] “What is Modular Construction?” http://www.modular.org/HtmlPage.aspx?name=why_modular.

[51] https://earthwiseradio.org/2016/03/reduced-waste-from-modular-construction/

[52] Ibid.

[53] https://www.autodesk.com/redshift/the-benefits-of-modular-construction/

[54] Ibid.

manufacturing of the modules. As such, the building is completed quickly with the assembly of modules on-site, meaning the buildings are occupied sooner, creating a faster return on investment. As a whole, modular construction is becoming a global industry worth up to $130 billion and with varying degrees, can save 25% or more on labor costs.

3.3 Overcoming Obstacles

Existing obstacles for widespread use of modular construction encompass various factors, as with other methods, while also holding potential to change from the introduction of new policies within the near future. Some of the immediate setbacks of modular building include smaller standard room sizes, site accessibility, design changes, and excess planning required in the beginning phases of design and construction.[55]

The modules used in modular construction are the overall assets and limitations to the efficient method of assembly. Due to transportation issues, modules have standardized dimensions to follow which limit the size of each module and therefore, the space programming for its interior form.[56] The transportation and movement of the modules also affect its site accessibility, requiring the site to be accessed by trucks carrying the modules to its final assembly destination as well as providing room to host a crane and lift each module and form the overall structure. In general, a 95% prefinished module unit can’t be wider than 16 feet and longer than 60 feet in order to fit on the back of a semi-truck for transportation to the site.[57]

The misconception that there are design hindrances to modular design outweigh the freedom of utilizing modular design, though it is important to recognize the design process of modular construction differs from conventional methods in the significant weight placed upon design and planning in the initial phases of conception. As each module is built off-site with up to 95% completion incorporating finishes in the facility, design changes made later in the process are rare and difficult to implement later, limiting the flexibility of design changes to the initial portion of development.[58] The detailing of construction and assembly

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[55] “Advantages and Disadvantages of Modular Construction,” CRL, last modified July 18, 2018, https://c-r-l.com/content-hub/article/modular-construction/.
[56] Ibid.
[57] Ibid.
[58] Ibid.

are also crucial in the design phase to produce drawings and methods of how to assemble the modules early on and being precise and clear in determining specifications and joinery as each module will follow this procedure and any mistakes made will hinder the entire assembly process.

A significant disadvantage to the overall utilization of modular construction as expressed by some designers is the lack of awareness of the technology at hand. There is a repetitive, steep learning curve of the scope of modular construction and its process. This results in longer time spent on research within the design team and phase, costing the overall project more while also leaving room for repetitive mistakes or common challenges to be repeated.[59] Standardized units greatly reduce the cost of construction but also currently make it difficult to customize aspects of the building, or significantly raise the price of doing so. When transporting the modules, the units must be structurally sound for crane transportation and assembly, so each unit stacked becomes structurally redundant and a loss of ceiling height for the residents is experienced while using more material than needed with conventional methods. When using modular construction with prefinished units, other challenges arise that are unique to the construction method including vertical and horizontal alignment when assembling on-site with the crane as well as waterproofing the membrane between stacked units. However, despite these current limitations and challenges, modular construction is quickly catching on with the greater construction industry worldwide.

3.4 Types of Modular Construction

Due to the sheer size of encompassing subjects related to the term modular construction, it is apparent to categorize the many types of the form when discussing the method of prefabrication. In its broadest form, any prefabrication utilizing modules as its standardized dimension and massing for constructing a structure falls under modular construction. Yet, there are various ways of tackling the fabrication of the modules and the overarching goal of each modular design. In addition, contrary to popular assumptions of modular construction, the design forms of structures utilizing modularization are not

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[59] “Advantages and Disadvantages of Modular Construction,” CRL.

limited in form to create distinct, functional, and aesthetic buildings. Taking advantage of the module as the standard unit in the structure, many buildings have expressed their own unique spatial qualities, and in doing so, have opened subcategories of various types of modular buildings.

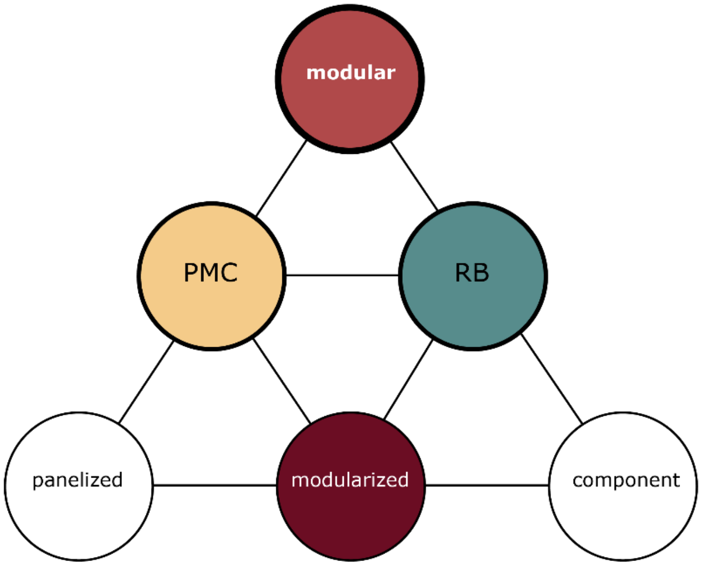

Figure 22: Types of Modular
Source: Author

When discussing modular construction, two major types are revealed as being permanent and relocatable or temporary structures. Permanent modular construction (PMC) is distinguished as being made of prefabricated modules that can be integrated into site-built projects or stand-alone with MEP, fixtures, and interior finishes already pre-installed.[60] It's used for high quality buildings that will remain on-site long term and with heavy foot traffic. In recent years, PMC has picked up and is expected to grow significantly in the construction industry globally. An example of PMC can be found with the analysis of Eviva Midtown, a condominium using permanent modular construction methods. Using a modular system of construction, the building was able to be completed with significantly reduced cost of construction, labor, and saved time with the assembly process as well.

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[60] "What is Modular Construction?" http://www.modular.org/HtmlPage.aspx?name=why_modular.

Figure 23: PMC Eviva Midtown

Source: Modular Building Institute

Relocatable buildings, however, are temporary modular structures that can be moved multiple times to different sites accordingly.[61] Portable classrooms and buildings of refuge are some examples of relocatable buildings that are slowly picking up traction but is still greatly behind permanent modular construction. Panel and component construction are a subcategory that is also a branch of prefabrication which has been previously discussed. They fall under modular construction as well due to the utilization of modular systems standardized throughout a building to allow for faster assembly and ease of transportation.

Within these types, modular construction has been able to accommodate various sizes and typologies of buildings. Building modular has been effective for single-family homes and low-rise residential buildings but has expanded and now includes mid-rise and high-rise buildings, too. In Europe, modular construction has been widely used for these latter typologies and is slowly beginning to catch on in the U.S. For example, Tide Construction is set to build two residential towers in south London which are claimed to be the world's tallest modular buildings at 44-storeys and 38-storeys.[62] The sky is seemingly the only limit of modular construction as development and research continues.

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[61] "What is Modular Construction?" http://www.modular.org/HtmlPage.aspx?name=why_modular.

[62] https://www.greystar.com/about-greystar/newsroom/2018/01/31/henderson-park-and-greystar-to-deliver-the-worlds-tallest-modular-towers-in-croydon

3.5 Singapore's PPVC

Though the Modular Building Institute was founded in the early 1980's, the term modular is still not officially prescribed and regulated by governmental bodies in the Western hemisphere. However, that has begun to change across the Pacific with Singapore. Celebrating its 53rd year of independence in 2018, Singapore is one of only three places in the world acknowledged as a city-state, the others being Monaco, and Vatican City. The distinguishable features of Singapore are further isolated with its geographic background being an island with the second most expensive housing costs worldwide; the first being Hong Kong. As such, in many ways Singapore is an extreme example of what Hawai'i's near future could be if population density increased to the level of the island-state.

In 2014, to address these housing issues the country formally defined their modular construction forms and regulations for the construction industry to follow, named prefabricated prefinished volumetric construction (PPVC). Analyzing Singapore and its recent advocacy for PPVC in future building developments, Hawai'i has the opportunity to exploit and learn from the lessons Singapore has to offer regarding modular construction and mitigating urban housing needs.

The availability of Prefabricated Prefinished Volumetric Construction (PPVC) has been present for many years, with new light recently being placed upon the construction method and its potential for mass use and production by Singapore's government. The design principles of PPVC has now been expressed meaningfully by the government in hopes of promoting its successful use throughout the country by developers for upcoming projects in an attempt to increase efficiency and savings during construction. Within Singapore's Building and Construction Authority, PPVC is defined as a "construction method whereby free-standing volumetric modules (complete with finishes for walls, floors and ceilings) are constructed or manufactured and assembled, in an accredited fabrication facility, in accordance with any accredited fabrication method, and then installed in a building under building works."[63] Their goal for implementing a new method of construction to be used across the region is to take advantage of PPVC's efficiency of

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[63] Authority, Building and Construction. 2017. Prefabricated Prefinished Volumetric Construction (PPVC). Accessed June 11, 2018. https://www.bca.gov.sg/BuildableDesign/ppvc.html.

time and manpower to offset the initial costs of materials and resources, reducing its overall expenses further as time and infrastructure for the technology becomes more standardized throughout the construction process.

Figure 24: PPVC Module Types
Source: DfMA Guide

As stated by Singapore's Housing and Development Board (HDB), all new HDB flats constructed will implement PBU's, Prefabricated Bathroom Units, by 2019 along with switching to the use of PPVC in 35% of new projects using specifically the concrete assembly method.[64] PBU's, alongside PPVC, is a built form of construction methods falling under the umbrella of DfMA or Design for Manufacturing and Assembly, Singapore's clearly defined guidelines regarding building prefabrication in the country. The promotion of DfMA just as PPVC and PBU strive for, is an overarching goal to introduce construction methods that reduce costs in labor and time by having the work done primarily offsite in a controlled environment to speed up the assembly process parallel to factories' work flow and reduce the hazards experienced with on-site construction.[65]

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[64] Government, Singapore. 2017. Housing and Development Board. September 06. Accessed June 1, 2018. http://www.hdb.gov.sg/cs/infoweb/press-release/new-initiatives-to-boost-construction-productivity.

[65] Building and Construction, Authority. 2016. BIM Essential Guide- Design for Manufacturing and Assembly (DfMA). Guide, Singapore: Building and Construction Authority & Bryden Wood.

Figure 25: PPVC Portable Bathroom Unit

Source: Singapore BCA

Modular is the general term describing technology using off-site manufacturing and PPVC sits at the top of the hierarchy of contemporary prefabrication or specifically, DfMA methodologies.[66] Prefabricated construction can potentially achieve 40% of overall savings in time and workforce as well as constructing higher quality finishes in a safe work environment. In current industry standards, PPVC can be used to achieve various projects ranging from residential, institutional, hotels, nursing homes, to also including dormitories. Singapore has expressed the success of its wide range of programming with the completion of the Crowne Plaza's extension adjacent to the Changi Airport as well as Nanyang Technological University's student dormitories completed in 2016. However, its use for residential programs is ideal due to its modular nature with the two current models of PPVC being broken into two forms, reinforced concrete, and steel frame modules, with two major types of framing system for concrete PPVC being the beam-column system and slab-shear wall system. While both are used throughout the industry, each has its own benefits and obstacles in determining cost and practicality of materials just as its raw and conventional use of materials have as well. Guidelines set by Singapore have been expressed, with ways to maximize standardization in components and design as well as the systems needed for transportation. Modules under eighty tons and below 4.5 meters in height, and 3.5 meters in width generally don't need a police escort for transport and can be carried on the bay of a semi-truck. The standardization of cranes used, and alignment techniques are also major

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[66] Building and Construction, Authority. 2016. BIM Essential Guide.

points of issue and observation. Singapore’s adaption of PPVC and their solutions to existing challenges related to construction help reveal overall benefits and feasibility to be adopted in Hawai‘i’s context.

Figure 26: Clement Canopy, Singapore
Source: Dezeen

A recent project utilizing PPVC technology in Singapore has been topped-off on July 10, 2018 acting as a new landmark for modular design. The Clement Canopy has been viewed as a milestone for PPVC development highlighting its 40-floor height, making the project the world’s tallest concrete PPVC building.[67] It’s expected to be completed in 2019 and will represent successful adoption of concrete PPVC at a high-rise scale, installing over 1,800 modules in just one year. As with other modular construction around the world, the interior finishes of the PPVC modules are 90% finished when installed on-site. The project is a joint venture between UOL and UIC with collaboration from Dragages Singapore, who is a pioneer of PPVC development in Singapore and will continue to advocate for its widespread use.[68]

3.6 Modular Fabrication Process

The construction of modular buildings strictly follows the International Building Code for multi-family dwellings and for small single-family dwellings, use the

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[67] “Topping-off of the World’s Tallest PPVC Development-The Clement Canopy,” Dragages Singapore Limited, accessed November 3, 2018, http://dragages.com.sg/news-post/topping-off-of-the-worlds-tallest-ppvc-development-the-clement-canopy/.

[68] Ibid.

International Residential Code in addition to local codes. Modular construction can adapt to different building materials and can be formed using different, commonly used materials such as wood, concrete, and steel. Each material has its own characteristics and bring their own advantages and obstacles to overcome when considering a project.

3.6.1 Concrete

One of the most versatile construction materials, concrete is widely used in prefabrication and modular construction. Load-bearing wall modules are commonly used in concrete buildings, with the walls transferring transfer gravity loads to the foundation, as well as resisting the lateral loads. Similar to Singapore's PPVC modules, concrete modules in the U.S. and Europe rely on rebar and formwork to prefabricate the modules before shipping to the site for final assembly. Its primary setback, however, is its weight during crane assembly and transportation, and the need of formwork for the concrete to take shape. This along with limited demand as compared to Asia has made concrete modular construction not as popular as its steel counterpart.

Figure 27: Precast Concrete Module

Source: Zebra Construction; Clement Canopy

3.6.2 Steel

Steel modular units are prefabricated and pre-assembled off-site in a facility with up to 95% completion. As such, steel modules are the most popular to use in modular construction because of its inherent light weight, strength, and flexibility. The modules are finished in the factory with insulation, infill framing, wiring, ducting, finishes, appliances, and millwork so they are as complete as possible before shipping. When transported on-site, the steel modules reveal inter-unit connections to be joined and small weatherproofing to complete the project.[69] As steel modular construction has taken hold as the frontrunning material for modular construction in the western world and abroad, many variations of the modules now exist. Connect-Homes, a firm specializing in offering steel modular construction has become a successful precedent to building modular. They have critiqued other modular construction methods with their own, instead focusing on a smaller, standardized unit close in size to shipping containers except distinctly designed as its own module. Many current modules oversize dimensions to accommodate residential units, however this causes problems with transportation such as increased costs for shipping and being met with safety hazards during road transportation on oversized-loading trucks. Modular construction can be both practical and desirable as shown with Connect-Homes.[70]

Figure 28: Steel Modular Home Options

Source: Connect-Homes

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[69] Construction, American Institute of Steel. 2018. Modular Construction. accessed October 23, 2018.

[70] Gordon Stott, "How to Fix Prefab Architecture? Make It More Like Product Design," core77. https://www.core77.com/posts/44632/How-to-Fix-Prefab-Architecture-Make-It-More-Like-Product-Design, accessed October 29, 2019.

3.6.3 Wood

Though not immediately associated with the term, the common building material is widely used in all forms of construction methods, including modular. Wood, because of its material attributes, is used largely for single-family modular homes and low-rise modular buildings. Typical wood modular construction is effective up until a three-story height, after which the cost of strengthening the structure within the module renders it uneconomical, at least until the recent development of mass timber which will be covered further to understand its distinct properties. Wood construction is limited to Type III or Type V construction and wood modular buildings also require a deep ceiling to floor connection. The modules are usually finished with primed gypsum wall board before shipping, but appliances, millwork, and heavy finishes like tile and stone are installed after placement at the site.[71] During transit, modules often require temporary bracing since the wood framing may not be engineered to withstand transportation loads, varying extra steps and requirements in comparison to steel and concrete modules. Still, wood modules can be effective, as seen in Figure 29, and is paired with a concrete podium in Michael Maltzan Architecture's Star Apartments to provide affordable housing for Los Angeles' former homeless, and achieving LEED Platinum.

Figure 29: Wood Modular Construction

Source: Guerdon Modular Buildings

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[71] Hickok Cole Architects.

3.6.4 Assembly On-Site

Transportation plays a critical role in modular construction and extra effort and planning is required for transporting the modules safely and assembling on-site. It takes about 8-12 days to ship from the continental U.S. (Seattle) to Honolulu.[72] The transportation of the modules is limited by roadways, overhangs, and power lines. The builders must scout out all these factors before delivery, but in general each unit must be less than 16 feet wide, 60 feet long and 11 feet high. Roads become an issue of size with federal guidelines for commercial truck widths being 8 ft-6 in. Hawaiʻi is the only exception with a 9-ft-0-in. width allowance.[73] Because travel can be unpredictable, buyers are usually on site with independent contractors to inspect the units for scrapes and cracks.

Once on site, various options for foundations and footings using modular construction exist to work efficiently with the units. Conventional foundations are acceptable, though with modular construction, smaller foundations are generally needed, allowing for reduction in costs and materials. Foundations are typically made of concrete and the vertical and horizontal connections of the modules with the each other and the foundation must be carefully planned.

Figure 30: Modular Foundation Types

Source: Prefab Architecture

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[72] "Hawaii Transit Times," Pac-Rim Building Supply, Accessed November 16, 2018, https://www.pacrimbuilding.net/markets/hawaii/.

[73] Smith, *Prefab Architecture,* 195.

To lift the modules onto both the foundation and to stack with each other, the location of construction cranes become critical to the successful assembly of the building and must work in collaboration with all parties involved in assembly. Standard crane footprint dimensions are 15’ x 15’ – 20’ x 20’. In addition to the crane itself a larger area is to be considered for the four piers anchored beneath the footprint. The piers are drilled and anchored 100’ below grade with 6’ of concrete topping poured over to support the crane. Cranes are usually installed on-site adjacent to the building; however, some are occasionally installed at the center of the building in reaction to difficult site conditions and sizes. While most construction of the units is completed off-site, the final assembly and connection points of the modules regardless of chosen material, becomes one of the primary focus of modular construction.

Table 1. Construction Crane

Crane Attributes	Tower Crane	Mobile Crane	Crawler Crane
Crane Capacity	50 tons	700 tons	500 tons
Lifting Capacity	25 tons-40 tons	25 tons-40 tons	25 tons-40 tons
Equipment Height	120m	40m	80m
Radius of Work	40m	40m	40m

3.7 Ongoing Development

Modular construction has worthwhile capabilities in the construction industry to provide rapid construction times with efficient building systems and reduced material use, leading to more building savings and adhering to the environmental challenges by producing less carbon emissions than conventional construction methods and prefabricating in a controlled environment. These benefits grasped by all types of modular construction allow for Hawaiʻi to seek appropriate adaptations of the prefabricated methods. When implementing modular design on a larger scale, the thoughtful resolution of connection joints and transportation should be focused on and more time allocated to this process for a successful building project. Despite the current obstacles faced with building modular, the overall benefits and techniques used can greatly influence Hawaiʻi’s construction systems in a positive manner.

4. Modular Housing Case Studies

4.1 Modular to Date

Modular design and construction have taken a prominent role in architecture within the last few years, yet modular construction has been around for quite some time. The tallest modular project up until the last five years in the United States has been the 1968 Hilton on the Riverwalk, in San Antonio, Texas built from precast modules. The hotel is four lower stories of site-cast reinforced concrete. Floors 5 through 21 are constructed from precast modules. The modules were entirely fit out on the interior, each with an exterior window preinstalled in the module. Seventeen units a day were set, with a total of 496 units. Each module had a code number that determined its location. The building was conceived as being able to be changed out over time. Similar projects of the era include Habitat 67 by Moshie Safdie. However, the reality is that concrete modules are heavy—35 tons each—and the logistics of module change-out is not possible when the units depend on one another for structural stability. Still, the Hilton on the Riverwalk project was constructed in 200 days by Zachary Construction Corporation and still stands as a testament to a great feat for 1968 (Prefab Architecture, 2010). This structure and many like it have set the precedence for modern modular design and construction. More recent projects using modular construction are briefly summarized here to provide an introduction into the newly built projects pushing modular beyond its limits, broadening the discussion of modular construction's precedence, and to help understand and inspire the design decisions regarding the modular system for the final design proposal.

4.2 Atlantic Yards B2, New York, Shop Architects

Figure 31: Tallest Modular Building in U.S., Shop Architects 2018

Source: Dezeen

The recently completed project in New York City by Shop Architects has generated multiple discussions and coverage of the design due to its utilization of steel modules and becoming a primary example modular construction. Recently completed in July 2018, the high-rise building is currently the largest modular building in the U.S. whose title was taken by the previously mentioned Hilton on the Riverwalk. Atlantic Yards B2 had over 930 steel modules used to assemble the structure and provide 363 rental apartments for the community.[74]

The building now stands adjacent to the Barclays Center and is a 32-story tower with 60% of work done in factory, and 40% on site, greatly reducing the construction schedule. Housing is 50% at market rate and 50% below market rate and includes 4,000 square feet of ground floor retail and luxury amenities. With completion on a high-end building, Atlantic Yards B2 helps promote the use of modular construction for all building typologies.

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[74] https://www.dezeen.com/2016/11/18/worlds-tallest-modular-prefabricated-apartment-tower-shop-architects-brooklyn-new-york/

4.3 NTU Dormitory, Singapore, SAA Group

Figure 32: NTU Dormitory with PPVC Construction

Source: https://zhengkeng.com.sg/student-hostel-at-nanyang-technological-university-of-singapore-ppvc/

An example of PPVC technology recently implemented, the dormitory was designed for Nanyang Technological University of Singapore to develop one 11-story, and three 13-story height student housing, with a 4-story car park and ancillary facilities. The student dormitories were the third PPVC project in Singapore and the second largest in 2015. Up to 25% of workforce was reduced with a 40% increase in productivity.[75] It started in 2015 and was completed in June 2017.

Some challenges faced was the initial project being converted to a design-build contract where Zheng Keng, a team of contractors and consultants had to re-design the original development from a reinforced concrete structure to a modular system for PPVC.[76] It was also crucial to have a balance between the PPVC modules' hoisting and installation

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[75] https://zhengkeng.com.sg/student-hostel-at-nanyang-technological-university-of-singapore-ppvc/

[76] Ibid.

efficiency, and the cost of site operations. Increasing crane numbers on-site increased efficiency but also operation costs, a reminder again of the importance of assembly.

4.4 4801 Shattuck, California, RAD Urban

Figure 33: 4801 Shattuck, RAD Urban

Source: RAD Urban

Built by RAD Urban in 2017, the project located at 4801 Shattuck is a 5-story apartment complex with 43 units and has an area of 47,300 square feet. The firm located throughout California with a few offices, developed their own modules to use for future projects. The firm utilizes their fourth-generation modular system which improves the stacking capability from 4 to 8 modules per day. They also distinguish their modules by having designed a unique 4-sided boxed unit instead of the typical 6-sided rigid modular box. By doing so, they're able to remove excess materials and provide more efficiency to the building design, such as allowing the floor of one module act as the ceiling for another.[77] Their low-rise project is an example of the design strategies used for constructing with modules and how module systems are continuing to be developed to meet the requirements of the building industry as effective tools for construction.

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[77] https://radurban.com/modules/, accessed November 2, 2019.

4.5 Discussion

Each case study utilizes modular construction and design effectively while having varying programs and building typologies that had each of their own unique challenges brought to the project. The consolidation of research regarding modular construction and prefabrication, with the various case studies looked at throughout the analysis of understanding the developing prefab type has revealed the overwhelming benefits of designing with modular construction. The evolutionary history of prefabrication leading to modular design and construction supports the rising discussions of modular becoming a main construction type within the near future.

The standardization of modular construction throughout the U.S. still faces challenges before it can be practiced on a leveled scale such as is seen with Singapore's recent implementation of official regulations regarding PPVC, the country's local modular construction methods. Challenges that need to continue to be addressed are modular design's limitations of size and transportation challenges. Connect-Homes offers precedent solutions by standardizing modules and working within the set parameters of shipping containers to effectively mitigate transportation costs and issues, while RAD Urban has also developed their own module to reduce material waste and structural redundancy, a critical issue with modular construction, especially when constructing with concrete.

The materiality of modular construction has proven to be an interesting aspect of the building system. Many of the case studies utilize steel for its lightweight and flexible design, while concrete, though easy to use is heavy and requires formwork and its own set of rules to be used effectively. Typically neglected or limited to low-rise construction with the help of other structural materials, as seen with Michael Maltzan Architecture's project, the recent development of mass timber on a large scale may now offer a new take on modular construction. The possible combination of both prefabrication methods is experimented with in the design proposal, becoming a hybrid model utilizing both modular construction and mass timber, before potentially adopting it to assist with Hawai‘i's local challenges. The precedents analyzed have proven that modular construction is continuously evolving, and that the standardization of modules can lead to more freedom in designing and constructing rather than hindering the building form as is initially assumed.

5. Ascent of Mass Timber

5.1 Introduction

Solid wood construction has traditionally been known as heavy timber and used thick structural wood members with a strong fire-resistance for its buildings. Mass timber technology has evolved since then, now covering different types of wood members including glue-laminated timber and cross-laminated timber (CLT) as popular choices. Currently defined as an overall category of the various assemblies using small wood members that are glued, nailed, or laminated together to form into large, panelized, solid wood construction materials, mass timber is at the turning point of distinguishing itself away from a green trend towards a key progression point in architecture.[78]

Buildings using mass timber construction has rapidly expanded in Europe for more than twenty years despite its small presence in the U.S. Cross-laminated timber (CLT), a popular type of mass timber was invented in the early 1990's and researched heavily by Austria, Germany, and Switzerland.[79] It has since taken off throughout the continent and is now gaining traction in the Pacific Northwest. By comparison, the U.K. currently has hundreds of structures built with mass timber, and key case studies expressed in, "100 Projects UK CLT," published in 2018. Recently, the U.S. has started to build upon the growing industry with the first certified U.S. producer of mass timber opening in Riddle, Oregon in 2015 and many buildings now using the technology for its construction throughout the region.

The progression of the material's use has been pursued due to the many inherent benefits of using mass timber as the primary construction material compared to the popular materials used for most currently built structures such as steel and concrete. The notion of concrete and steel reigning supreme for the last 100 years in construction is now being challenged once again by wood as past neglect in research and development of the material is being expunged with new innovations of mass timber. Specifically, the advances of CLT

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[78] 100 Projects UK CLT
[79] 100 Projects UK CLT

has allowed mass timber construction to reach new heights. While buildings contribute 40% of global carbon emissions with concrete and steel both contributing 5%-8% of carbon emissions, wood distinguishes itself as a renewable resource with a low carbon footprint.[80] Similar to modular construction, mass timber is gaining attention for its environmental benefits as well as the increased speed of construction associated with the prefabrication process. Renewed attention has shown that the US is in an ideal position to take advantage of wood, with prominently regulated forests and reserves throughout the country, to provide a sustainable resource for construction that will push the 21st century towards the verge of another construction revolution.

Figure 34: CLT panel assembly
Source: 100 Projects UK CLT

5.2 Benefits of Mass Timber

The primary benefits of using mass timber are paramount for the built environment's successful transformation of cutting carbon emissions and promoting sustainable development. Locally, mass timber's future role may be more heavily weighted in Hawaiʻi. As previously mentioned, the state has taken measures to assess and curb the carbon dioxide emissions from the islands. Hawaiʻi has recently been ranked as the most dependent state in the nation reliant on fossil fuels, largely due to electricity production. As a response to this, recording and publishing the annual carbon emissions has been implemented by officials as well as Hawaiʻi becoming the first state in the US to adopt the

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[80] https://www.designingbuildings.co.uk/wiki/Can_Concrete_and_Steel_Ever_be_Carbon_Neutral%3F

Paris Climate Agreement into its own regulations and having taken steps to become a carbon neutral state by 2045, using 100% clean energy.[81] To reach this goal set by the state government, mass timber has immense potential to be used to offset current carbon emissions and completely transform the construction industry.

Mass timber has received wide, global attention and investment in construction development due to the rise of contemporary environmental and social challenges. Wood itself is a carbon-sequestering resource and recent sources argue that the planting of 1-trillion trees can reverse the harshest effects of climate change.[82] Its benefits and role in reversing the global crisis can then be categorized into some key characteristics which have widespread positive consequences. Environmental advantages such as a reduced carbon footprint and sequestration is a primary trait, alongside the speed of construction, overall safety of use, reduced weight, thermal performance, health and well-being related to building interiors, and cost effectiveness to summarize the major benefitting factors of using mass timber for construction as opposed to traditional methods and materials.

5.2.1 Carbon Sequestration

To emphasize mass timber's environmental benefits, using the material in buildings reduces the global carbon footprint and aligns with the goals of Architecture 2030 as covered in the first chapter.[83] However, it is not a straightforward exercise to directly compare the embodied carbon of one cubic foot or a pound of a specific material, as the volume or weight of material used for the same building will vary depending on the structural system and performance. Research studies have compared the embodied carbon of concrete, steel, and hybrid structural frames, all generally illustrating a similar level of embodied carbon, at around 55lbs.CO2/ft2 (225kgCO2/m2) for the superstructure of an open plan commercial type building. This embodied carbon figure is for 'cradle to site' incorporating extraction, processing and delivery. To compare based on a pure timber commercial building, the embodied carbon of the timber structure, not including the

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[81] https://www.eia.gov/state/analysis.php?sid=HI

[82] https://e360.yale.edu/digest/planting-1-2-trillion-trees-could-cancel-out-a-decade-of-co2-emissions scientists-find

[83] reThinkwood, Mass Timber in North America

sequestered carbon, is 12lbs.CO2/ft2 (63kgCO2/m2). By substituting a CLT frame for a concrete or steel structure the embodied carbon of the building can be vastly reduced.[84] To generalize the comparative attributes, the carbon footprint of mass timber is significantly smaller than most construction materials used, and up to 70% lower than concrete.

The material is inherently a carbon sink, storing carbon throughout the lifespan of the building. At dry weight, wood is 50% carbon, the other 50% being oxygen, hydrogen, and a small amount of nitrogen, less than 5%.[85] On a microscopic level expressed in Figure 35, wood is made up of cells with cell walls located in the cambium layer behind the bark layer primarily comprised of three chemical compounds: cellulose, hemicelluloses and lignin.[86] Lignin acts as a gel-like adhesive bonding with the fibrous cellulose to form the protective layer while vessels behind the cell wall carry water and nutrients as needed. Consideration of the cell structure of wood is critical to note and understand the material, especially when considering that trees need to absorb two tons of carbon dioxide to produce one ton of its dry mass.[87]

Figure 35: Anatomy of Wood

Source: David's Timber

As a brief summary of carbon sequestration, trees absorb carbon while they are alive and keep the carbon stored within the wood until it is burned or decomposed, and when done so, only releases the same amount of carbon it had sequestered during its life. Depending on the species, a single tree sequesters 22 lbs. – 40 lbs. of carbon dioxide per

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[84] 100 Projects UK CLT.

[85] http://www.woodenergy.ie/woodasafuel/listandvaluesofwoodfuelparameters-part3/

[86] David's Timber: http://www.davidstimber.com.au/resource-centre/timber-properties/cell-structure-and-grain/

[87] Ibid.

year. Some percentages vary as more in-depth analyses are required, such as rates of reforestation and transportation, though the wood itself sequesters carbon dioxide at a rate of 1 to 1.2 tons per square meter of wood, a significant contribution to combating global carbon emissions.[88] This is an average of a fully mature tree at 40 years old before being milled for lumber. As shown in Figure 36, popular trees used for construction vary on maturity and height, though the U.S generally manages the trees and mills at 40 years.[89] To put into more perspective, another source states that for every kilogram of wood grown, 1.5 kg of CO2 is removed from the atmosphere and stored until the tree burns or decomposes.[90] In addition to the wood used for a building storing carbon, the trees it came from can be replaced and re-planted in a well-managed forest for new trees to grow and continue more carbon sequestration, referring to the forests as carbon sinks for their immense ability to sequester carbon. When used appropriately and managed effectively in collaboration with U.S. forest services, mass timber may help achieve carbon neutrality and push forward to be carbon negative, absorbing more carbon from the atmosphere than the structure emits during construction and life cycle operations.

Figure 36: Tree Attributes

Source: 100 Projects UK CLT

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[88] https://www.hdrinc.com/insights/why-mass-timber
[89] Susan Jones, Mass Timber Design and Research
[90] https://materialspalette.org/wood/

5.2.3 Structural Attributes

For construction manufacturing and assembly, mass timber has various characteristics that benefit the overall process of designing and constructing buildings. In general, a mass timber project is approximately 25 percent faster to construct than a similar project in concrete. This is due to a combination of material characteristics. The cross-laminated and glue-laminated timber are manufactured off-site in a factory for precise dimensions, quality control, while its overlay crossing form creates a strong material capable of structural support. According to APA, the Engineered Wood Association, "Pound for pound, glulam is stronger than steel and has greater strength and stiffness than comparably sized dimensional lumber."[91] Mass timber is also cheaper depending where wood is sourced, and will be considerably cheaper than concrete and steel as production scales up and as its manufacturing infrastructure is developed further.

"How much does your building weigh, Mr. Foster?" The famous quote and film name depicting Norman Foster's works and his conversation with Buckminster Fuller has given architects and designers a different perspective to critically analyze when designing. Mass timber is extremely light compared to concrete. To compare, Bernhard Gafner of structural engineering firm Fast + Epp, has stated on one of his projects, "If this building were designed in concrete, which was considered, the weight would be six times more than the mass timber design."[92] In addition, many of the CLT structures built do not require a concrete podium for support. The ongoing tool developments, such as a new screw implementation method between two boards and easy crane assembly have also reduced construction time and eased labor. For projects utilizing mass timber, only 4-5 people are needed to assemble panels and components, addressing both labor shortages and high labor costs. Aesthetically, interiors of buildings utilizing mass timber are inherently warmer and inviting. The benefits of mass timber are far-reaching and make the new construction type a competitive material to build with.

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[91] APA, Engineered Wood Association
[92] reThinkwood, Mass Timber in North America

Utilized effectively, mass timber construction can align with the goals of Architecture 2030 Challenge and allow for carbon neutral buildings.[93] When compared to the carbon footprint of concrete and steel, it becomes apparent for wood to be the preferred environmentally responsible material choice. The inherent benefits of mass timber coupled with the many innovations encompassing the material in recent years to increase efficiency and strength has made mass timber a growing prefabrication method with many stakeholders and government officials now investing heavily in its development.

5.3 Overcoming Obstacles

The relatively rapid development of mass timber and advocacy for its use has given room for many challenges still needed to be faced and resolved before it becomes a standard means of construction on the same scale as concrete and steel. Beverly Law, a professor of global change biology and terrestrial systems science at Oregon State University, and who led the Oregon forest study, says there hasn't been a thorough analysis of carbon emitted by mass timber production because it is enormously complex to track the factors that produce CO2 in forest ecosystems and in production. Some of the data needed, she said, is incomplete or absent. It took her team of researchers more than a decade of analysis to figure out that the Oregon wood products industry was the largest emitter of CO2 in the state. So even mass timber's largest attribute of being a carbon sink needs to be analyzed further to define an acknowledged standard. However, the most critical obstacle, the researchers said, is the need to certify that the wood is logged sustainably and certified as such before more development and demand of the material is pursued.[94]

5.3.1 Fire Protection

One of the most common questions asked when discussing mass timber is its fire resistance and how to protect it. The main principle giving mass timber a proven fire-rating is its inherent char rate. Mass timber panels such as cross-laminated timber are thick, laminated wood panels that form a dense, solid wood piece. Its thickness and density make it difficult to ignite depicted below with Figure 37, instead charring at a steady, measurable

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[93] https://architecture2030.org/2030_challenges/2030-challenge/

[94] https://e360.yale.edu/features/as-mass-timber-takes-off-how-green-is-this-new-building-material

rate which can be standardized for approved fire-rating. To ensure the safety and resilience of mass timber, rigorous testing was done in controlled environments on the material over the course of a few years with government funding.

Figure 37: CLT char test

Source: 100 Projects UK CLT

There were six Fire Protection Research Foundation (FPRF) fire tests overall to test aspects such as the heat release rate, for example. Mass timber's fire performance has continually been one of the most concerned areas in terms of additional research information—but suffers more from misperception than lack of research data. The predictability of wood's char rate has been well-established for decades and has also been recognized for years in U.S. building codes and standards.[95] The 2015 National Design Specification (NDS) for wood construction includes a char calculation procedure to provide calculated fire resistance of up to two hours. The U.S. CLT handbook also shows the allowable thicknesses of CLT panels for appropriate fire performance. Still, research on fire performance was conducted on CLT including building model rooms and structures to test the char rate, and even filling the room with flammable household items in varying experiments, examples shown in Figure 38 taken from the CLT handbook.[96] During the tests, they also tested covered CLT walls versus exposed walls, and using sprinklers to prove that they were still effective for a CLT structure.[97]

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[95] reThinkwood, Mass Timber in North America

[96] CLT USA

[97] CLT USA

Figure 38: Mass Timber Fire Testing
Source: CLT US

The impressive ability of CLT to meet two and three hours of fire resistance with and without gypsum protection seems to be overshadowed by concerns about its combustibility. Other tests included a three-story CLT apartment simulation that ran for three hours. Results of the apartment simulation showed the effectiveness of encapsulation in significantly delaying CLT's potential contribution to fire growth and proved that the structure can withstand complete burnout. Another test focused on a 25ft CLT stair and elevator shaft with two layers of gypsum protection on the fire side. The test ran for 2 hours and showed no sign of smoke or heat penetration into the shaft.[98]Additional studies and panel tests continue to be done, not necessarily to prove legitimacy of the CLT char methodology, but to support expansion of its application. Expanding areas include new assembly configurations and exploring mass timber's performance under non-standard fires. The various and ongoing tests have shown with many perspectives and conditions that mass timber is a fire-rated material capable of being used for building structures and requires more advocacy of awareness to remove the stigma and doubt around constructing with wood, instead of repeating tests that prove its safe to use.

5.3.3 Termites and Weathering

The largest concern for using mass timber, especially in tropical climates such as Hawai'i, is the risk of termites and how to protect the wood from being infested by the

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[98] CLT USA.

insects. Basic understanding of termites, then, should be discussed as well as the available treatment options for protecting the structural panels from being destroyed. There are two main types of termites present on the islands, having arrived in the 1800's with the many ships trading goods. The Formosan subterranean termite and the dry-wood termite are both present in Hawaiʻi and contribute to the destruction of residential homes, with the subterranean termite causing significantly more damage. The importance of knowing the cell structure of wood as shown earlier is prominent to understand wood's vulnerability to termites. The insects are attracted to wood as food because of its abundance in cellulose which termites rely on for sustenance. The cell walls of wood are made of cellulose and lignin protecting the vessels and fibers which carry water and/or nutrients, wood itself is about half cellulose and 15-30% lignin. The concentration of cellulose make wood the perfect target for termites.

Current building codes exist that prove to be effective against termites such as the height above grade, slope of grade away from structure, and insulation requirements to mitigate wet conditions that support the development of wood destroying insects. The damages made by termites and other wood destroying insects throughout the U.S. is revealed to be a multibillion-dollar industry. Repairing mass timber buildings will be difficult because of the limitations in accessing elements and the large size of individual members. Preventing deterioration will be especially important in these structures. There are a variety of existing approaches to prevention that may be suitable for specific elements in a mass timber building.[99] Protection using either chemical or physical barriers will be essential for performance of structures build in areas with high termite pressure. Common existing practices and codes express the necessary separation of wood members directly contacting the ground, instead using solid concrete foundations and in some cases, steel meshes as a supplementary barrier to protect the wood member. Borate and chemically treated wood are also often used, though the structural effects of using it on CLT is still being researched and the effectiveness of the chemicals binding with the panels to form a protective, repelling barrier is also unknown. However, recent tests have concluded that exposed CLT panels when coming into contact with subterranean termites, are vulnerable

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[99] J.Y. Wang, Durability of Mass Timber Structures: A Review of the Biological Risks.

and susceptible to damage. The need for more research and novel solutions to termites and moisture is necessary for mass timber to be widely adopted in tropical climates such as Hawaiʻi, with ongoing research turning to redwood and other natural termite deterrents.[100]

5.4 Meeting IBC 2021

The many tests conducted on mass timber have been to assess its safety and performance characteristics to provide a measurable standard, which is will now be implemented in the revised International Building Code (IBC). The acceptance of mass timber as a construction type and being acknowledged within the IBC is a huge feat that has taken the course of years to achieve, with the fire rating tests contributing a large part of research for the advocacy of mass timber. The Pacific Northwest has already adopted and implemented local codes allowing for mass timber construction, but the widespread use of it has been constricted due to the codes. As recent as December 2018, the International Code Council announced that fourteen code change proposals related to expanding the allowable heights and areas of mass timber buildings had been approved by its voting members.[101] The allowable building heights for mass timber buildings may reach up to eighteen stories, a significant opportunity for using mass timber in future projects. The current 2018 IBC has nine construction types, with five identified as the main categories. Due to the successful characteristics of mass timber and the continued testing to prove its safety, the revised IBC 2021 will include three new sub-categories within Type IV construction: IV-A, IV-B, and IV-C which will begin to be put into effect at the end of 2020.[102] The currently existing Type-IV construction guidelines will be categorized as Type IV-HT for conventional heavy timber use. This will allow new buildings to utilize mass timber and its engineered wood options as a construction material and achieve market demand while following the revised code.

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[100] J.Y. Wang, Durability of Mass Timber Structures: A Review of the Biological Risks.

[101] reThinkwood, Mass Timber in North America.

[102] Ibid.

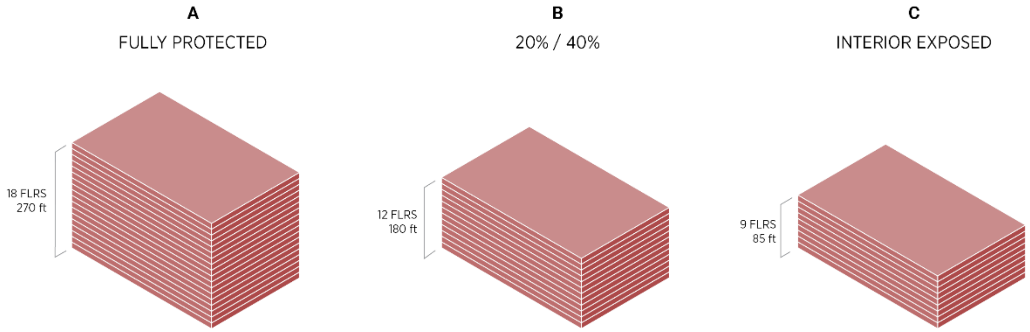

Figure 39: Mass Timber Construction Types

Source: reThinkwood

The revised code adoption will indefinitely contribute to a new wave of building construction transforming the industry towards more sustainable means of practice. Those who are early to adapt the codes and implement mass timber locally will become the models for surrounding urban areas slow to transition to the recognized prefabrication methods. To summarize the revised codes for mass timber, Type IV-A, IV-B, and IV-C follow the same principles for the structure and mainly vary regarding height requirements, interior exposure, and fire rating utilizing sprinkler systems. For the exterior envelope, all three subcategories using mass timber must have the entire exterior envelope covered and protected with noncombustible material, reflecting the practiced caution towards the new material. Even so, the beneficial consequences of the IBC revision outweigh the restrictions, including the increased allowance of building height for mass timber projects and concrete podiums not required for the wood structure.

5.4.1 Type IV-A

The first category of Type IV is the most conservative. It requires the entire building structure utilizing mass timber to be covered with a protective noncombustible layer. The trade-off of being protective is to allow the building to reach 18 stories for both residential and business occupancies, or a maximum of 270 feet.[103] Visually, most people would not be able to guess that the finished building would be made of wood rather than conventional

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[103] reThinkwood, Mass Timber in North America.

concrete and steel and the added height requires two water supply mains. Still, the benefits of mass timber are far-reaching, with the wood sequestering carbon regardless.

5.4.2 Type IV-B

The second category of the new construction type allows for some mass timber exposure when desired or appropriate for the program. Buildings can expose units' ceilings that equal up to 20% of the dwelling's floor area, and walls can reach 40% exposure of the unit's floor area. However, the unprotected portions of walls and ceilings must be at least 15 feet away from other unprotected portions of other walls measured horizontally along the ceiling and horizontally along the floor. Concealed spaces and egresses are still required to be protected with a layer of noncombustible material. The height limit for Type IV-B is 12 stories or 180 feet, making both Type IV-A and B construction exceed 120 feet with the updated codes. The opportunity for some structural exposure on the interior side imply the success of Type IV-B with residential and luxury programs where the exposed timber can be viewed as an asset to the overall building.[104]

5.4.3 Type IV-C

The last subcategory of mass timber construction, Type IV-C allows for complete exposure within the interior of the building. All mass timber elements must meet minimum sizes and fire rating yet Type IV-C's allowance for complete interior exposure excluding concealed spaces allow for exploration in form and material for low to mid-rise buildings. Due to the exposed timber, Type IV-C is only allowed to reach nine floors or 85 feet. [105]Oregon and Washington have adopted the wood codes already and some already built projects challenge the height limits as being too conservative. However, the advancement of mass timber is clear, and the potential of wood is only beginning to be found.

5.5 Types of Mass Timber

There are many existing mass timber products, with cross-laminated timber (CLT) as the most popular in use. All mass timber come from trees but the manufacturing process of the wood into structurally grade panels can vary, giving subcategories of the engineered

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[104] reThinkwood, Mass Timber in North America.

[105] Ibid.

wood to exist and have architects and contractors to choose from. Though each panel shares similar characteristics, each one has its own properties that are significant to note, and which helps distinguish it from other options available.

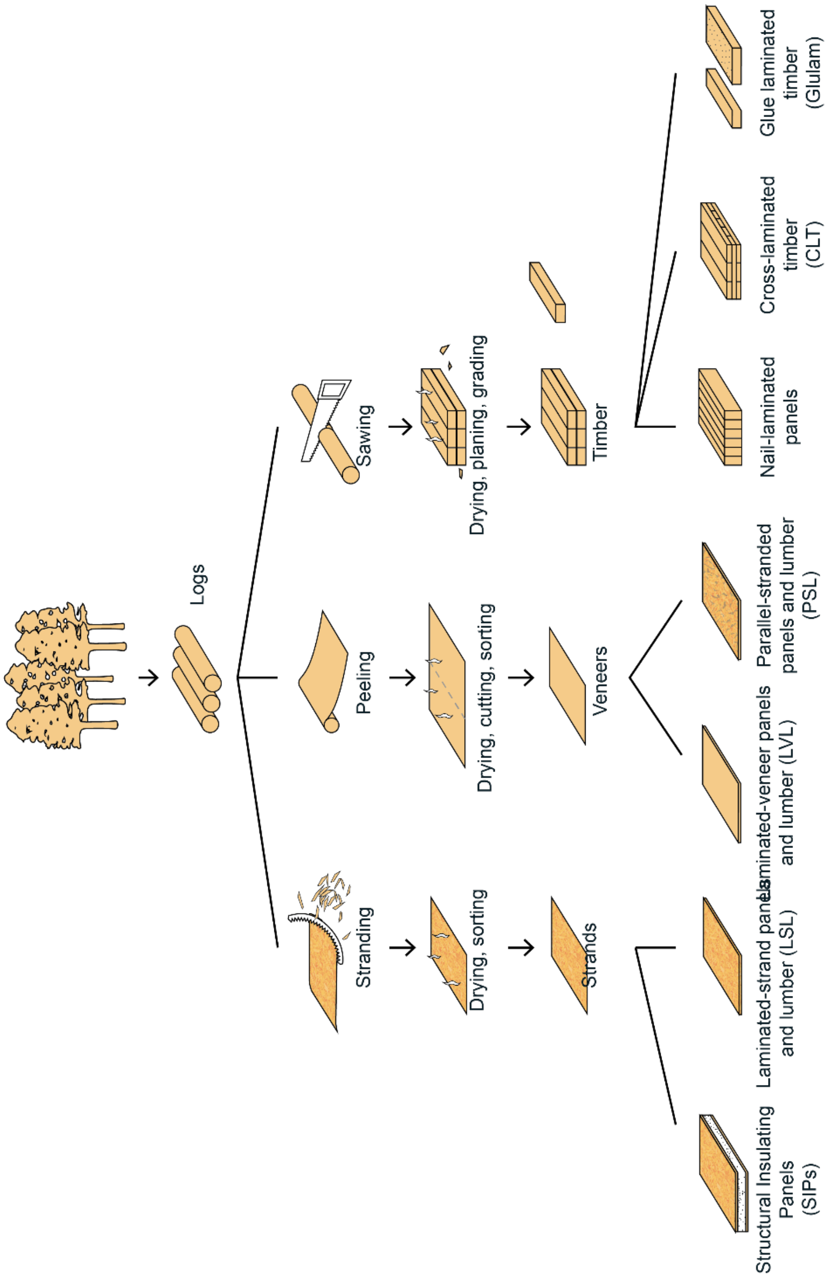

Figure 40: Mass Timber Panel Types

Source: https://www.sciencedirect.com/science/article/pii/S1364032116306050

5.5.1 Traditional Heavy Timber

The solid wood structural members have a strong fire-resistance performance and do not require as much prefabrication labor to assemble the panels since the heavy timber is naturally a large, dense wood member. Heavy timber is one of the oldest types of building construction used in the U.S. with effective implementation for multi-story and industrial buildings, though recently it is used more often for churches, schools, and other public buildings.[106]

5.5.2 Cross-Laminated Timber (CLT)

CLT is a structural panel usually consisting of 3,5, or 7 wood layers glued together perpendicular to each other to form thick panels with exceptional strength. The glue in the panel is soybean-based and so is non-toxic, however the length of the panel is limited to transportation, typically to 60 feet. [107] The standardization of the panels being manufactured at a maximum of 10 feet width and 60 feet length has made it easy to transport and assemble, while its crossing wood members greatly increasing its structural properties have made CLT the most popular mass timber product and a soon-to-be household term.

5.5.3 Glue-Laminated Timber (GLT)

Glulam is composed of individual wood laminations (dimension lumber), selected and positioned based on their performance characteristics, and then bonded together with durable, moisture-resistant adhesives. The grain of all laminations runs parallel with the length of the member to give effective strength and stiffness properties. In addition, the engineered wood is available in a range of appearance grades for structural or architectural applications.[108] While typically used as beams and columns, designers can use glulam in the plank orientation for floor or roof decking. With the flexibility of glulam manufacturing, glulam ‘panels’ can be used to create complex curves and geometry. When used in these

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[106] CLT UK 100 Projects.

[107] reThinkwood, Mass Timber in North America.

[108] CLT UK 100 Projects.

unique panel configurations, glulam is seen as an extension of the mass timber product family and sometimes referred to as GLT.

5.5.4 Nail Laminated Timber (NLT)

NLT is created from individual dimension lumber members (2-by-4, 2-by-6, 2-by-8, etc.), stacked on edge and fastened with nails or screws to create a larger structural element. NLT has been used for more than a century, though it is picking up momentum along with the mass timber ascent.[109] It is mainly used in floors, roofs, and decks. The material can be used with a variety of textured appearances in exposed applications. Nail-laminated timber has also been used to create elevator and stair shafts in mid-rise, wood buildings, an extraordinary feat. NLT naturally lends itself to the creation of unique roofs by slightly offsetting and rotating each board relative to the others to form the necessary geometry. Advantages of NLT include the ability to use locally available wood species and the fact that specialized equipment generally isn't necessary. Prefabricated NLT panels typically come in sizes up to 10 feet wide and 60 feet long, same as CLT panels, with wood sheathing preinstalled. [110]

5.5.5 Dowel Laminated Timber (DLT)

Dowel-laminated timber panels are a new mass timber product commonly used in Europe. Panels are made from softwood lumber boards (2-by-4, 2-by-6, 2-by-8, etc.) stacked like the boards of NLT and friction-fit together with dowels. Typically made from hardwood lumber, the dowels hold each board side-by-side, similar to how nails work in an NLT panel, and the friction fit lends some dimensional stability to the panel.[111]

5.5.6 Timber Concrete Composite

Mass timber systems vary widely, and hybrids are an option for wood high-rises, very long spans, or other project-specific requirements. No material is perfect for every job, and it's important for designers to choose a combination of materials that effectively meets

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[109] CLT UK 100 Projects.

[110] Ibid.

[111] Ibid.

the performance objectives. Timber-concrete composit is one such option to provide a resilient product.

5.5.7 Structural Composite Lumber (SCL)

SCL is a family of wood products created by layering dried and graded wood veneers, strands, or flakes with moisture-resistant adhesive into blocks of material, which are subsequently re-sawn into specified sizes. Two SCL products—laminated veneer lumber (LVL) and laminated strand lumber (LSL)—are considered part of the mass timber category, as they can be manufactured as panels in sizes up to 8 feet wide, with varying thicknesses and lengths, depending on the product and manufacturer.[112] Parallel strand lumber (PSL) columns are also used with the other mass timber products.

5.6 Fabrication and Assembly

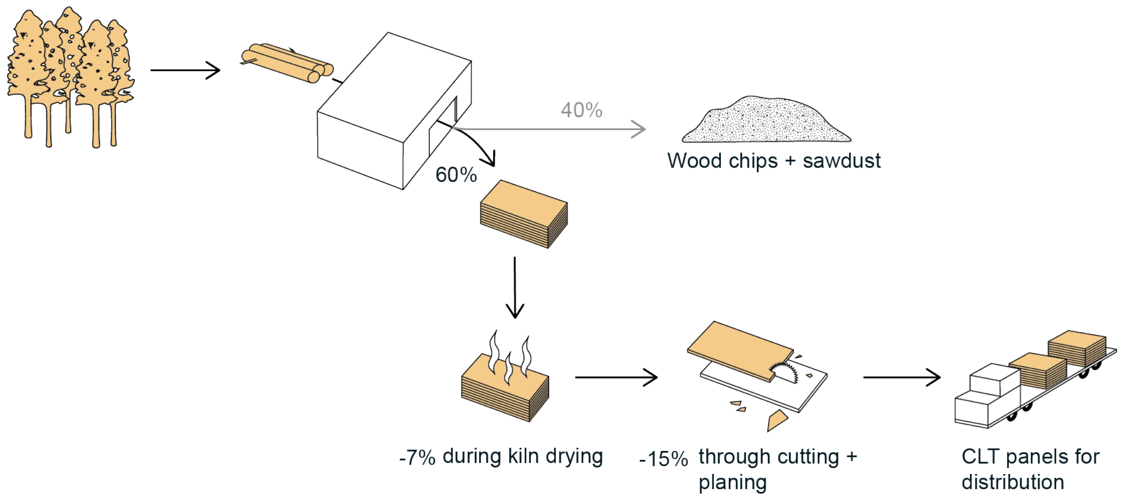

Figure 41: Mass timber assembly

Source: CLT UK 100 Projects

The varying mass timber product types and panels have their own distinguishing factors, though the main fabrication and assembly process of the engineered is mainly coherent throughout with the milling and breaking down of the tree’s raw material to a standardized one. Trees are milled and kiln-dried with cutting and planning occurring in a

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[112] reThinkwood, Mass Timber in North America.

controlled factory setting. CLT and glulam as well as other products can also be easily cut with CNC routers to provide precut spaces for window, doors, and even unique wall panel shapes and sizes. The continuous research and engineering of wood into structural materials has also reduced the waste of milling trees and has efficiently processed as much of the lumber as possible into capable products.

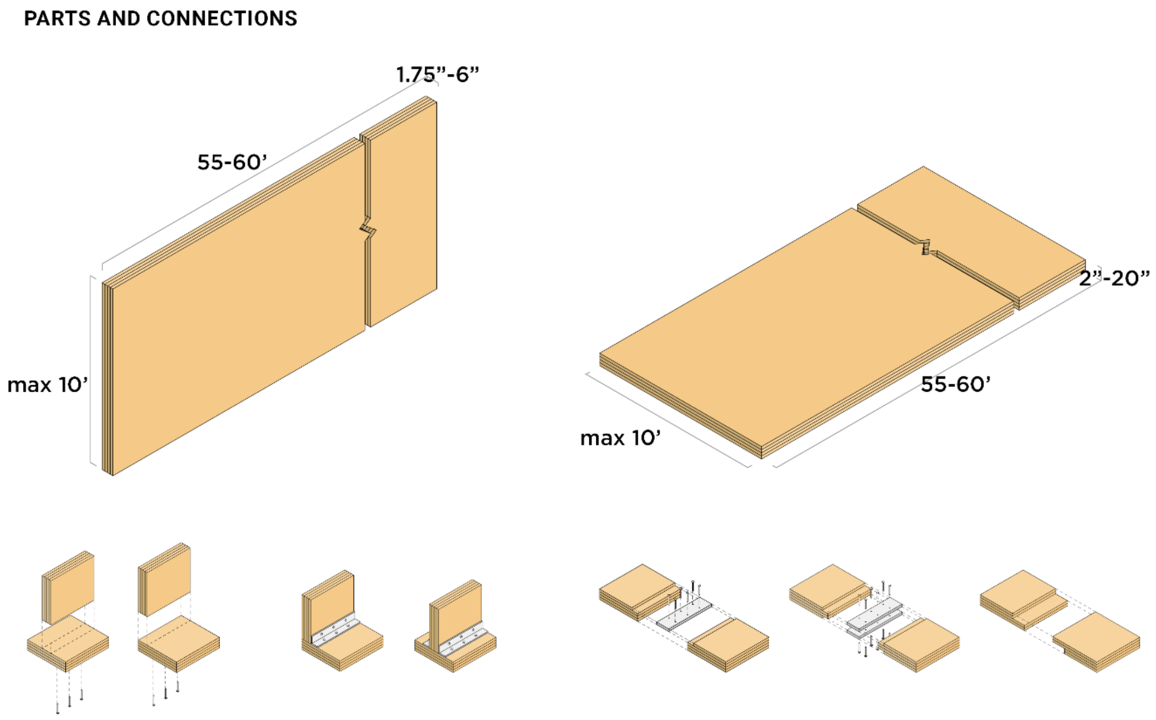

Figure 42: CLT Floor, Wall, & Connections
Source: CLT USA

Panel thicknesses usually range between 100 to 300 mm (4 to 12 in), but panels as thick as 500 mm (20 in) can be produced. Panel sizes range from 1.2 to 3 m (4 to 10 ft) in width and 5 to 19.5 m (16 to 64 ft) in length. The maximum panel size is limited by the size of the manufacturer’s press and transportation regulations.[113] The use of steel plates as joinery is popular with CLT columns and wall slabs, while long screws are used to connect panels together into a solid floor slab. The connections available vary widely and can be a mixture of wood-to-wood and wood-to-steel.

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[113] https://cwc.ca/how-to-build-with-wood/wood-products/mass-timber/cross-laminated-timber-clt/

Figure 43: CLT Floor Panel Connection

Source: CLT UK

5.7 Potential in Hawaii

As introduced before, Hawaii’s 2045 Neutral Carbon Policy has made the use of wood and mass timber as an appealing construction material alternative to current practices. Wood throughout the state has gained traction, with recent developments in large part done by Joey Valenti and the other members comprising the Hawaii Wood Utilization Team. The team have begun and continue to conduct a statewide Hawaii Wood Inventory to bridge the communication gap between manufacturer and consumer as well as increase the infrastructure of milling and utilizing local wood for projects of all scales.[114]

There is a critical need for renewable, sustainable materials to be used in the construction industry which mass timber can easily offer. However, as expressed with the Hawaiʻi Wood Utilization Team, there is a current absence of scalable infrastructure for the state to use locally grown wood as well as sizable mills to harvest the wood. In order for mass timber to be quickly implemented in Hawaiʻi and contribute to the current goals and challenges, continued support and awareness from government officials and the greater community are needed. Engineered wood, with its recent development, can continue to quickly adapt and evolve to meet the needs of residents in all types of environments, and while it does, Hawaiʻi’s stakeholders can prepare the archipelago for the positive rise of this new material.

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[114] Hawaii Wood Utilization Team. https://hawaiiwoodproducts.com/. accessed September 27, 2019.

6. Mass Timber Precedent Studies

6.1 Prescribed Paper Building

A culmination of both built projects and conceptual proposals are gathered here for both form and function analysis. The inclusion of both conceptual and built projects is to provide a clear understanding of what is already possible in the current construction industry and where the direction of architecture in regarding mass timber and modular design is headed within the near future. The precedent studies that were chosen show the possibilities and benefits of using mass timber as a structural material while also revealing the systems used with mass timber to achieve the building form desired with the necessary program and building codes. Sizing and assembly dimensions are also considered as references for the design proposal. As a result, the extraction of information is used to provide precedence and a basic toolkit for designing with mass timber within the final design proposal in chapter seven.

Chris Precht, co-founder of Penda, worked with his wife Fei under Studio Precht to propose a high-rise wood structure made of A-Frame modules to create an interlocking vertical farm in the city, appropriately named Farmhouse.[115] Fueled by personal conflict of food production and food accessibility in urban environments, Precht designed each module to be productive and efficient for food, energy, and wastewater processing. It took two years for the project to manifest and the results are apparent throughout the project. The main material proposed for construction is CLT or cross-laminated timber panels used to make the modules which are broken down into three layers. CLT was proposed as the module material for its sustainable properties, having a smaller carbon footprint than concrete and steel to manufacture while also absorbing carbon throughout the building's life cycle. The module system is built around the kit-of-parts prefab type where the A-Frames would be built in factories off-site and then shipped as flatpacks and assembled.

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[115] India Block, "Precht's The Farmhouse Concept Combines Modular Homes with Vertical Farms," Dezeen, March 07, 2019, , accessed February 27, 2019, https://www.dezeen.com/2019/02/22/precht-farmhouse-modular-vertical-farms/.

Figure 44: The Farmhouse, Precht

Source: Dezeen

The outer layer of the A-Frame holds the water supply and other gardening/farming elements to allow the plants to be expressed throughout the structure. The middle layer makes up most of the structure and insulation, and the interior layer has the pipes and electric hardware finishes.[116] The smallest module is nine square meters with a two-and-a-half square meter balcony, but others grow larger to meet different needs. The V-shaped gardening area allows for communal and individual food production as well as offering ventilation and a privacy buffer between the adjacent apartment units. As the unifying concept of producing food in the urban area, the modular system allows for food production to continue to grow vertically in the city and express it explicitly to the surrounding community as an example of sustainable design.

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[116] Eric Baldwin, "Precht Designs Timber Skyscrapers with Modular Homes and Vertical Farming," ArchDaily, February 25, 2019, , accessed March 2, 2019, https://www.archdaily.com/912058/precht-designs-timber-skyscrapers-with-modular-homes-and-vertical-farming

6.4 Brock Commons, British Columbia, Acton Ostry Architects

Figure 45: Brock Commons
Source: Archdaily

The structure of the Brock Commons Tallwood House is a hybrid system comprised of CLT floor slabs, glulam columns, steel connectors, and concrete cores. Completed in 2017, it has been designed to achieve LEED Gold certification. UBC is a strong proponent of utilizing wood for its carbon benefits, and Brock Commons Tallwood House is just the latest of several mass timber buildings on its campuses.[117] Built as a student residence building for the University of British Columbia, Brock Commons is one of the tallest mass timber buildings in the world standing at 18 stories. After the mass timber components arrived on-site, it only took seventy days to complete structure assembly. It rests upon a concrete podium with two concrete cores which is then complemented by the seventeen floors of mass timber structure, earning its title as a hybrid wood structure.[118]

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[117] reThinkwood, Mass Timber in North America
[118] Ibid.

6.5 Carbon 12

Figure 46: Carbon12

Source: Carbon12pdx

In the Pacific Northwest, the developer/ architect team responsible for The Radiator has also designed an eight-story (85-foot high) residential building known as Carbon 12. The building includes a heavy timber gravity frame, CLT floors, and CLT core walls.[119] It is currently the tallest mass timber building in the U.S. The elevator core and parking level is still made of concrete, being an example of a "hybrid building" to utilize mass timber while meeting local codes and feasibility parameters faced in Portland. The building's efficient structural system has given it 1/5 the weight of a conventional concrete building with the same program, and simultaneously sequesters 32 tons of carbon from the CLT used for the building.

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[119] reThinkwood, Mass Timber in North America

6.6 Discussion

The introduction and overview of the mass timber precedent studies have given a visual framework of how mass timber is used to construct a building. The way that the prefabricated panel construction system works is similar in many ways to other prefab types, yet the material of mass timber gives the building distinctly new parameters to follow and guidelines that must be met including fire protection and in-depth details on the connections between panels, floors, and walls. Reviewing Brock Commons highlighted mass timber's ability to work with other materials to construct a mid-rise building. The prefabricated panels and components are flexible enough to work with concrete and steel when needed, creating a hybrid system of materials and construction techniques to achieve a designed form conscious of its surroundings and program.

Though mass timber is a recent development with many challenges still being faced, the many established options already available, and case studies using the products explicitly show that mass timber is here to stay and grow. The era of the so-called plyscrapers will take hold of the construction industry inevitably, it's only a question of when and how fast these paper buildings will become tall-wood structures.

7. Hybrid M3 Proposal: A Mid-Rise Modular Mass Timber Residence

7.1 Design Framework

The introduction and analysis of both recent construction developments in prefabrication, modular and panel construction using mass timber as the primary construction material, has led to the question of what lies ahead in the future of construction. The design proposal within this chapter explores this by attempting to combine both prefab methods and material to construct a residential building and bring out the positive aspects of prefabrication. By doing so, it offers a glimpse into possible alternatives of construction methods used here in Hawai‘i, while also shedding light on the local practices and codes, and how it will affect the use of mass timber on a large urban scale.

The prior expression of modular construction has revealed the benefits of prefabrication including speed of construction, reduced waste, quality control, and less material use leading to considerable cost savings and reduced timelines, as well as environmental benefits. In the last section, recently developed prefabrication methods of mass timber as a structural material has led to a movement of wood construction utilizing CLT as the main component in the building due to the undeniable environmental benefits of mass timber complemented by other benefits of the prefabricated panels such as precision of material, being a significantly lighter material than concrete and steel, faster construction and assembly time, a reduced required foundation size, and the inherent properties that make mass timber fire resistant.

To understand the obstacles to these options, the challenges faced with each prefabricated method was also distinguished, with current challenges of modular design and construction being its limitations on the size of the module due to transportation factors, the redundancy of structural walls and floors when stacked by crane hoisting, and the ongoing balancing act between standardization of modules and mass customization for form and site context, before becoming too expensive. Mass timber, being a recent development in the US still faces challenges of meeting local building codes and the need of updating codes to allow its widespread use. Fire, weather, and pest protection is also needed for the structure with more research being developed on the long-term effects and life cycle of mass timber buildings. The existing challenges of both methods is recognized in the design proposal and uses modular design and mass timber to complement each other and mitigate the weaknesses of using the prefabricated method alone.

As the design scheme has evolved throughout this body of work, the resulting building proposal acts as a hybrid model of mass timber and modular construction. Using a light module in comparison to standard modules currently used in construction which will be discussed further, and finished mass timber panels to reduce waste and speed up construction assembly are some examples of how the design addresses the use of modular mass timber construction for a residential building. Hawai‘i’s history of low-rise development mixed with high-rise intrusion is also acknowledged, along with program zones and land use ordinances which has acted as the main project parameters in terms of size, location, and scale, influencing the proposed mid-rise footprint. The current guidelines are followed to respect context and allow this project proposal to act as a primary example for future prefabrication development and reveal the potential of mass timber and modular construction in urban Honolulu as tools for accessible housing options for the city’s residents.

7.2 Site Selection

The process of choosing an appropriate site for the modular mass timber design proposal involved many steps to find a location that would provoke the goals of using modular design with mass timber for housing and enhance the form’s relationship to the site’s surroundings. Primary attributes for the site was guided by Honolulu’s Transit-Oriented Development (TOD) Plan and analysis released for different portions of the island in direct reaction to the construction of the Honolulu Rail Transit Project. Complemented by the TOD plan was the special action team’s report of housing needs throughout the islands with Honolulu having the largest demand, in particular for affordable housing units within the dense, urban areas.

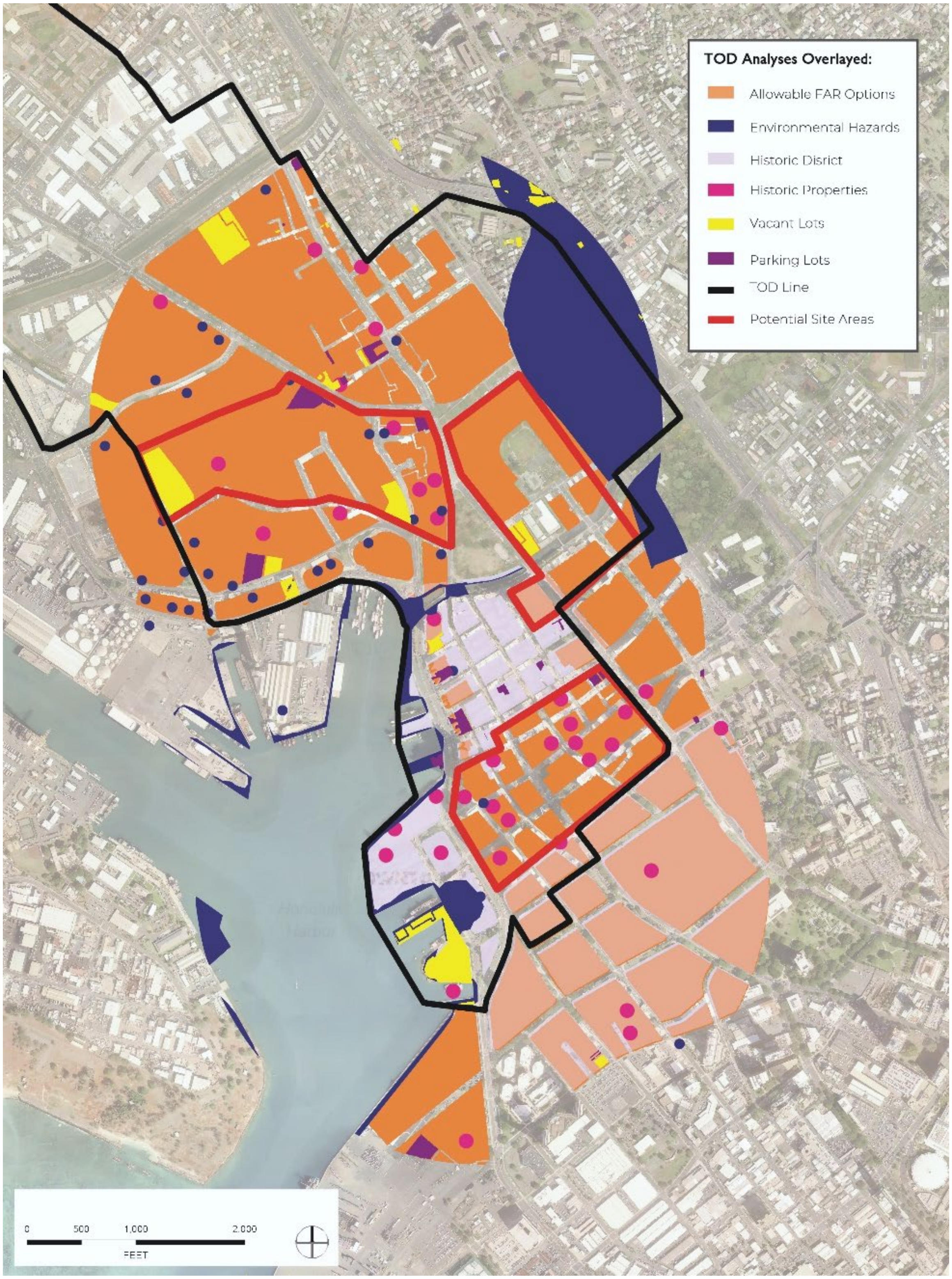


Figure 47: TOD Analysis Overlay of Chinatown

Source: Honolulu TOD

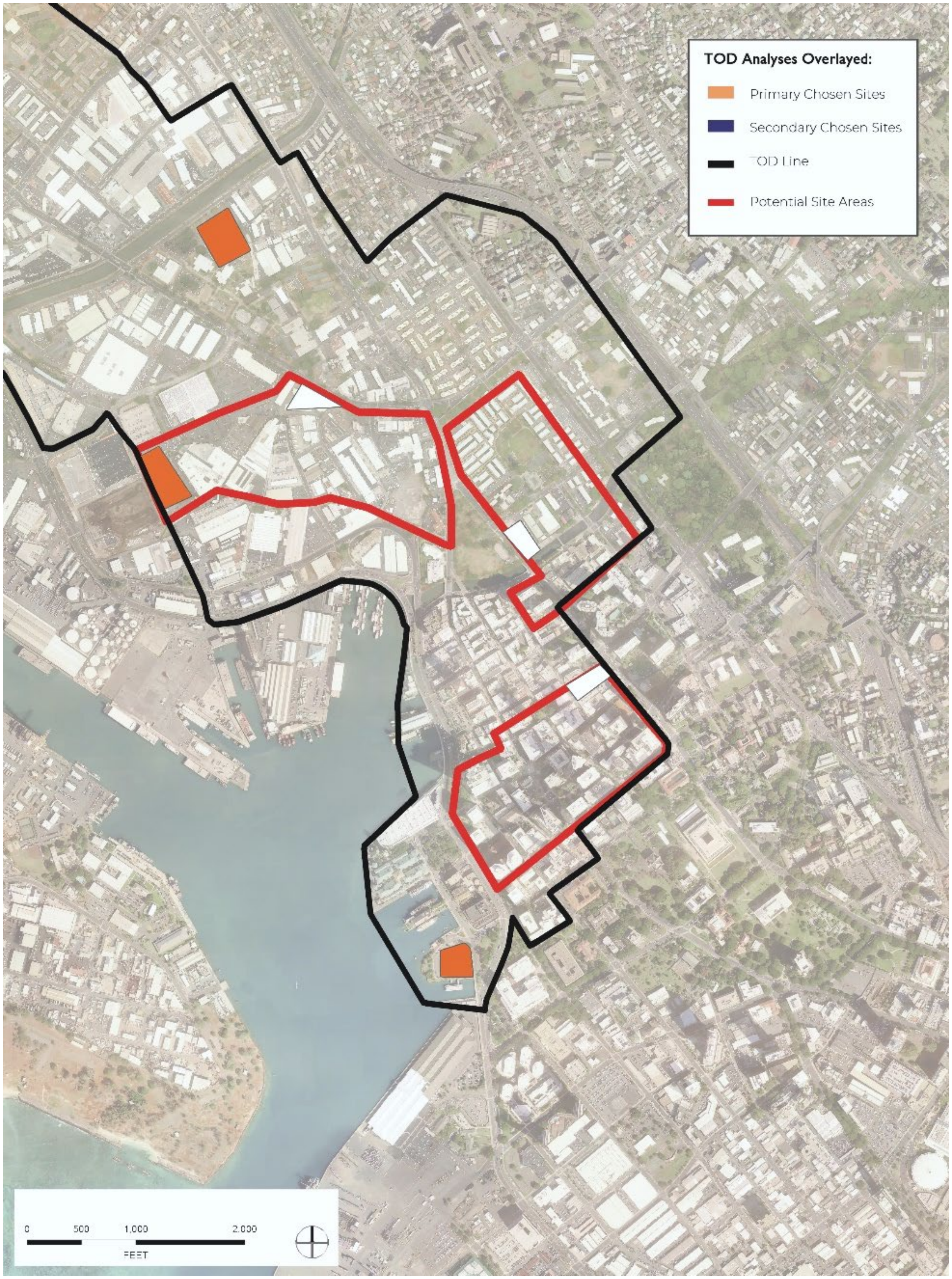


Figure 48: Potential Sites for Building Design Proposal

Source: Author

As shown in the maps above, an overlay of the many TOD analysis maps of Downtown Honolulu and in particular, Chinatown, was conducted to understand the many characteristics affecting the area, as well as narrowing down the potential sites of interest for a residential building design. Characteristics that were paid focus to in Chinatown were the established floor area ratio allowances and parking requirements, as well as any vacant lots available. The vicinity of historic districts and buildings were also observed, in particular, wood buildings, and finally the environmental hazards that the site may be subject to such as flooding and erosion.

The contributing factors affecting the dense urban area of Honolulu distinguished potential sites for further development and narrowed down the considerations to six possible lots within and surrounding Chinatown. Of the six potential sites, further review of the TOD Plan for Chinatown was done including the parking requirements and needs of the area to solidify the design proposal’s parameters of having real-world restrictions. The final contributing factors revealed the lot across from A‘ala Park as a suitable theoretical model that would still tackle and mitigate existing local regulations.

Figure 49: Selected Chinatown Site

Source: Author

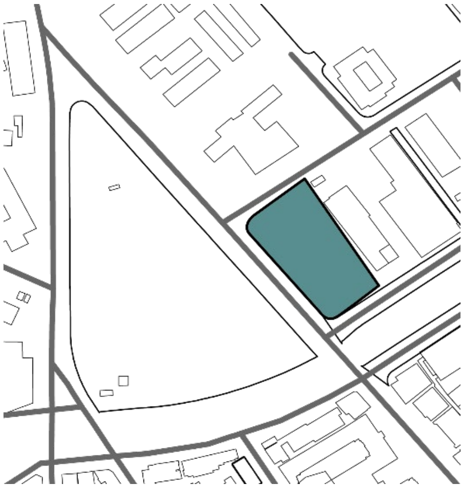
7.3 Site Context

Located at 300 N. Beretania street, American Savings Bank's new flagship branch borders Chinatown and occupies the chosen project site. Recently completed construction in late 2018, it opened to the public on April 18, 2019. The building is a commercial office with a stacked parking structure making it eleven stories high. The land cost $12 million to acquire, with construction costs at $100 million using precast concrete as the construction material covering an area of 373,000 sq. ft.

The conceptual design proposal designates this as the selected site despite the completed building already resting on the lot. The site is in a strategic location for the future development of urban Honolulu, especially for Chinatown in regards to the TOD guidelines to produce a mixed-use, walkable area that activates the community. The placement of a bank in such a critical spot, therefore goes against the recommendations stated in the TOD Downtown Plan, and is seen as a loss for site activation, the lot being in a designated mixed use zone (BMX-3).[120] With the surrounding context of homelessness spread throughout Chinatown and A'ala Park, and the established affordable housing developments of Mayor Wright Homes, the 215 N. King Street high-rise, and the Public Housing Authority high-rise property directly adjacent to the bank, the argument of an accessible residential property for Honolulu's locals with mixed-use businesses is established as a missed alternative project proposal which is now explored in this body of work.

Figure 50: ASB Hawai'i Flagship Building on Site

Source: ASB Hawaii



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[120] Honolulu Downtown TOD Plan.

Building upon the significance of site context, directly adjacent to the chosen site runs a canal holding Nuʻuanu Stream. Its source coming from Waipuilani and Waipuhia Falls as part of upper Nuʻuanu Valley. Nuʻuanu Stream and the surrounding area of Nuʻuanu Valley holds a rich history within Hawaiʻi, the place being known to Hawaiians as, "fertile breadbasket". The land was primarily agricultural with a variety of produce being grown, especially taro and breadfruit. To expand food production and cultivation, a series of auwai or small, man-made canals were used to diverge water from the stream, flow through the terraced loʻi and provide irrigation before returning to the stream.[121] As Ahupuaʻa are largely described as mountain to ocean, mauka to makai, the natural direction of the flow of water holds cultural significance and is seen as sacred.[122]

Figure 51: Nuuanu Stream Canal

Source: Author

Population and urban development have affected Nuʻuanu stream greatly with reservoir retention beginning in the 1880's with King Kalakaua who used the first reservoir as a hydroelectric plant to power the electricity within the palace. More reservoirs were developed, as well as new residential districts which disrupted the flow of auwai and broke them into small parcels that were no longer monitored and controlled by a single party. Instead, each auwai today is distributed within the private property lines of individual

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[121] RDK Herman, Nu'uanu, O'ahu - The Land: Water, , accessed March 26, 2019, http://www.pacificworlds.com/nuuanu/land/water.cfm.

[122] Ibid.

homeowners of which the responsibility of maintenance and preservation falls upon. Of the fourteen original auwai throughout Nuʻuanu Valley, only eight remain with water flowing and in need of repair. [123] Due to these man-made developments, the entire watershed of Nuʻuanu Valley has greatly deteriorated.

As recent as of March 2019, a brown water advisory was announced to Nuʻuanu residents by the Health Department warning of the brown water runoff polluting the stream.[124] Investigations revealed that the cause came from the Board of Water Supply's Nuʻuanu Reservoir 4 due to a stuck gate. The resulting silt runoff had flown throughout the stream, killing koi fish and other marine life with pollution flowing directly through Chinatown and into Honolulu Harbor.[125] The pollution of Nuʻuanu Stream is an ongoing conflict with other advisories happening back in 2007. The stream's degradation in health shares its story with streams throughout Oahu, the catalyst placed upon the Ala Wai Canal. Landmarks of sacred heritage such as Nuʻuanu Stream must be considered with respect and high regard when designing within its vicinity.

Figure 52: Aʻala Park Site Context

Source: Author

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[123] RDK Herman, Nu'uanu, O'ahu - The Land: Water.

[124] Rick Daysog, "Nuuanu Stream Runs Chocolate Brown after Board of Water Supply Reservoir Work," Hawaii News Now, March 05, 2019, , accessed March 26, 2019, http://www.hawaiinewsnow.com/2019/03/06/nuuanu-stream-runs-chocolate-brown-after-board-water-supply-reservoir-work/.

[125] Ibid.

Another significant space to consider within the site’s surrounding environment is A‘ala Park on the other side of Beretania Street. In the 1890’s, plans began to be laid for reclaiming the marshy area of Iwilei and in 1898 the fill project began. By 1899, masonry work was finished to contain the stream and remaining areas were filled with sand and volcanic material. Bordering Nu`uanu Stream and Chinatown on one side, with local shops, businesses, and residences on the other three sides, A`ala Park was born. The current site is shrouded in controversy, with activity of homelessness and violence continuously surrounding the area and occurring within the park at times. Considerations of development on the site have also been proposed, but nothing stands as solid solutions to the site or its conflicting context. Regardless, A‘ala Park also rests in a strategic location with opportunities to positively influence the area with the development of the transit rail station nearby and other public space and walkability initiatives.

7.4 Pre-Design

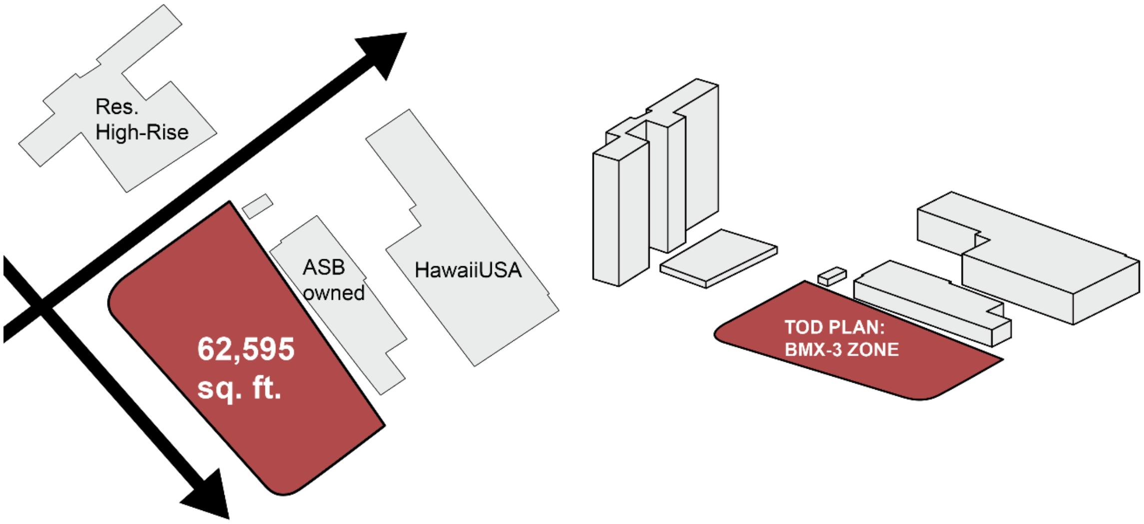

Figure 53: Selected Site Area

Source: Author

The solidification of a proposed site and analysis of its surrounding context gave way to a coherent study of Honolulu's local building codes and land use ordinances directly affecting the lot size and building height. The progressive review of set regulations highlighted the parameters that was decided to be closely followed by the conceptual building model to exercise the feasibility of implementing the evaluated prefabrication methods of mass timber and modular design within a realistic Honolulu setting.

The site rests in a BMX-3 zone, allowing for a floor-area ratio between 2.5-4.5, though BMX-4 allows for more.[126] Continuing to break down the local regulations of the site, the lot rests right outside of the half-mile radius of the anticipated Chinatown Rail Station, missing the TOD parking exemption zone. In effect, parking requirements are needed on site at a minimum of one stall per residential unit and one stall per 300 square feet of commercial retail space. For height limits, a maximum of 200 feet height is limited along with the FAR designation. Setbacks are also followed, with BMX-3 zoning requiring

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[126] Honolulu Land Use Ordinance.

every 10-ft height interval surpassing 40-ft requires an additional 1-ft setback in addition to standard setbacks for residential buildings.[127]

With the main parameters of the lot area prescribed, a detailed review of various FAR scenarios for the selected lot was performed to narrow down the building program size and height limits in accordance with the IBC's Type IV height limits regarding mass timber construction, with a maximum height of 270-ft being reached with Type IV-A. The first exercise of FAR 2.5-4.5 scenarios was conducted with no parking allocation to understand and highlight the opportunities of increased living spaces possible with the ongoing development of effective public transit eliminating high car usage and parking. The equations and data used to calculate the FAR scenarios and in turn visualizing them in the following diagrams, are attached within the appendix of this document and are also referenced within in the list of tables.

Table 2. Proposed Average Dwelling Unit Sizes

Proposed Units	
Studio	400 sq. ft.
1-Bedroom	600 sq. ft.
2-Bedroom	800 sq. ft.
3-Bedroom	1100 sq. ft.

Table 3. Honolulu LUO Parking Requirements

Parking Dimensions	
BMX-3 and BMX-4 Zone	1 stall per dwelling unit
Minimum length x width	18′ x 8′ 3″ = 148.5 sq. ft.
Minimum aisle width (dependent on angle)	100′ – 182′
Proposed Average Parking Unit Size with Estimated Mech/Circ./Ramp Allocation	**400 sq. ft.**
Parking at 25 units/stalls	**10,000 sq. ft.**
Parking at 50 units/stalls	**20,000 sq. ft.**
Parking at 75 units/stalls	**30,000 sq. ft.**
Parking at 100 units/stalls	**40,000 sq. ft.**
Parking at 200 units/stalls	**80,000 sq. ft.**

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[127] Honolulu LUO.

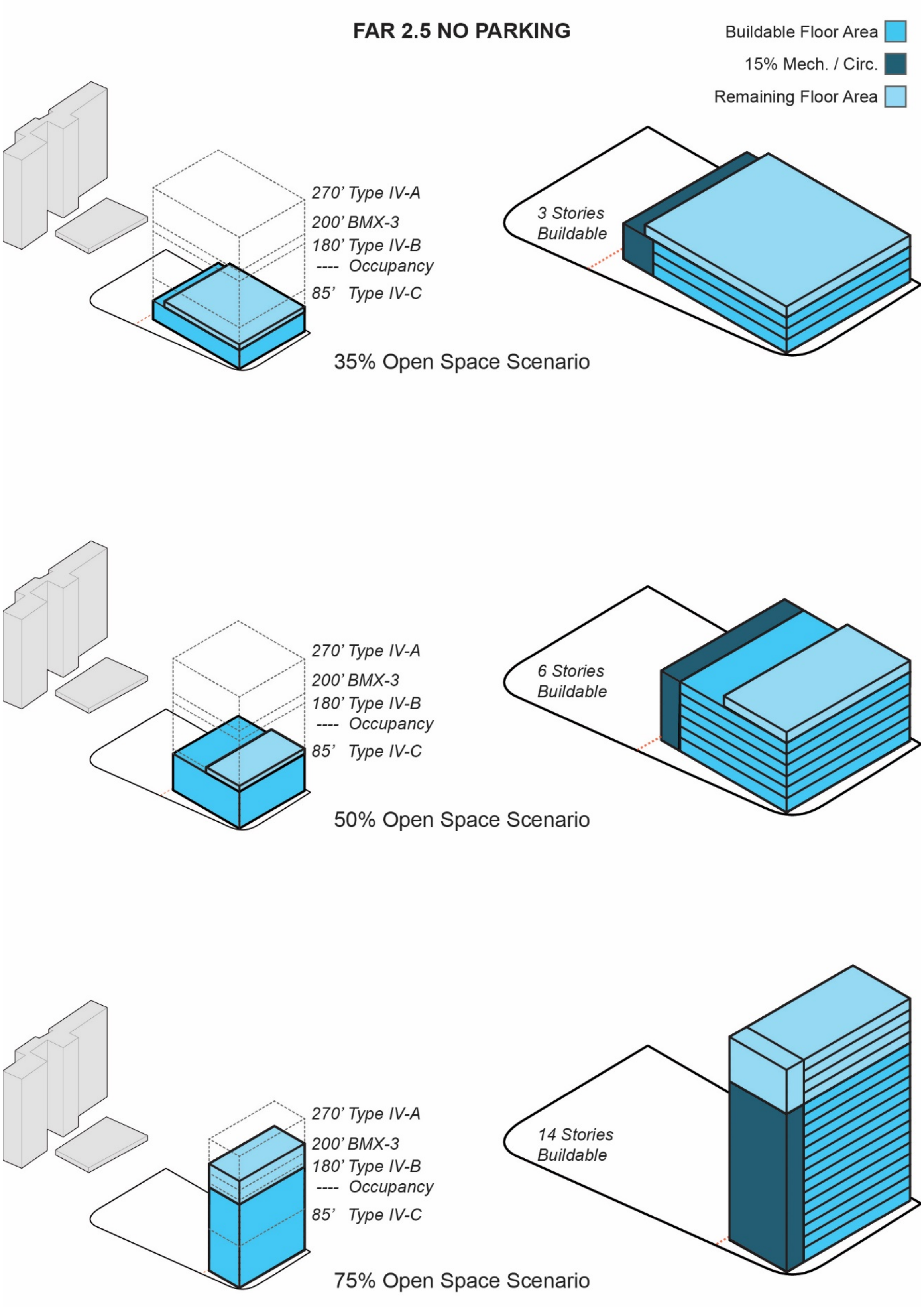

Figure 54: 2.5 FAR Scenario with Parking Exemption

Source: Author

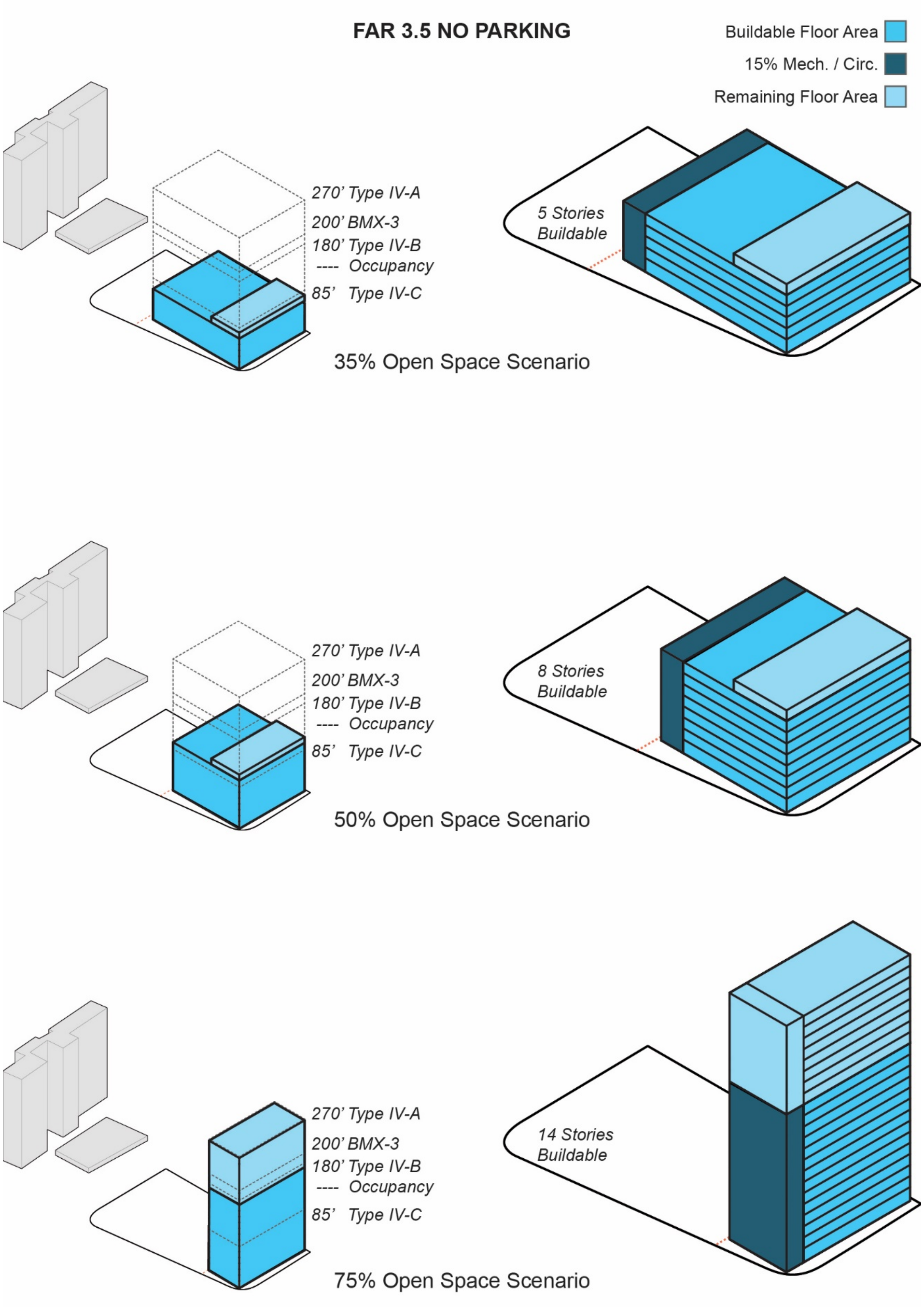

Figure 55: 3.5 FAR Scenario with Parking Exemption

Source: Author

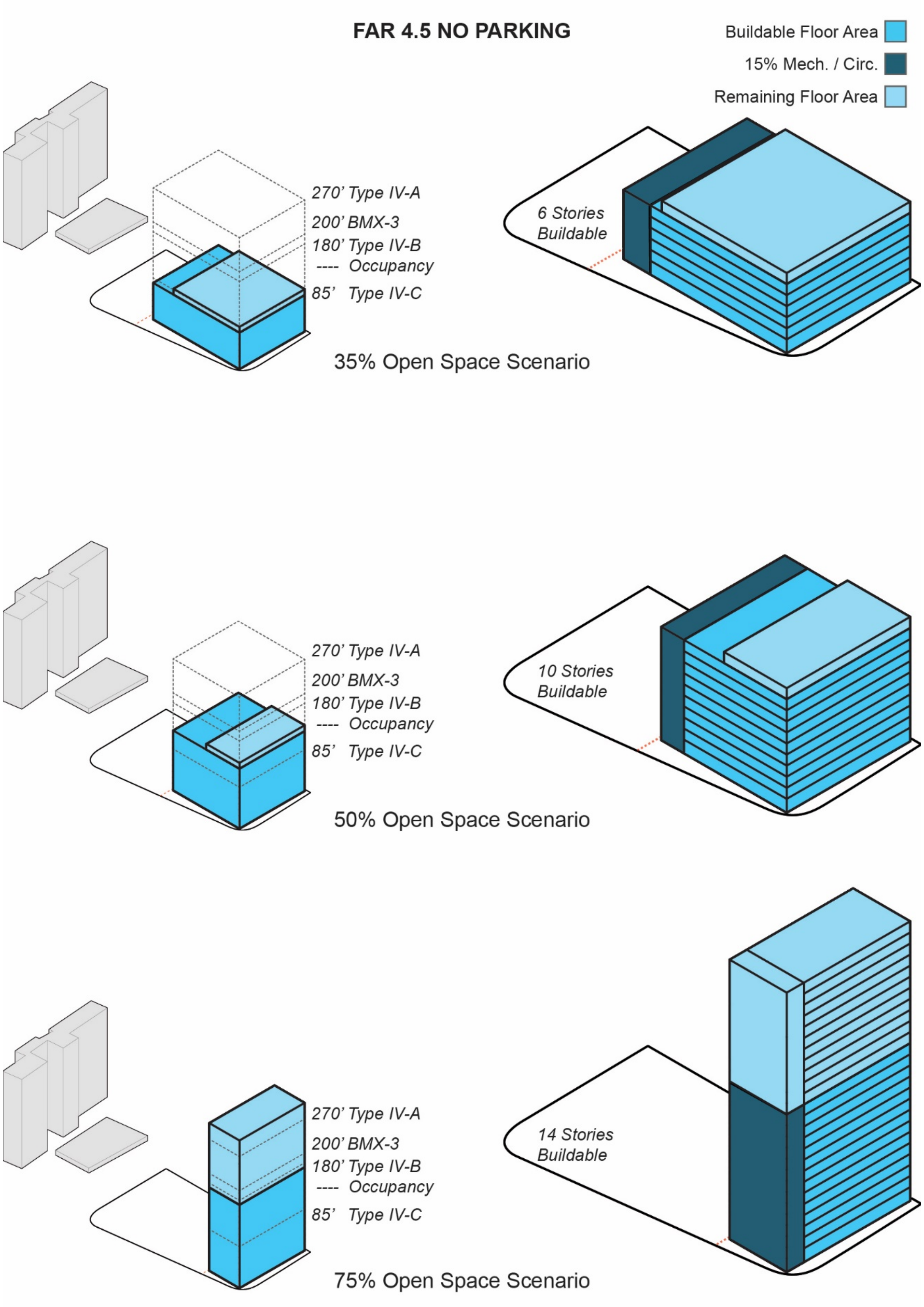

Figure 56: 4.5 FAR Scenario with Parking Exemption

Source: Author

The exercise of highlighting the building massing under different FAR scenarios with no required parking and various levels of open space requirements showed that the maximum height possible for the lot is 14 stories regardless of FAR due to the zoning's height limit of 200-ft. With 200-ft set as the maximum, using either Type IV-B or IV-C mass timber construction was implied to allow for the possible exposure of structural elements within the building's units. Moving forward, the next set of scenarios focused on massing options with the required parking set as an adjacent structure to the building. Again, open space requirements were also acknowledged, the minimum being 35% with an average of 50% open space seemingly reasonable for the lot area and building size.

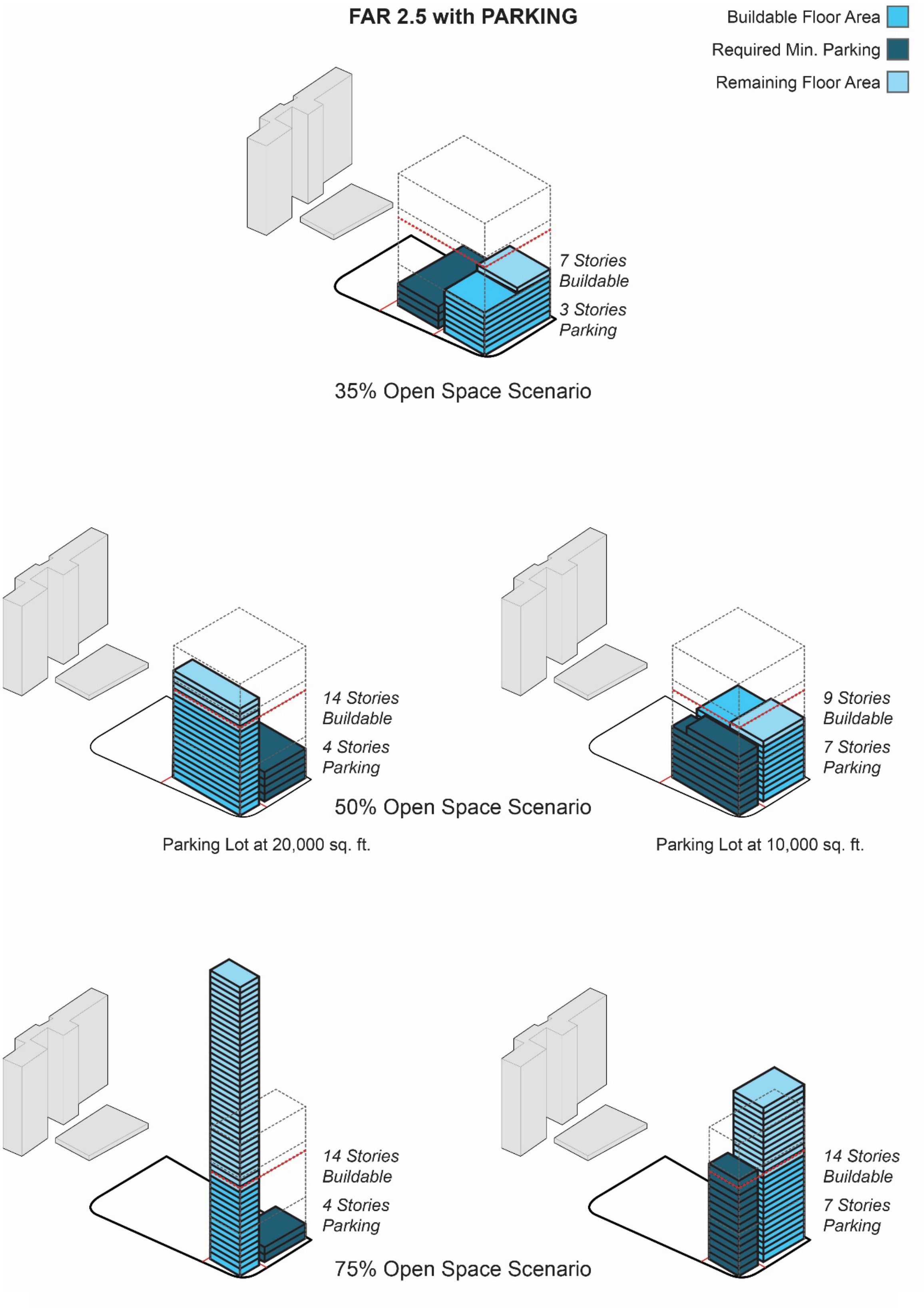

Figure 57: 2.5 FAR Massing Scenario with Parking Requirements

Source: Author

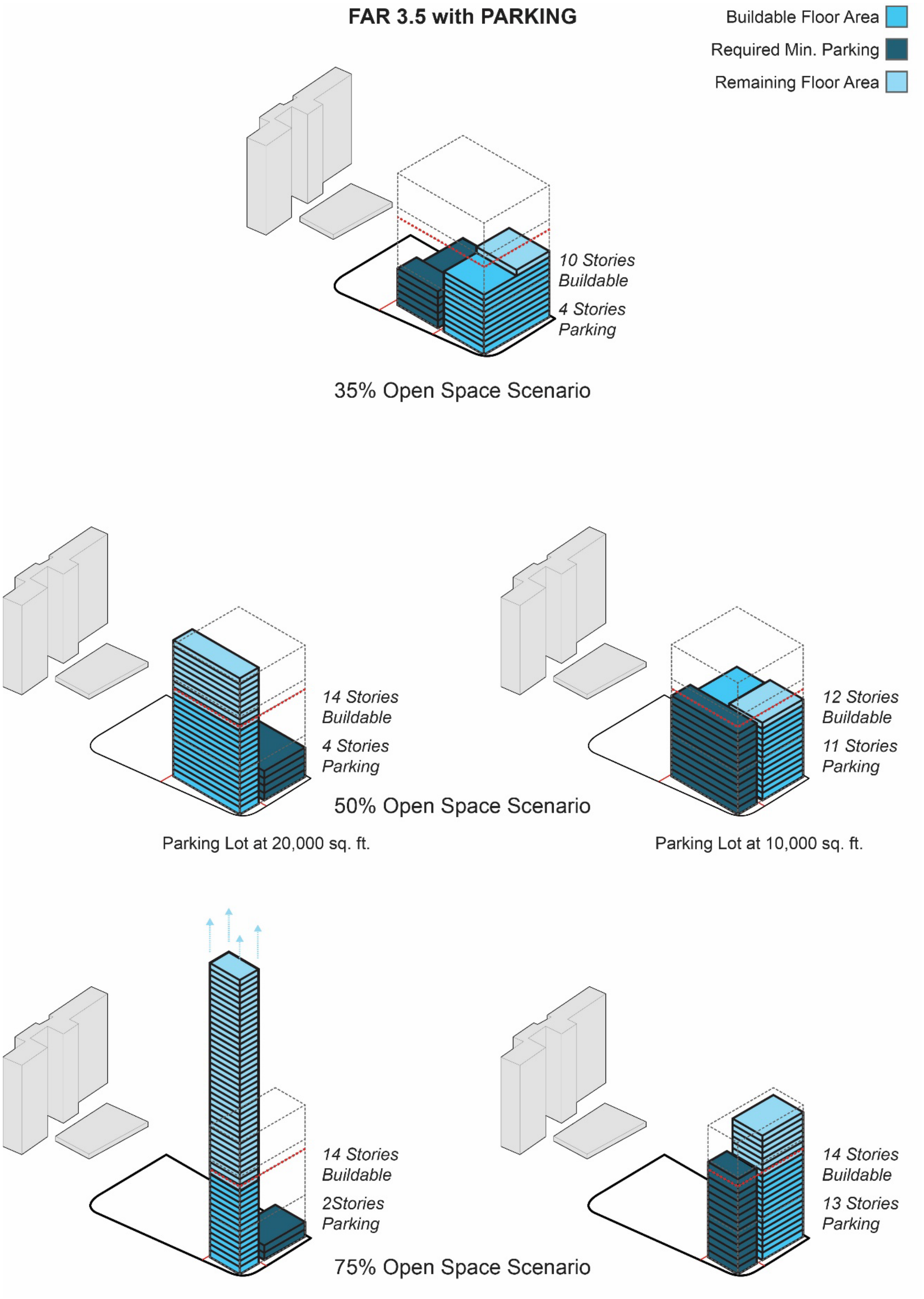

Figure 58: 3.5 FAR Scenario with Parking

Source: Author

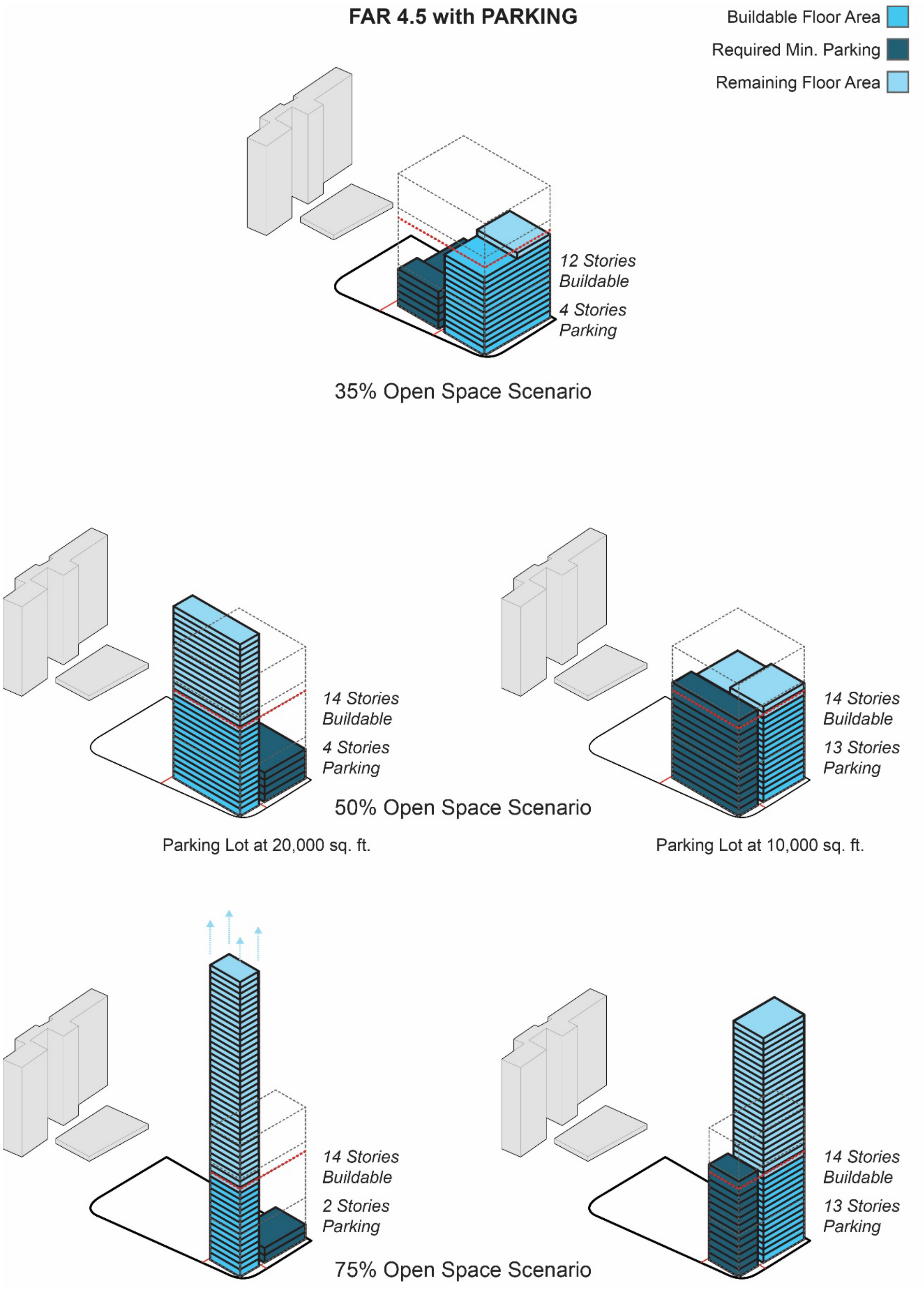

Figure 59: 4.5 FAR Scenario with Parking

Source: Author

The parking requirements added to the site and in reaction to the FAR scenarios blatantly revealed the excessive land use spent on parking alone. Implementing a floor-area ratio of 4.5 was also seen as unsuitable for the site, with most of the allowable building height not being utilized due to site constraints. A 75% open space requirement was also a contributing factor in making the higher FAR unreasonable to pursue, while a 2.5 FAR was deemed not enough to use the lot size efficiently with the height allowances not being reached unless the 75% open space requirement was implemented. To summarize the findings, a 3.5 FAR scenario seemed most reasonable with the building massing reaching an average height between10-14 stories tall. A final FAR scenario was completed with parking resting within the building's lower levels to compare the effectiveness and appropriation between choosing an adjacent parking structure or an included stacked parking structure within the building.

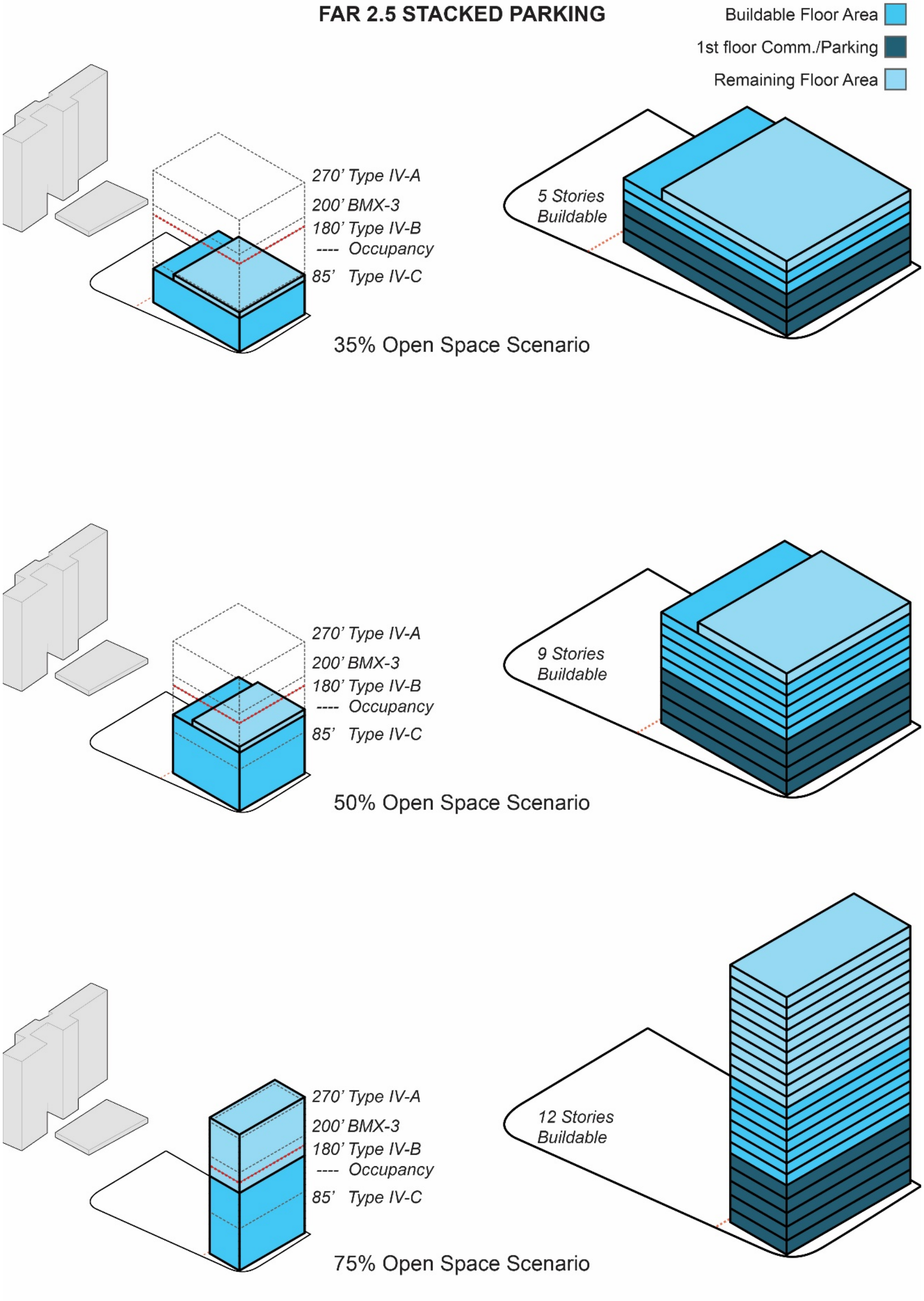

Figure 60: 2.5 FAR Scenario with Stacked Parking

Source: Author

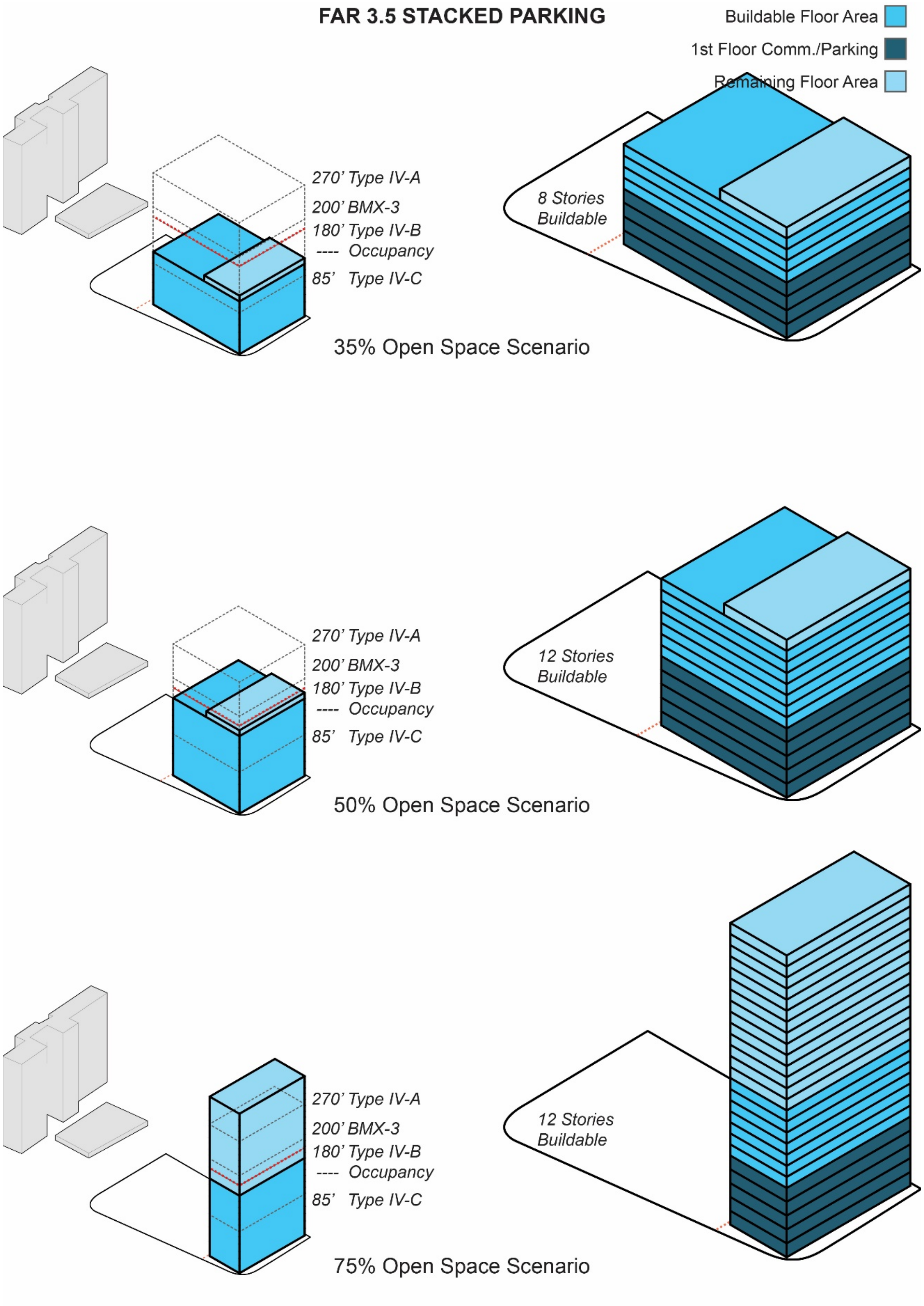

Figure 61: 3.5 FAR Scenario with Stacked Parking

Source: Author

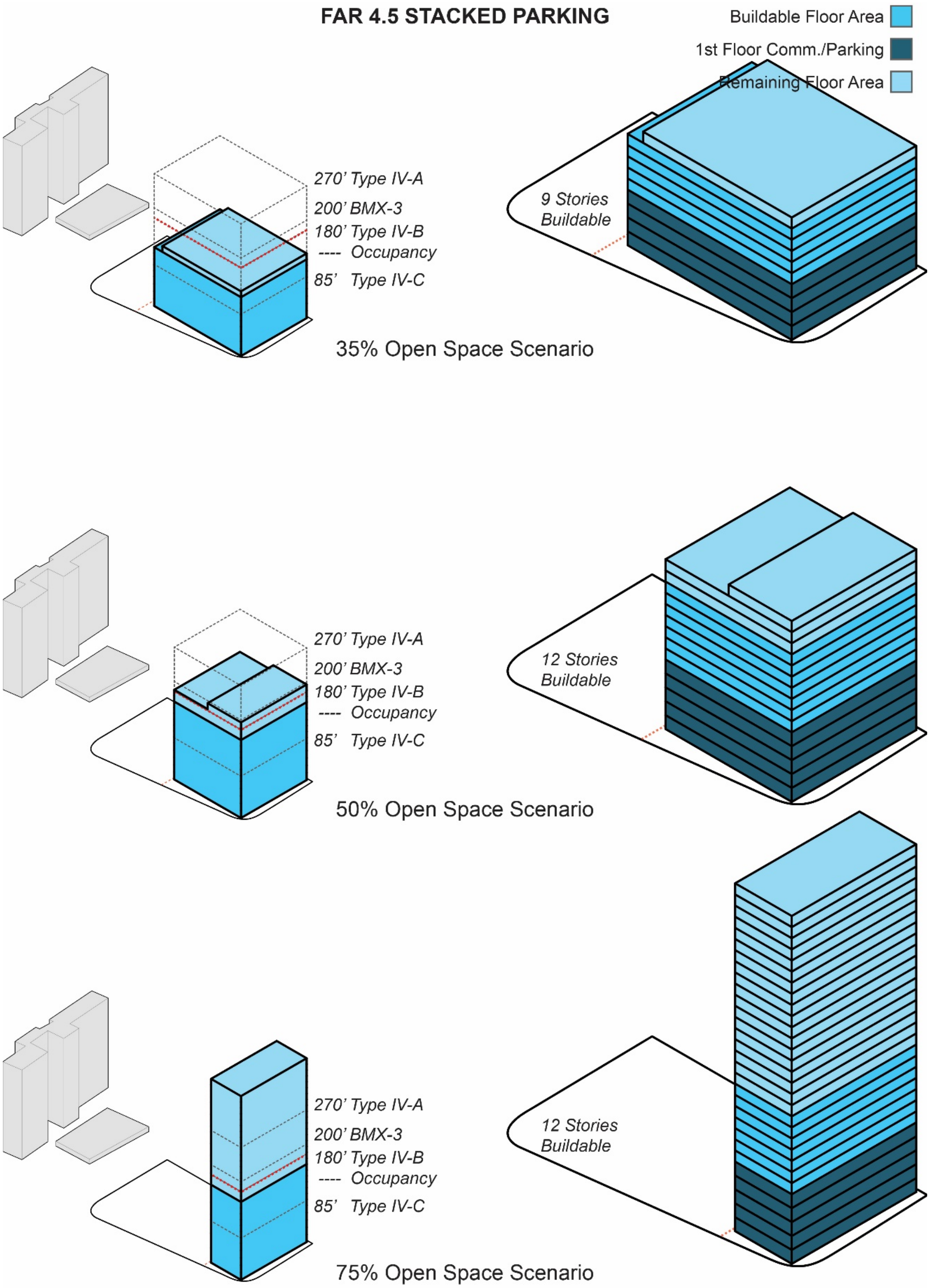

Figure 62: 4.5 FAR Scenario with Stacked Parking

Source: Author

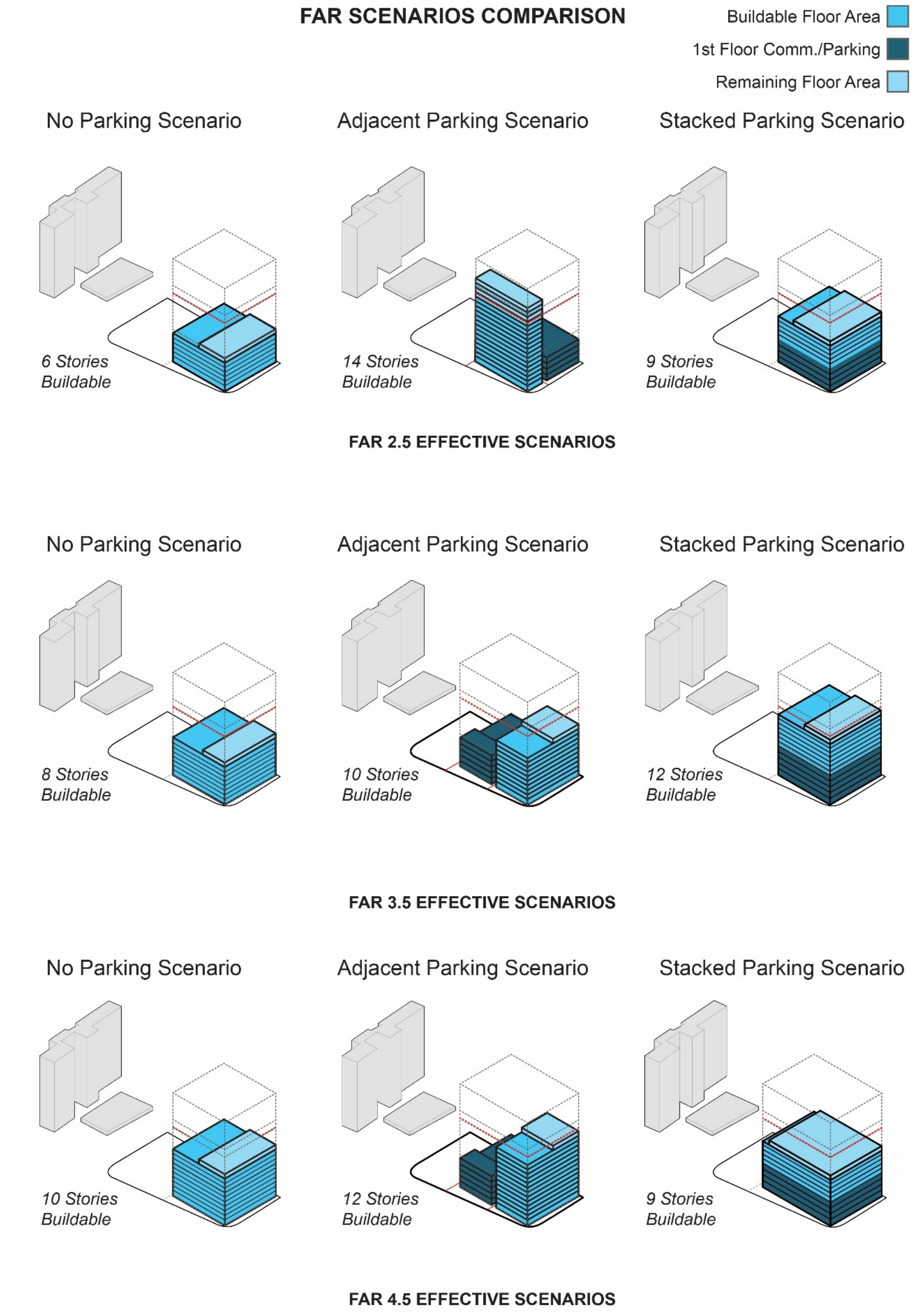

Figure 63: Effective Scenarios Comparison

Source: Author

35% Open, Adj. Park	**50% Open, Stack Park**
Building Lot: 20,695 Ft.2	Building Lot: 31,297 Ft.2
Parking: 4.25 stories	Parking: 5 stories
10 Stories 123’ height	12 Stories 159’ height
53 units each **212 max units Total**	36 units each **252 max units Total**

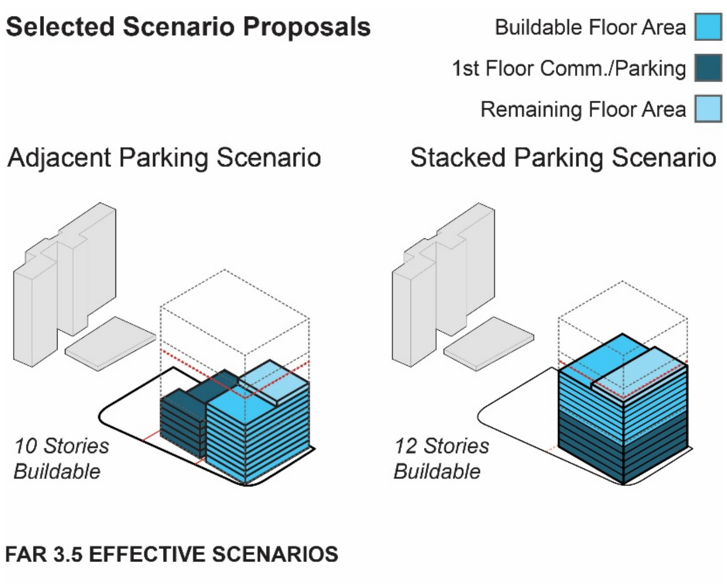

Figure 64: Selected FAR Parking Scenarios
Source: Author

The review of all massing schemes expressed various scenarios that would be effective in utilizing both the given FAR and maximizing the height limit and lot size of the BMX-3 zone. Between the compared scenarios, a FAR of 3.5 was selected as being the most effective adjacent parking massing with 35% open space, and as the most effective stacked parking massing with 50% open space requirements. The selected massing schemes provided a rough estimate of the maximum number of units possible to develop within the given parameters, reaching a maximum of 252 residential units and approaching the height limit. With the Downtown TOD plan highlighting the potential for new construction of 1,500 units in the area as a result of the Chinatown rail station development, the evaluation of efficient construction means and possible unit developments on appropriate sites is necessary for housing development to be successful.

The massing scenario of a 3.5 FAR with 50% open space was then chosen for further development in the design process to explore the stacked parking typology and to begin developing a rigid building. Programmatic issues were then explored including which occupants are being accommodated, and for what reason. To act as a reminder for guiding design principles, an excerpt from the Downtown Honolulu Community Vision is expressed as, “Downtown Honolulu will continue to be the region’s premier employment center with a substantial residential population and easy access to stores and everyday amenities. An accessible and activated waterfront with promenades and community uses, a vibrant, historic Chinatown, and a new high-intensity mixed-use Iwilei district as an extension of Downtown will create a new image for Downtown Honolulu."[128]

Precedents were then studied to determine a suitable program for the building design proposal. A primary example taken into account was the Association of Collegiate Schools of Architecture's (ACSA) Timber in the City competition.[129] A design competition highlighting the use of mass timber for a residential building in Queens, New York, the building typology and proposed program relates to the goals of the building proposal here. A summary of the competition's program is listed below within Table 4, highlighting the residential requirements and overall square footage of the proposed building to compare with the Chinatown site.

Table 4. ACSA Timber in the City Competition Program

PROGRAM COMPARISON	**ACSA TIMBER IN THE CITY**			
Residential	Type	Sq. Ft.	Quantity	Total
	Micro	325	20	6,500
	1 Bedroom	650	20	13,000
	2 Bedroom	850	25	21,250
	3 Bedroom	1,000	35	35,000
Laundry		750	1	750
Lobby/Mail		1,500	1	1,500
Restrooms		300	1	300
Bike Parking		1,500	1	1,500
Bike maintenance		400	1	400
Residential Subtotal				80,200
Mech/Circ Gross		14% Res. GSF		11,228
			Residential Total	**91, 428**
Community Wellness Center				
			Community Wellness Total	**22,713**
Early Childhood Education Center				
			Program Total	**145,406**

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[128] Downtown TOD Plan.

[129] ACSA, "Timber in the City." https://www.acsa-arch.org/competitions/2018-2019-timber-in-the-city/, accessed November 30, 2018.

Developing a clear occupancy type for the proposed prefabricated building was able to be defined after analyzing the ACSA competition brief with other existing residential projects. The final program proposal focuses on accommodating working class families living and working within or near the area of Chinatown, providing an array of single-family unit options including a studio, 1-bedroom, 2-bedroom, and 3-bedroom unit type. With the program guidelines set, design iterations of the proposed building typology using mass timber and modular construction began, attempting to accommodate the proposed 125-units with a commercial ground floor, and required parking spaces taking the lower levels of the structure.

Table 5. Proposed Building Program

Program Proposal for Chinatown Residence					
Residential	Type	Sq. Ft.	Percentage	Quantity	Total
	Studio	400	10%	15	6,000
	1-Bedroom	600	15%	20	12,000
	2-Bedroom	800	50%	60	48,000
	3-Bedroom	1100	25%	30	33,000
				Subtotal	**99,000**
Commercial	Retail/Local Business	500	60%	24	12,000
		1000	40%	8	8,000
				Subtotal	**20,000**
			15% Mech/Circ		17,850
				Program Total	**136,850 ft2**
				Unit Total	**125**

7.5 Designing Hybrid M3

The advancement of accessible construction techniques to all major urban areas provides exciting opportunities to incorporate them into building design and exploit the beneficial attributes of each method used. Following the codes and proposed program for the building as discussed in earlier sections, the final design proposal named, “Hybrid M3,” is a mid-rise modular mass timber project using hybrid modular design strategies to expand the prefabrication methods for appropriate adaptation within Hawai‘i’s local context. The structure embodies the benefits of prefabrication, experimenting with modular construction and using a variation of the module to allow for greater flexibility while complementing the mass timber structure. Hybrid M3 adheres to Hawai‘i’s building codes and LUO while also following the updated IBC 2021’s Type IV construction codes to express the feasibility constraints and necessary requirements of mass timber construction. The design exercise has expressed the regulations of CLT for increased safety as well as showing the ongoing research revolving around the material properties and long-term effects of mass timber. As the research continues to be pushed and mass timber is further developed, this design proposal hopes to promote its use by joining it with modular construction strategies and act as an example for widespread prefabrication use in the construction industry’s near future to ultimately meet the rising challenges and demand brought on by goals stated in Architecture 2030, the UN Paris Climate Agreement, and Hawai‘i’s 2045 Clean Energy Initiative. The overwhelming benefits of prefabrication and mass timber will continue to advance the construction industry’s future development, with Hybrid M3 as one example expressing a feasible and alternative form.


Figure 65: Exposed Modular System

Source: Author

7.5.1 Mass Timber Structure

The utilization of mass timber as the primary structure for the design proposal was decided upon the research of the material as a beneficial option to constructing in Hawai‘i and is performed here to show the tangible possibilities of mass timber throughout the islands. There are many existing options to constructing with mass timber, with building examples throughout Europe using little to no foundation, and the unnecessary implementation of a concrete podium resulting in building weights being reduced to 1/6th of a conventional structure. Cases of using mass timber as a composite structure with steel and concrete, or as a solely mass timber structure, also exist and showcase the structural methods used. In reaction to the Downtown Honolulu’s TOD plan and LUO, the primary mass timber structure of Hybrid M3 is framed as a 12-story building with 180’ height limit to meet IBC 2021’s Type IV-B requirements, and allow for some interior exposure of the mass timber structure within the residential units. Included with this parameter, Hybrid M3 lies within Hawai‘i’s BMX-3 zone involving parking requirements for each residential unit and set commercial spaces. Considering these various factors and local context, the project explores a hybrid structure of concrete podium and parking structure for the first five floors connected by the mass timber CLT panel construction for the seven floors resting atop the podium.

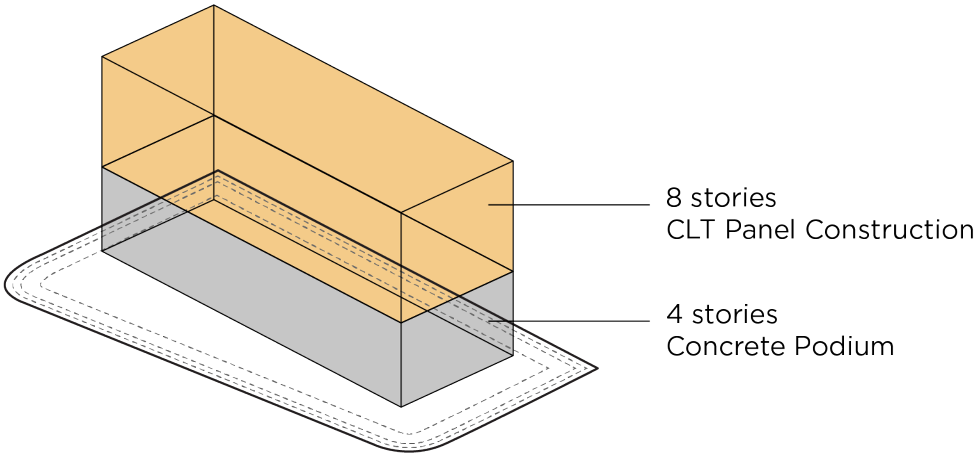

Figure 66: Structure Concept

Source: Author

The combination of materials and construction methods imply increased safety of the CLT structure from fire, weathering, moisture, and termites, being offset from the ground by four floors of concrete while accommodating parking for 144 residences with an additional 81 stalls towards commercial use for a total of 225 parking stalls. The contrast of wood and concrete is also used to highlight the structure as a landmark for the Chinatown community. CLT is used as the main type of mass timber, taking advantage of the benefits of CLT's structural qualities which make it the most popular mass timber type in buildings. A mixture between CLT columns and shear walls are also interchanged throughout the structural grid to accommodate programming when appropriate within the floor plan. To ensure overall safety and stability, the 7-ply CLT panel was chosen for the structure's floor and wall panels with 1-ft columns implemented throughout the 21-ft x21-ft centerline grid that the building follows throughout its form, allowing for the spacing between the panels to be a flush 20 feet for the module system to be integrated with effectively.

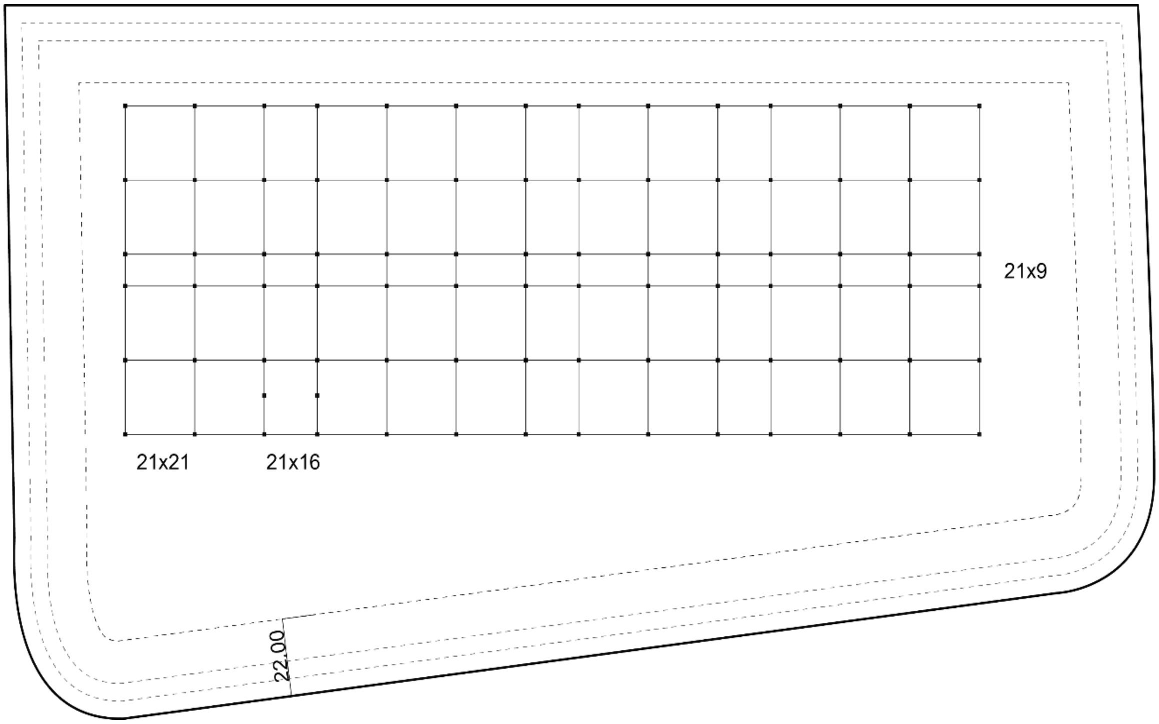

Figure 67: Structural Grid

Source: Author

7.5.2 Hybrid Light Module

The process of using modular construction with mass timber evolved through multiple iterations, resulting in the decision to develop a distinct module for this residential building design. Specified as a "light" module throughout this project, it distinguishes itself from conventional modules used in modular construction by breaking up the standard finished module into smaller pieces. In doing so, the light system module attempts to resolve multiple issues at once.

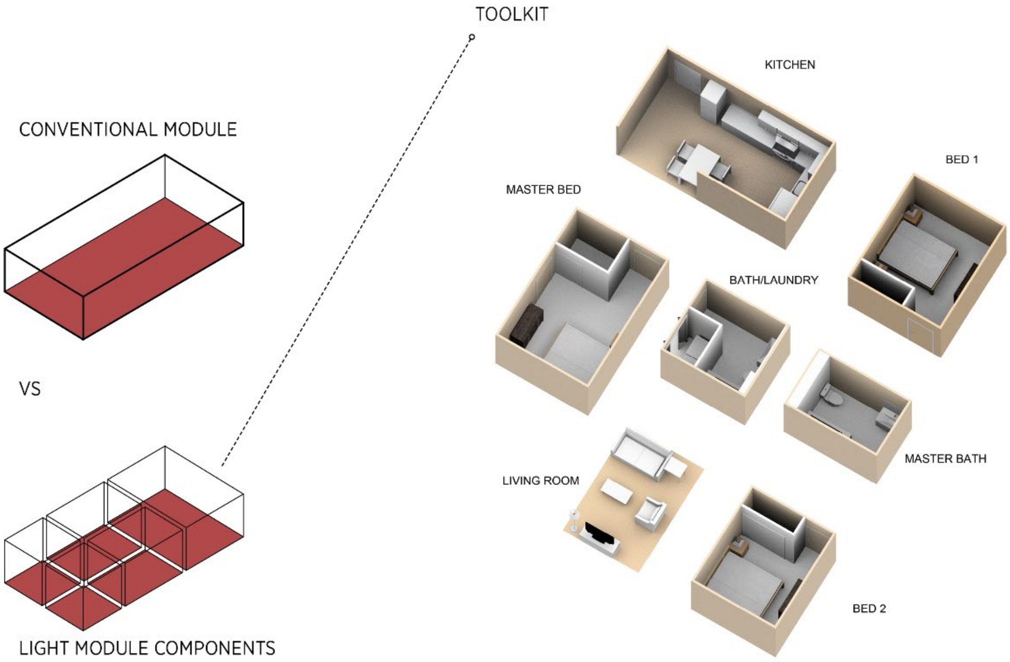

Figure 68: Light Module Toolkit
Source: Author

As expressed in Figure 68, the conventional module typically used throughout the U.S. and in previous case studies is broken down to complement the mass timber structure. Instead of adhering to current modular construction techniques where the module is 95% prefinished, structural, and represents an entire room unit or half-unit waiting to be stacked together, the light modules proposed for this design are non-structural. Allowing the modules to be non-structural addresses a major issue in current modular construction methods which have a redundancy of floor and wall thicknesses, doubling both sides when stacked atop and beside each other. In this building proposal, the CLT panels are the main structure and constructed first using its prefabricated panel and assembly system, with the light modules being placed into the building after a floor or multiples floors are complete.

In addition to addressing excess material, the non-structural walls and floors of the module are built with a light-gauge steel frame to hold the cabinetry and furniture within, while being 95% constructed prior to on-site assembly. More importantly, the light module itself covers the mass timber interior structure when snapped into place, ensuring that the IBC Type-IV construction requirements of only being allowed to expose 20% of ceiling area and 40% of interior wall area are adequately met. The light modules act as the fire protection layer for the mass timber structure while being prefabricated off-site and assembled on-site, reducing construction time, labor intensity, and material waste.

For the building, seven varying types of light modules were developed to meet the program parameters of accommodating the proposed studio, one-bedroom, two-bedroom, and three-bedroom unit types. The light modules were categorized by the spatial aspect of the unit, including a standard kitchen module, living room module, bathroom module, and three types of bedroom modules with a master bath component attached to the master bedroom. The varying types of light modules promote flexibility of unit organization within the space as well as standardizing transportation methods and increasing overall ease of transport with a smaller sized module that can fit within typical shipping containers and loaded atop semi-trucks for site assembly. This was developed as a result of analyzing the previous modular case studies, with high regard put upon the study of Connect Homes' modular construction firm, and the issues pointed out of existing modular design practices often oversizing their units and maxing out dimensions to meet higher spatial demand, but ultimately causing transportation issues and increasing overall cost of construction.[130]

A complementary result of breaking the module units down into smaller, lighter units is the potential for flexible building layout and design. Highlighted in the floor plan of Figure 69, the light modules act as the main component and driving force of the overall design organization. They're expressed clearly in contrast to the residential unit types to express how the modules can align in varying degrees to produce unique and distinct unit

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[130] https://www.core77.com/posts/44632/How-to-Fix-Prefab-Architecture-Make-It-More-Like-Product-Design

layouts upon demand and appropriate context. As such, Hybrid M3's form and floor plan it follows is only one example of how the modules can be organized and placed together. For the building's program requirements, three light modules are assembled to form one studio unit type, while all seven modules are used to assemble a single 3-bedroom unit type. There are eighteen residential units per floor, with 104 light modules used on each floor to assemble the room types, giving a total amount of 728 light modules established throughout the building. The seven varying light modules used can continue to grow from each other to make larger units with differing bedroom sizes or micro-units utilizing necessary amenities and implying the greater potential use of the modular system developed for Hybrid M3.

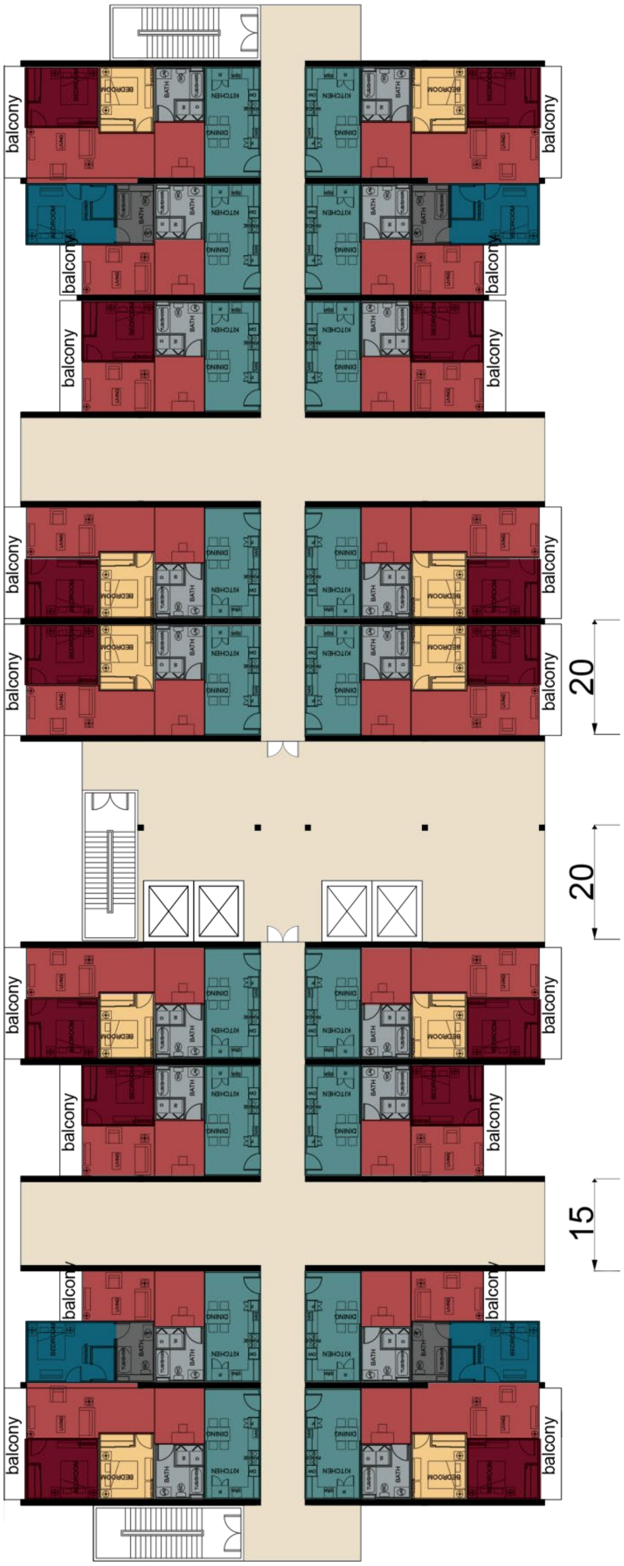

Figure 69: Typical Floor Plan

Source: Author

7.5.3 Assembly On-Site

The construction process for Hybrid M3 first takes place off-site in a controlled environment to prefabricate the mass timber panels and light modules. With the majority of the fabrication taking place in factories, 95% of the construction is complete before reaching the site, and the remaining construction takes the form of assembling the panels and pieces into the building form. The mass timber panels are pre-cut to the specific dimensions required for the structure while the light modules are prefabricated with complete interior finishes.

Assembling the light modules on-site differ from typical modules. A mobile module mover is proposed to help transport the modules from factory to site. Acting as a large jacking platform, the module mover can carry the module from factory to truck bed and unload it to the site for crane hoisting. In order to do so, the light modules that are prefabricated with a steel frame and finish decking, have an additional steel pallet platform system which it rests upon using sufficient spacing to allow the module mover to roll underneath and pick it up and carry the pieces into place.

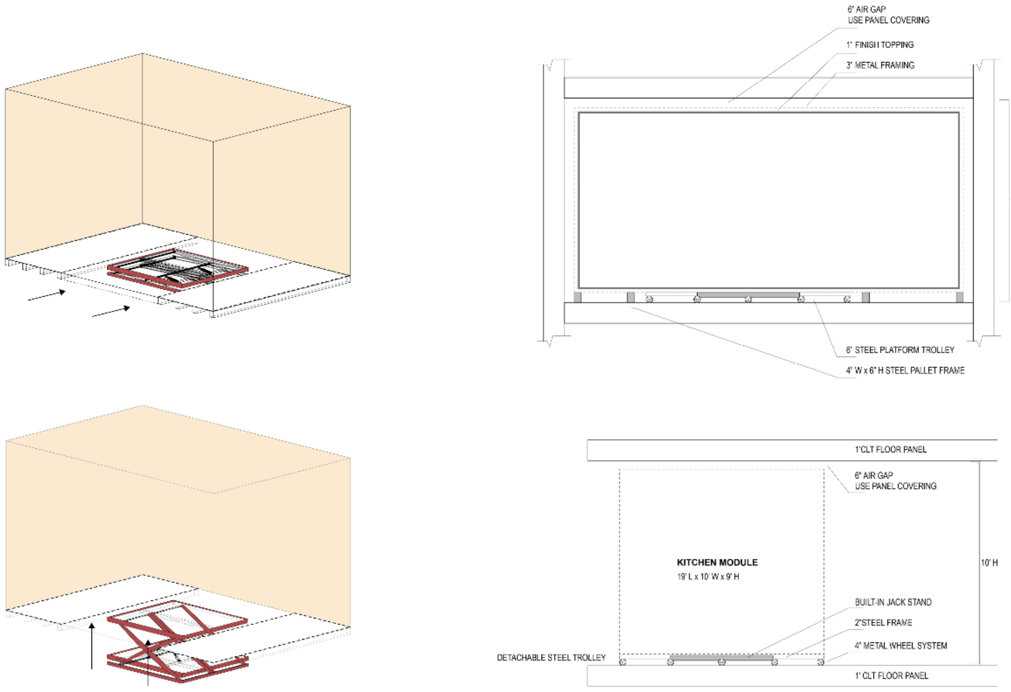

Figure 70: Module Mover

Source: Author

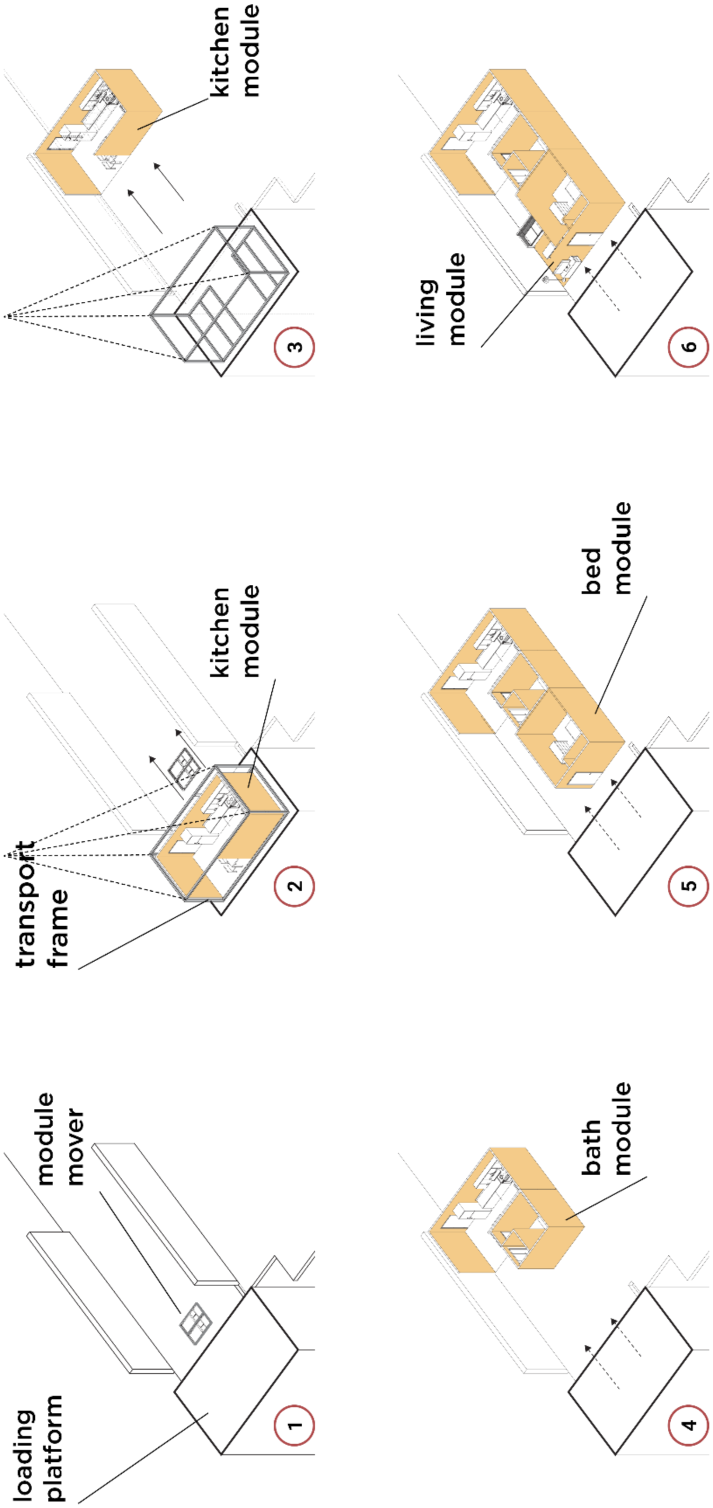

Figure 71: Unit Assembly with Light Modules

Source: Author

The use of the module mover and steel pallet system allows for the light modules to be easily transported both to the site and during the final assembly process within the building. The module mover works with the crane on-site hoisting a reusable, detachable 23’ x 23’ steel frame that carries the structural load of the modules during transportation from the truck bed to the elevated loading platform externally attached to the completed mass timber floors. As expressed in Figure 71, the module mover is reusable and repeats the loading and unloading steps with the crane and detachable steel compartment to carry each light module and safely place them within the 20’ width space bordered by CLT wall panels organizing the unit size. Each light module is rolled, placed, and snaps with other module panels to create a finished and assembled unit type. The modules efficiently work with the mass timber structure by removing unnecessary structural redundancy while still taking advantage of the module’s benefitting 85-95% completion ratio and using the non-structural walls, ceilings, and floors of the light module to safely cover and protect the CLT structure, meeting the IBC 2021’s code of having interior wall spaces fire-protected with non-combustible materials. The light modules also take advantage of the CLT panels’ properties such as the floor and wall panels being thinner than other structural shear wall options and eliminating additional protruding beams taking up ceiling height due to the panels’ cross-laminated structure.

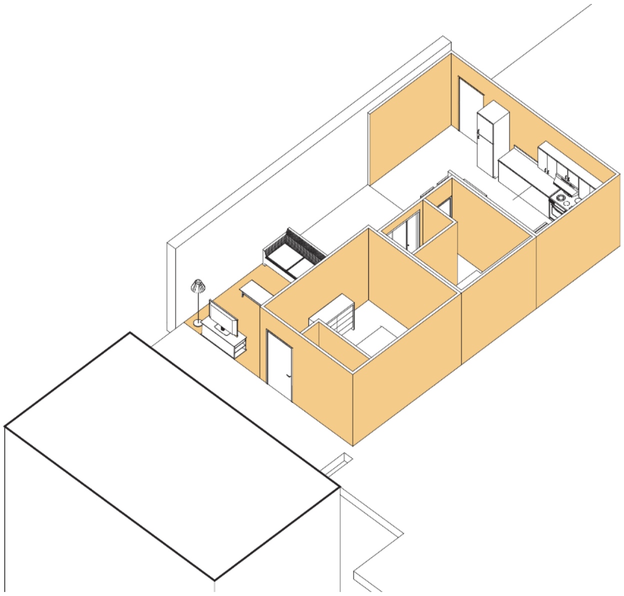

Figure 72: 1-Bedroom Assembled Unit

Source: Author

7.5.4 Connections

Consideration of the connecting components between the modules themselves after placement were analyzed and went through design iterations before resolving the issues of rigidity, stability, and efficient use of material. Since the light modules are non-structural, it was critical to use only the material necessary to hold itself up and protect the finishes and furnishings within the module. Invasive screws and bolts that could damage the finishes after placement were considered high-risk and unnecessary for solely keeping the modules in place and flushed against each other, not needing to support or carry heavy loads. In addition, the modules' walls and floors flatly residing adjacent to each other raised challenges of determining the placement of connection joints.

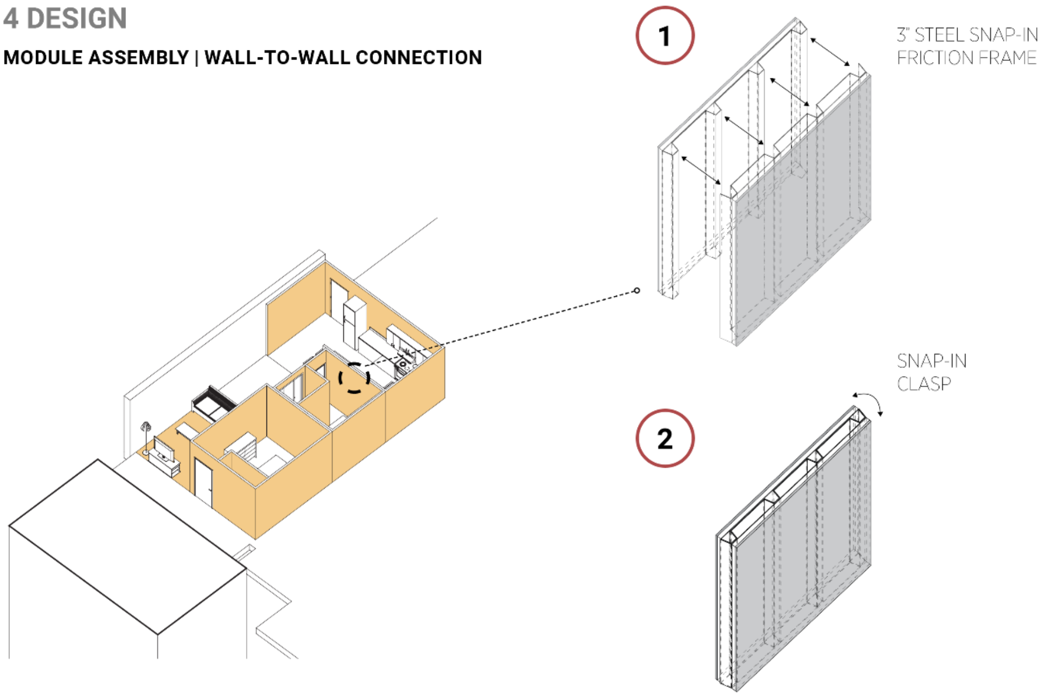

Figure 73: Module Wall-to-Wall Connection

Source: Author

Analysis of the steel frame supporting the light module and construction methods regarding it revealed the existing use of steel friction frames to snap into place different components with each other. The proposed connection pieces for the light module scales up the snap-in friction frame to act as the primary connection system for the modules. The relating Figure 73 and Figure 74 express the 3-inch steel frame jutting out from the module where the wall panel will meet another module. The teeth-like and hollow steel C-framing are pushed together with the module mover and snap as one to become a rigid, whole module. The details shown in Figure 75 distinguish the floor and wall connections, with the floor connections following the same snap-in principal while flipped horizontally to accommodate the shape.

The snap-in-place friction frame was chosen above other options for its efficient use of material and emphasis on keeping the modules intact and stable without over-structuring the support system and connection joints. The snap-in frame also addressed the floor and wall panels being flush with each other, which prevented standard floor connection systems using a long screw drilled through the overlapping center of the panel from being pursued. The wall resting directly above the floor pronounced difficulty for connecting the screw and bolts through both the walls and floors at a conventional angle. The snap-in frame has proven ideal for this system of light modular placement and non-load bearing connection points.

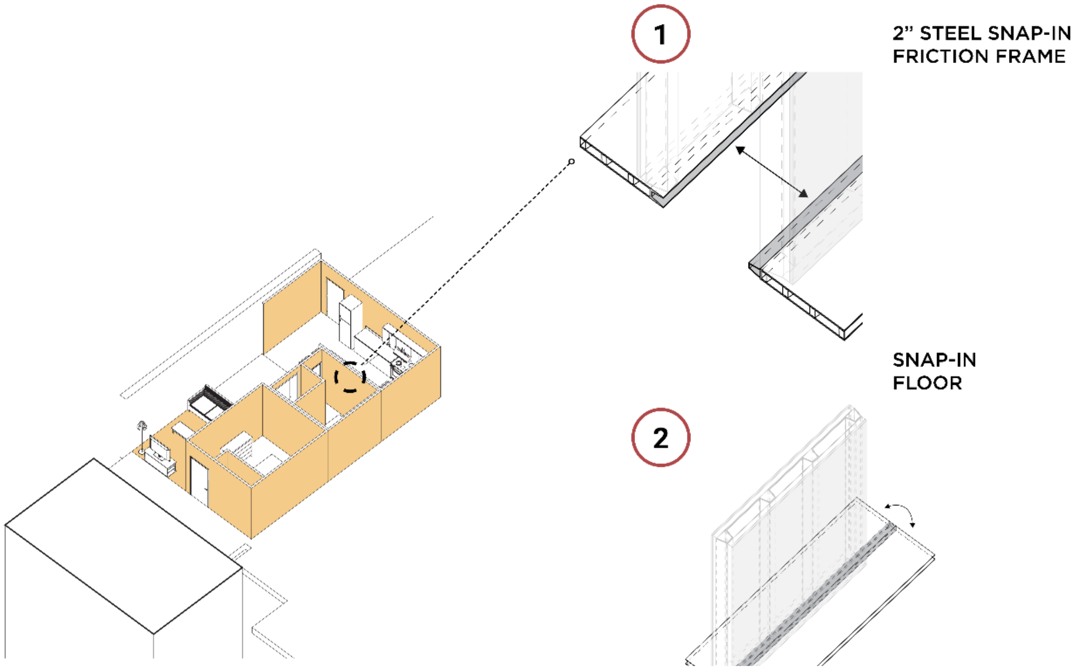

Figure 74: Module Floor-to-Floor Connection

Source: Author

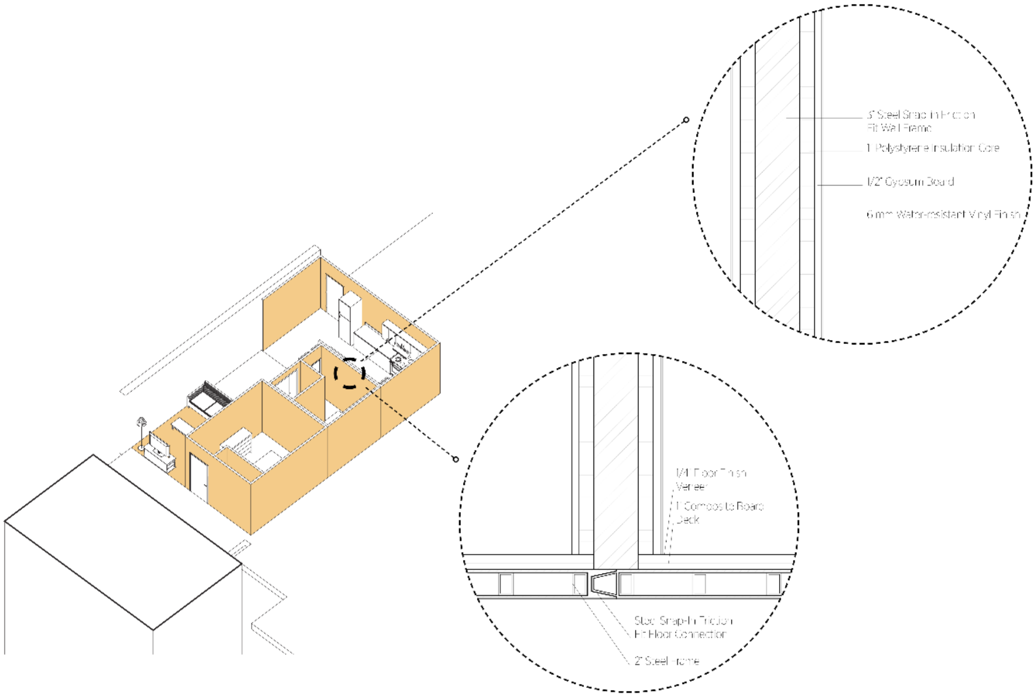

Figure 75: Module Connection Details

Source: Author

7.5.5 Building Form

Critical processions of research and design iterations gave rise to Hybrid M3's form that tackles the issues of mass timber, modular construction, and building codes while emphasizing the benefits of using the recently developed prefabrication methods. The building envelope as mentioned before is a hybrid design using a concrete podium with the mass timber structure resting above and finished using light modules that slide into the structure to complete assembly of the residential units. The resulting building has a distinct form and works with different systems to meet the program requirements and construction opportunities.

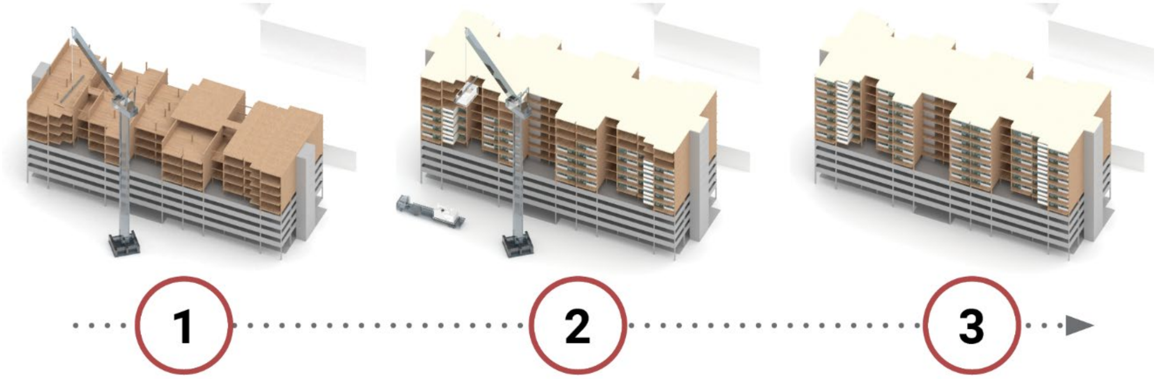

Figure 76: Building Form Construction Process

Source: Author

Following the grid throughout the building, the ground floor is open to commercial space with the central core containing the lobby space and main vertical circulation. The façade of the building grows from the modular construction form and acts as a tool for implementing greenery throughout the structure. The following renderings from Figure 77 to Figure 79 show the unit railings of the balconies also acting as gardening screens with the main feature of the façade being the green fins vertically cutting the building in half to emphasize the double height public space feature for every other floor as a communal gathering space that can be used by the community. The public space and green screens implemented complement the structure to allow for the users to reconnect with mass timber's natural state and the green spaces of A‘ala Park.

Figure 77: Exterior Building Perspective

Source: Author

Figure 78: Interior Public Space Perspective

Source: Author

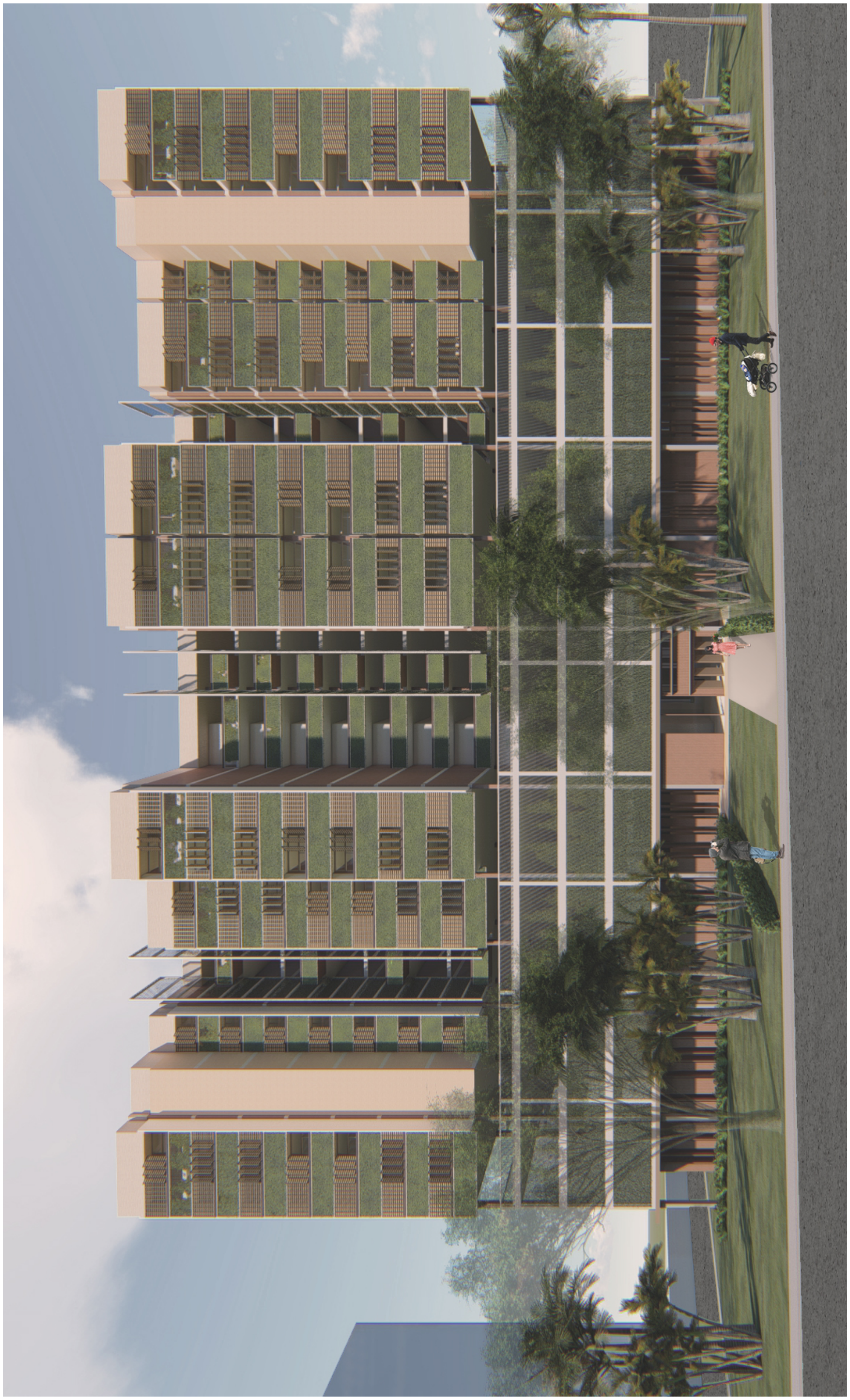

Figure 79: Elevation Building Perspective

Source: Author

7.6 Design Review

The building design proposal’s unifying goal has been to apply the learned systems of modular construction and mass timber towards Hawai‘i’s context. The hybrid design was explored in order to evaluate the benefits and challenges of using these recent prefab developments together on-island to potentially mitigate current housing and climate issues. The selected downtown Honolulu site and building footprint adhered to Hawai‘i’s building codes while also following the upcoming 2021 IBC to frame a realistic portrayal of a locally constructed mass timber building form.

Reflecting upon the design parameters set by Hawai‘i’s TOD plan and LUO, the Hybrid M3 building model successfully adheres to the many regulations affecting the site and building, including a 50% open space requirement, which is complemented by the vertical green fins and screen railings to visually interact and connect with A‘ala Park which it directly faces. Implementing a 3.5 FAR, Hybrid M3 reaches a maximum height of 142 feet to stay within the 180 ft. limit. The square footage per floor is 22,858 square feet, making a total residential and commercial ground floor area of 182,864 square feet with an added four floors of parking to accommodate the 225 stalls for both residents and retail space. The 182,864 sq. ft. building is more than the anticipated program floor area of 136,850 sq. ft. However, Hybrid M3 was able to accommodate more units than previously thought, providing 144 residential units as compared to the planned 125 room types, while also remaining below the max 3.5 FAR of 250,376 sq. ft. floor area.

Hybrid M3 sets a precedent notion of buildings using mass timber and modular construction to evaluate the benefits and costs of implementing such design and prefabrication strategies. The combination of mass timber and light modular design reveals the status of mass timber being a structurally sound and practical material for different building heights and typologies, and modular construction having the increasing capability of crossing building scales. The implications of light modules used with mass timber and other structural forms can be further explored within the near future as well as being used in different building types Hybrid M3’s utilization of both methods pushes the envelope of current practices and exposes the nature of prefabrication having as havng the ability to construct an all-rise building.

8. Moving Forward

8.1 Research Parameters

The body of research collected to this point has acknowledged the rising trend of prefabrication methods taking hold of the construction industry. The evaluation of two recent developments known as modular construction and mass timber construction was chosen to explore their implied future use in Hawai‘i as positive alternatives to local construction. Modular construction, becoming more of an established method of building practices in recent years was first seen as a viable method of construction in Hawai‘i to explore further, known for its quick assembly, efficient prefabrication, and the pre-finished module sizes could potentially cut material costs and ease transportation issues when following a standardized size. However, with in-depth analyses, issues regarding the use of modules and building modular exposed common challenges such as the doubling of structural materials per individual unit when assembled, increased transportation costs with oversized dimensions, and steel being the main choice of material for modular units in the U.S., a material not locally available in Hawai‘i. The research then began to view the use of mass timber as a possible complement to modular construction in order to resolve internal issues commonly found with modular construction.

Mass timber construction has developed rapidly, with many advocates supporting the new structural material for its inherent properties that are seen as a powerful asset to combating environmental issues and giving stakeholders of the built environment a tool to directly counter buildings’ known 40% contribution to global carbon emissions. The research gained traction on the possible implementation of mass timber in Hawai‘i alongside modular construction methods, with the new revisions of the IBC acknowledging mass timber as a main construction type and setting guidelines to follow when using the material for different project types. The updated International Building Code, then, became a main influence of the building proposal resulting from the gathered research highlighting mass timber and modular design as preferred methods of prefabrication and plausible construction methods for Hawai‘i.

The use of the revised IBC 2021 as a primary guideline to follow helped ground the building design proposal with real-world constraints that was beneficial to the compiled investigation moving forward with feasible arguments for implementing mass timber construction throughout the islands. Doing so, though, also limited the experimentation of both prefabrication methods' potential future forms and evolution. In addition to the IBC, local codes were also followed, giving apparent site constraints, and building form limits regarding both floor area and max height. These limitations overall provided authentic rules for the research and design proposal to react to accordingly and give a plausible glimpse of modular mass timber construction in Hawaiʻi. Consequently, the building design's conventional form in the final proposal should be noted as not a reflection of modular construction and mass timber's internal limitations, but as being influenced by the current building codes and the decided approach of designing for working families.

The outcome of adhering to the available building codes and regulations when designing with modular and mass timber construction, has led the research and design to propose an alternative building typology seen as a hybrid form. The resulting Hybrid M3 structure attempts to effectively bridge modular design with wood to propose a mid-rise building in Honolulu, while typical modular wood construction has been limited to low-rise structures. The development of proposed light modules is expressed as a possible alternative form for modular construction to improve efficiency and flexibility. In this case, the light modules work with mass timber to reconcile issues both methods currently face while maximizing the benefits from combining the prefabrication types together. As discussed earlier, the light modules could be developed by relying on mass timber as the building's primary structure. By being non-structural, the modules could be transported easily, following standardized, more mobile dimensions, and could then be placed within the mass timber structure to protect the engineered wood and meet fire safety standards that mass timber faces. The building design proposal researched and experimented upon concludes with the argument that implementing a hybrid method of construction as proposed is both feasible to do and could greatly benefit modular and mass timber construction by combining the two methods to improve efficiency and speed of construction, while taking advantage of the environmental benefits of using a renewable resource that could locally-sourced in the near future.

8.2 Evolving Prefabrication Methods

The research and design proposal expressed within this body of work is but one example of the possible alternatives to current construction methods in Hawaiʻi and other major urban hubs. It begins to ask the question of what the future of building and the construction industry as a whole looks like when facing the encompassing challenges and offers glimpses into what can potentially be provided as a building form The discussion of future buildings being quick to assemble, sustainable, and experientially appealing to its users can be pushed further while still serving the needs of the building program. The construction industry is already beginning to react to the pressures of sustainability as well as economic constraints to build faster, cheaper, and cleaner structures. Within the last twenty years, to counter carbon emissions and overall waste, prefabrication has evolved and branched into modular construction, panel, and kit-of-parts construction, while standard construction materials have expanded to include wood as a viable option for low, mid, and now high-rise buildings. These emerging methods and materials will allow modular design to be increasingly versatile and incorporated into the design process as an inherent asset to the architect's toolkit. As shown throughout the body of work, prefabrication, and the continuous evolution of its methods of construction solidify its placement at the head of efficient construction practices being adopted throughout the building industry. The increasing use of modular design and construction for buildings explicitly represents the outweighing benefits of the emerging construction methods against current conventional ones. The excess waste, pollution, and carbon emissions of mainstream construction practices can be offset with modular construction's inherent benefits. Building off-site within controlled factory environments allows for precision of building components and overall quality control, increased safety of workers and reduced labor costs, with fast, efficient fabrication and assembly.

Building upon modular systems and construction, this research has proposed the development of light modules as an alternative form of modular construction, which has potential to be developed and scaled further. By choosing this option, modular construction's flexibility and accessibility to faraway sites can be greatly increased and can overcome module units' inherent challenges such as redundancy of structural walls and floors, the rigidity of form, and the structural assembly obstacle of being carried by a crane on-site. Moreover, the light modules proposed was made to work with Hybrid M3's structure and mid-rise residential program. Light modules, and the use of mass timber, though, have the potential capability of being scaled to meet all building typologies and sizes. The light modules' ease of transportation benefits and microscale could be used for future refugee sites and designing temporary structures while the continuous advocacy and research on mass timber will keep increasing the height limits of the material to match that of concrete and steel across all fronts, providing wood high-rises in the next few years.

The urban built environment experienced today will undoubtedly change and transform into unfamiliar structures within the next five, ten, and twenty-five years in order to meet rising demands brought on by social, economic, and spatial pressures. It must to meet the United Nations' goals highlighted within the Paris Climate Agreement. The construction industry will also need to drastically adapt to meet Architecture 2030's mission, and on a local scale, to meet the state of Hawaiʻi's 2045 Clean Energy Initiative. To build effectively and sustainably, architects and all stakeholders of the built environment need to promote and support the emerging building methods that are addressing the carbon emissions crisis

Two goals attempting to be fulfilled within this body of work has been to analyze where does currently evolving prefabrication techniques stand and which of these methods appropriately benefit Hawaiʻi and its unique urban context. The second intention offers what an alternative housing model in Hawaii could soon be when exploring the newly approved construction type of mass timber and applying it with modular construction. The development of the light modules is this work's own proposal for alternative construction methods that continue to build off developed prefabrication methods. Innovations and experimentation of housing is in need now with the current projection of Hawaiʻi's housing needs illustrated in the 2015-2025 report expressing the sensitive time constraints of building quickly to support Honolulu's residents within the next five years. Combined with mass timber's fast production and assembly, with some mid-rise projects taking only a few weeks to complete and needing 4-5 laborers on-site, show the far-reaching benefits of the construction material while simultaneously being environmentally conscious. Though the exact percentages of wood and trees' carbon sequestering rates vary depending on differing data, the notion of mass timber as a feasible construction material repeatedly proven and the U.S. is ready to take advantage of it. The 2021 International Building code will take into effect by the end of 2020, solidifying mass timber as both a structurally sound material and a competitive alternative to steel and concrete. A new reign using emerging prefabrication methods such as potential light modular design, mass timber construction, and other sustainable construction methods for structures begins now with the turn of the decade.

Appendix

Floor Area Ratio Sizing Tables

Table 6. FAR Scenarios with Parking Exemption

Site	1332 Aala St. 19,857 ft2	300 N. Beretania St. 42,738 ft2	Total Lot Size: 62,595 ft2 BMX-3 Zoning 200' height limit 15' height comm. 12' height res. Occupancy height limit: 180'	FAR Bonus: exceed min. open space: 1 ft2 open = +5 ft2 floor area
FAR	**Allowable Floor Area**	**Public Open Space**	**Allowable Building Height**	**Allowable Building Area**
2.5	156,487.5 ~156,480 ft2	Min. 35%: 21,900 ft2	40,690 ft2/floor 3 stories, 39' height	122,070 ft2
		50%: 31,290 ft2 (+9390 ft2 open= +46950 ft2)	31,300 ft2/floor 6 stories, 75' height	187,800 ft2
		75%: 46,940 ft2 (+25,040 ft2 open= +125,200 ft2)	15,655 ft2/ floor 14 stories, 171' height	219,170 ft2
3.5	219,082.5 ~219,080 ft2	Min. 35%: 21,900 ft2	40,690 ft2/floor 5 stories, 63' height	203,450 ft2
		50%: 31,290 ft2 (+9390 ft2 open= +46950 ft2)	31,300 ft2/floor 8 stories, 99' height	250,400 ft2
		75%: 46,940 ft2 (+25,040 ft2 open= +125,200 ft2)	15,655 ft2/floor 14 stories, 171' height	219,170 ft2
4.5	281,677.5 ~281,670 ft2	Min. 35%: 21,900 ft2	40,690 ft2/floor 6 stories, 75' height	244,140 ft2
		50%: 31,290 ft2 (+9390 ft2 open= +46950 ft2)	31,300 ft2/floor 10 stories, 123' height	313,000 ft2
		75%: 46,940 ft2 (+25,040 ft2 open= +125,200 ft2)	15,655 ft2/floor 14 stories, 171' height	219,170 ft2

Table 7. FAR 2.5 Unit Availability with Parking Exemption

FAR 2.5: 156,480 ft2							
	Allowable Building Area	Open Space at 35%: 122,070 ft2		Open Space at 50%: 187,800 ft2		Open Space at 75%: 219,170 ft2	
	15% Mech/Circ	18,310.5 ft2		28,170 ft2		32,876 ft2	
	Commercial Floor Area	40,690 ft2		31,300 ft2		15,655 ft2	
	Allowable Built Residential Area	63,070 ft2		128,330 ft2		170,639 ft2	
	Allowable # of units	**all**	**equal**	**all**	**equal**	**all**	**equal**
Average unit sizes	studio 400 ft2	157	22	320	44	426	58
	1-Bed 600 ft2	105	22	213	45	284	58
	2-Bed 800 ft2	78	21	160	44	213	58
	3-Bed 1100 ft2	57	22	116	44	155	58

Table 8. FAR 3.5 Unit Availability with Parking Exemption

FAR 3.5: 219,080 ft2							
	Allowable Building Area	Open Space at 35%: 203,450 ft2		Open Space at 50%: 250,400 ft2		Open Space at 75%: 219,170 ft2	
	15% Mech/Circ	30,517.5 ft2		37,560 ft2		32,876 ft2	
	Commercial Floor Area	40,690 ft2		31,300 ft2		15,655 ft2	
	Allowable Built Residential Area	132,242.5 ft2		181,540 ft2		170,639 ft2	
	Allowable # of units	**all**	**equal**	**All**	**equal**	**all**	**equal**
Average unit sizes	studio 400 ft2	330	45	453	62	426	58
	1-Bed 600 ft2	220	46	302	63	284	58
	2-Bed 800 ft2	165	45	226	62	213	58
	3-Bed 1100 ft2	120	46	165	63	155	58

Table 9. FAR 4.5 Unit Availability with Parking Exemption

FAR 4.5: 281,670 ft2							
	Allowable Building Area	Open Space at 35%: 244,140 ft2		Open Space at 50%: 313,000 ft2		Open Space at 75%: 219,170 ft2	
	15% Mech/Circ	36,621 ft2		46,950 ft2		32,876 ft2	
	Commercial Floor Area	40,690 ft2		31,300 ft2		15,655 ft2	
	Allowable Built Residential Area	166,289 ft2		234,750 ft2		170,639 ft2	
	Allowable # of units	**all**	**equal**	**all**	**equal**	**all**	**equal**
Average unit sizes	studio 400 ft2	415	57	586	80	426	58
	1-Bed 600 ft2	277	57	391	81	284	58
	2-Bed 800 ft2	207	58	293	81	213	58
	3-Bed 1100 ft2	151	57	213	81	155	58

Table 10. FAR 2.5 and 35% Open Space Scenario with Parking

FAR 2.5: 156,487.5 sq. ft. (Total Lot size: 62,595 sq. ft.)	
Open Space at 35%: 21,900 sq. ft.	
Parking Buildable Lot Area at: 20,000 Sq. Ft.	Building Lot Area: 20,695 Sq. Ft.
156,487 / 20,695 = 7.5 stories max 7 x 20,695= 144,865 sq. ft. - 20,695 (Ground Floor Business) - 21,730 (15% mech/circ.) = **102,440 sq. ft. allowable residential floor area**	
102,440 / 2900 (1 unit each) = 35.3 units each 35 units each (**140 units total**) x2900= 101,500 sq. ft. + 20,695 (Ground Floor Business) +18,329 (15% mech/circ.) =140,524 sq. ft. allowable built area = 7 stories = 87' height	
Parking: 400 sq. ft stall space x 140 units = 56,000 sq. ft. / 20,000 lot space= 3 stories	

Table 11. FAR 2.5 and 50% Open Space Scenario with Parking

<table>
<tr><td colspan="4">**FAR 2.5: 156,487 sq. ft. (Total Lot size: 62,595 sq. ft.)**
+46,990 sq. ft. open space bonus =
FAR 2.5= 203,477</td></tr>
<tr><td colspan="4">**Open Space at 50%:**
31,298 sq. ft.</td></tr>
<tr><td>Parking Buildable Lot Area at:
20,000 Sq. Ft.</td><td>Building Lot Area:
11,297 Sq. Ft.</td><td>Parking Buildable Lot Area at:
10,000 sq. ft.</td><td>Building Lot Area:
21,297 sq. ft.</td></tr>
<tr><td colspan="2">203,477 / 11,297 = 18 stories max height
Buildable area = 171’ = 14 stories
11,297 x 14 =158,158 sq. ft.
- 11,297 (Ground Floor Business)
- 23,724 (15% mech./circ.)
= **123,137 sq. ft. allowable residential floor area**</td><td colspan="2">203,477 / 21,297 = 9.6 stories max height=
9 stories = 111’
21,297 x 9 = 191,673 sq. ft.
- 21,297 (Ground Floor Business)
- 28,751 (15% mech/circ.)
= **141,625 sq. ft. allowable residential floor area**</td></tr>
<tr><td colspan="2">123,137 / 2900 = 42 units each
=**168 units total**</td><td colspan="2">141,625 / 2900 = 48 units each
= **192 units total**</td></tr>
<tr><td colspan="2">Parking:
400 sq. ft stall space x 168 units =
67,200 sq. ft.
/ 20,000 lot space =
4 stories</td><td colspan="2">Parking:
400 sq. ft. stall space x 192 units =
76,800 sq. ft.
/ 10,000 lot space =
7.7 stories</td></tr>
</table>

Table 12. FAR 2.5 and 75% Open Space Scenario with Parking

<table>
<tr><td colspan="4">**FAR 2.5: 156,487 sq. ft. (Total Lot size: 62,595 sq. ft.)**
+125,200 sq. ft. open space bonus =
FAR 2.5= 281,687</td></tr>
<tr><td colspan="4">**Open Space at 75%:**
46,940 sq. ft.</td></tr>
<tr><td>Parking Buildable Lot Area at:
10,000 Sq. Ft.</td><td>Building Lot Area:
5,655 Sq. Ft.</td><td>Parking Buildable Lot Area at:
5,000 sq. ft.</td><td>Building Lot Area:
10,655 sq. ft.</td></tr>
<tr><td colspan="2">281,687 / 5,655 = 49 stories=591’
14 stories=171’ allowable max height
5,655 x 14 = 79,170 sq. ft.
-5,655 (Ground Floor Business)
- 11,876 (15% mech./circ.)
= **61,639 sq. ft. allowable residential floor area**</td><td colspan="2">281,687 / 10,655 = 26 stories = 315’
14 stories = 171’ allowable max height
10,655 x 14 = 149,170 sq. ft.
- 10,655 (Ground Floor Business)
- 22,376 (15% mech./circ)
= **116,139 sq. ft. allowable residential floor area**</td></tr>
<tr><td colspan="2">61,639 / 2900= 21 units each
=84 units total</td><td colspan="2">116,139 / 2900 = 40 units each
= **160 units total**</td></tr>
<tr><td colspan="2">Parking:
400 sq. ft stall space x 84 units =
33,600 sq. ft.
/ 20,000 lot space =
2 stories</td><td colspan="2">Parking:
400 sq. ft. stall space x 160 units =
64,000 sq. ft.
/ 5,000 lot space =
13 stories</td></tr>
</table>

Table 13. FAR 3.5 and 35% Open Space Scenario with Parking

<table>
<tr><td colspan="2">**FAR 3.5: 219,080 sq. ft. (Total Lot size: 62,595 sq. ft.)**</td></tr>
<tr><td colspan="2">**Open Space at 35%:**
21,900 sq. ft.</td></tr>
<tr><td>Parking Buildable Lot Area at:
20,000 Sq. Ft.</td><td>Building Lot Area:
20,695 Sq. Ft.</td></tr>
<tr><td colspan="2">20,695 x 10 = 206,950 sq. ft. (allowable floor area)
- 20,695 (Ground Floor Business)
- 31,042 (15% mech/circ.)
= **155,213 sq. ft. allowable residential floor area**</td></tr>
<tr><td colspan="2">155,213 / 2900 (1 unit each) = 53.5 units each
53 units each (**212 units total**) x2900= 153,700 sq. ft.
+ 20,695 (Ground Floor Business)
+26,160 (15% mech/circ.)
=**202,068 sq. ft. allowable built area**
= 10 stories = 123’ height</td></tr>
<tr><td colspan="2">Parking:
400 sq. ft stall space x 212 units =
84,800 sq. ft.
/ 20,000 lot space=
4.25 stories</td></tr>
</table>

Table 14. FAR 3.5 and 50% Open Space Scenario with Parking

<table>
<tr><td colspan="4">**FAR 3.5: 219,080 sq. ft. (Total Lot size: 62,595 sq. ft.)**
+46,990 sq. ft. open space bonus =
FAR 3.5= 266,070</td></tr>
<tr><td colspan="4">**Open Space at 50%:**
31,298 sq. ft.</td></tr>
<tr><td>Parking Buildable Lot Area at:
20,000 Sq. Ft.</td><td>Building Lot Area:
11,297 Sq. Ft.</td><td>Parking Buildable Lot Area at:
10,000 sq. ft.</td><td>Building Lot Area:
21,297 sq. ft.</td></tr>
<tr><td colspan="2">266,070 / 11,297 = 23.5 stories max height
Buildable area = 171’ = 14 stories
11,297 x 14 =158,158 sq. ft.
- 11,297 (Ground Floor Business)
- 23,724 (15% mech./circ.)
= **123,137 sq. ft. allowable residential floor area**</td><td colspan="2">266,070 / 21,297 = 12.5 stories max height=
12 stories = 147’
21,297 x 12 = 255,564 sq. ft.
- 21,297 (Ground Floor Business)
- 38,335 (15% mech/circ.)
= **195,932 sq. ft. allowable residential floor area**</td></tr>
<tr><td colspan="2">123,137 / 2900 = 42 units each
=**168 units total**</td><td colspan="2">195,932 / 2900 = 67 units each
= **268 units total**</td></tr>
<tr><td colspan="2">Parking:
400 sq. ft stall space x 168 units =
67,200 sq. ft.
/ 20,000 lot space =
4 stories</td><td colspan="2">Parking:
400 sq. ft. stall space x 268 units =
107,200 sq. ft.
/ 10,000 lot space =
11 stories</td></tr>
</table>

Table 15. FAR 3.5 and 75% Open Space Scenario with Parking

FAR 3.5: 219,080 sq. ft. (Total Lot size: 62,595 sq. ft.) +125,200 sq. ft. open space bonus = FAR 3.5= 344,280			
Open Space at 75%: 46,940 sq. ft.			
Parking Buildable Lot Area at: 10,000 Sq. Ft.	Building Lot Area: 5,655 Sq. Ft.	Parking Buildable Lot Area at: 5,000 sq. ft.	Building Lot Area: 10,655 sq. ft.
344,280 / 5,655 = 60 stories=723’ 14 stories=171’ allowable max height 5,655 x 14 = 79,170 sq. ft. -5,655 (Ground Floor Business) - 11,876 (15% mech./circ.) = **61,639 sq. ft. allowable residential floor area**		344,280 / 10,655 = 32 stories = 387’ 14 stories = 171’ allowable max height 10,655 x 14 = 149,170 sq. ft. - 10,655 (Ground Floor Business) - 22,376 (15% mech./circ) = **116,139 sq. ft. allowable residential floor area**	
61,639 / 2900= 21 units each **=84 units total**		116,139 / 2900 = 40 units each = **160 units total**	
Parking: 400 sq. ft stall space x 84 units = 33,600 sq. ft. / 20,000 lot space = 2 stories		Parking: 400 sq. ft. stall space x 160 units = 64,000 sq. ft. / 5,000 lot space = 13 stories	

Table 16. FAR 4.5 and 35% Open Space Scenario with Parking

FAR 4.5: 281,670 sq. ft. (Total Lot size: 62,595 sq. ft.)	
Open Space at 35%: 21,900 sq. ft.	
Parking Buildable Lot Area at: 20,000 Sq. Ft.	Building Lot Area: 20,695 Sq. Ft.
281,670 / 20,695= 13.6 stories max 20,695 x 13 = 269,035 - 20,695 (Ground Floor Business) - 40,355 (15% mech/circ.) = **207,985 sq. ft. allowable residential floor area**	
207,985 / 2900 (1 unit each) = 71.7 units each 71 units each (**212 units total**) x2900= 205,900 sq. ft. + 20,695 (Ground Floor Business) +33,989 (1 5% mech/circ.) =**260,584 sq. ft. allowable built area** = 12 stories = 147’ height	
Parking: 400 sq. ft stall space x 212 units = 84,800 sq. ft. / 20,000 lot space= 4.25 stories	

Table 17. FAR 4.5 and 50% Open Space Scenario with Parking

FAR 4.5: 281,670 sq. ft. (Total Lot size: 62,595 sq. ft.) **+46,990 sq. ft. open space bonus =** **FAR 4.5=328,660**			
Open Space at 50%: 31,298 sq. ft.			
Parking Buildable Lot Area at: 20,000 Sq. Ft.	Building Lot Area: 11,297 Sq. Ft.	Parking Buildable Lot Area at: 10,000 sq. ft.	Building Lot Area: 21,297 sq. ft.
328,660 / 11,297 = 29 stories max height Buildable area = 171’ = 14 stories 11,297 x 14 =158,158 sq. ft. - 11,297 (Ground Floor Business) - 23,724 (15% mech./circ.) = **123,137 sq. ft. allowable residential floor area**		328,660 / 21,297 = 15.4 stories max height= 14 stories = 171’ 21,297 x 14 = 298,158 sq. ft. - 21,297 (Ground Floor Business) - 44,724 (15% mech/circ.) = **232,137 sq. ft. allowable residential floor area**	
123,137 / 2900 = 42 units each =**168 units total**		232,137 / 2900 = 80 units each = **320 units total**	
Parking: 400 sq. ft stall space x 168 units = 67,200 sq. ft. / 20,000 lot space = 4 stories		Parking: 400 sq. ft. stall space x 320 units = 128,000 sq. ft. / 10,000 lot space = 13 stories	

Table 18. FAR 4.5 and 75% Open Space Scenario with Parking

FAR 4.5: 281,670 sq. ft. (Total Lot size: 62,595 sq. ft.) **+125,200 sq. ft. open space bonus =** **FAR 4.5= 406,870**			
Open Space at 75%: 46,940 sq. ft.			
Parking Buildable Lot Area at: 10,000 Sq. Ft.	Building Lot Area: 5,655 Sq. Ft.	Parking Buildable Lot Area at: 5,000 sq. ft.	Building Lot Area: 10,655 sq. ft.
406,870 / 5,655 = 72 stories=867’ 14 stories=171’ allowable max height 5,655 x 14 = 79,170 sq. ft. -5,655 (Ground Floor Business) - 11,876 (15% mech./circ.) = **61,639 sq. ft. allowable residential floor area**		406,870 / 10,655 = 38 stories = 459’ 14 stories = 171’ allowable max height 10,655 x 14 = 149,170 sq. ft. - 10,655 (Ground Floor Business) - 22,376 (15% mech./circ) = **116,139 sq. ft. allowable residential floor area**	
61,639 / 2900= 21 units each **=84 units total**		116,139 / 2900 = 40 units each = **160 units total**	
Parking: 400 sq. ft stall space x 84 units = 33,600 sq. ft. / 20,000 lot space = 2 stories		Parking: 400 sq. ft. stall space x 160 units = 64,000 sq. ft. / 5,000 lot space = 13 stories	

Table 19. FAR 2.5 and 35% Open Space Scenario with Stacked Parking

FAR 2.5: 156,487.5 sq. ft. (Total Lot size: 62,595 sq. ft.)
Open Space at 35%: 21,900 sq. ft.
Buildable Lot Area at: 40,695 Sq. Ft./ per floor
40,695 / 400 = 101 parking stalls per floor 40,695 x .15 = 6,105 sq. ft. Mech/Circ per floor at 15%
34,590 / 2900 (one dwelling unit type each) = 11.93 units each, 47.72 units total ~ 47 units per floor
180’ height limit 15’ commercial ground floor 15’ per parking floor 12’ per residential floor
1 parking stall per dwelling unit 1 parking stall per 500 sq. ft. average of commercial space 40,695 / 500 = 82 parking stalls per commercial ground floor area
156,487 / 40,695 = 3.85 floors = 1 floor commercial, 2 floors residential = 176 parking stalls needed~ 2 floors of parking
= 5 stories, 69’ = 122,085 floor area + parking

Table 20. FAR 2.5 and 50% Open Space Scenario with Stacked Parking

FAR 2.5: 156,487 sq. ft. (Total Lot size: 62,595 sq. ft.) **+46,990 sq. ft. open space bonus =** **FAR 2.5= 203,477**
Open Space at 50%: 31,298 sq. ft.
Buildable Lot Area at: 31,297 sq. Ft./ per floor
31,297 / 400 = 78.2 parking stalls per floor 31,297 x .15 = 4,695 sq. ft. Mech/Circ per floor at 15%
26,602 / 2900 (one dwelling unit type each) = 9.17 units each, 36.68 units total ~ 36 total units per floor
180’ height limit 15’ commercial ground floor 15’ per parking floor 12’ per residential floor
1 parking stall per dwelling unit 1 parking stall per 500 sq. ft. average of commercial space 31,297 / 500 = 63 parking stalls per commercial ground floor area
203,477 / 31,297 = 6.5 floors = 1 floor commercial, 5 floors residential = 243 parking stalls needed~ 3.1 floors of parking
= 9 stories, 120’ = 187,782 floor area + parking

Table 21. FAR 2.5 and 75% Open Space Scenario with Stacked Parking

FAR 2.5: 156,487 sq. ft. (Total Lot size: 62,595 sq. ft.) **+125,200 sq. ft. open space bonus =** **FAR 2.5= 281,687**
Open Space at 75%: 46,940 sq. ft.
Buildable Lot Area at: 15,655 sq. ft./ per floor
15,655 / 400 = 39.14 parking stalls per floor 15,655 x .15 = 2,348 sq. ft. Mech/Circ per floor at 15%
13,307 / 2900 (one dwelling unit type each) = 4.6 units each, 18.4 units total ~ 18 total units per floor
180’ height limit 15’ commercial ground floor 15’ per parking floor 12’ per residential floor
1 parking stall per dwelling unit 1 parking stall per 500 sq. ft. average of commercial space 15,655 / 500 = 32 parking stalls per commercial ground floor area
281,687 / 15,655 = 18 floors~ = 1 floor commercial, 7 floors residential = 158 parking stalls needed~ 4 floors of parking
= 12 stories, 159’ = 125,240 floor area + parking

Table 22. FAR 3.5 and 35% Open Space Scenario with Stacked Parking

FAR 3.5: 219,080 sq. ft. (Total Lot size: 62,595 sq. ft.)
Open Space at 35%: 21,900 sq. ft.
Buildable Lot Area at: 40,695 Sq. Ft./ per floor
40,695 / 400 = 101 parking stalls per floor 40,695 x .15 = 6,105 sq. ft. Mech/Circ per floor at 15%
34,590 / 2900 (one dwelling unit type each) = 11.93 units each, 47.72 units total ~ 47 units per floor
180’ height limit 15’ commercial ground floor 15’ per parking floor 12’ per residential floor
1 parking stall per dwelling unit 1 parking stall per 500 sq. ft. average of commercial space 40,695 / 500 = 82 parking stalls per commercial ground floor area
219,080 / 40,695 = 5.38 floors = 1 floor commercial, 4 floors residential = 270 parking stalls needed~ 3 floors of parking
= 8 stories, 108’ = 203,475 floor area + parking

Table 23. FAR 3.5 and 50% Open Space Scenario with Stacked Parking

FAR 3.5: 219,080 sq. ft. (Total Lot size: 62,595 sq. ft.) **+46,990 sq. ft. open space bonus =** **FAR 3.5= 266,070**
Open Space at 50%: **31,298 sq. ft.**
Buildable Lot Area at: 31,297 Sq. Ft./ per floor
31,297 / 400 = 78.25 parking stalls per floor 31,297 x .15 = 4,695 sq. ft. Mech/Circ per floor at 15%
26,602 / 2900 (one dwelling unit type each) = 9.17 units each, 36.68 units total ~ 36 units per floor
180’ height limit 15’ commercial ground floor 15’ per parking floor 12’ per residential floor
1 parking stall per dwelling unit 1 parking stall per 500 sq. ft. average of commercial space 31,297 / 500 = 63 parking stalls per commercial ground floor area
266,070 / 31,297 = 8.5 floors = 1 floor commercial, 7 floors residential = 252 parking stalls needed~ 4 floors of parking
= 12 stories, 159’ = 250,376 floor area + parking

Table 24. FAR 3.5 and 75% Open Space Scenario with Stacked Parking

FAR 3.5: 219,080 sq. ft. (Total Lot size: 62,595 sq. ft.) **+125,200 sq. ft. open space bonus =** **FAR 3.5= 344,280**
Open Space at 75%: 46,940 sq. ft.
Buildable Lot Area at: 15,655 sq. ft./ per floor
15,655 / 400 = 39.14 parking stalls per floor 15,655 x .15 = 2,348 sq. ft. Mech/Circ per floor at 15%
13,307 / 2900 (one dwelling unit type each) = 4.6 units each, 18.4 units total ~ 18 total units per floor
180’ height limit 15’ commercial ground floor 15’ per parking floor 12’ per residential floor
1 parking stall per dwelling unit 1 parking stall per 500 sq. ft. average of commercial space 15,655 / 500 = 32 parking stalls per commercial ground floor area
344,280 / 15,655 = 22 floors~ 13 stories allowable = 1 floor commercial, 7 floors residential = 158 parking stalls needed~ 4 floors of parking
= 12 stories, 159’ = 125,240 floor area + parking

Table 25. FAR 4.5 and 35% Open Space Scenario with Stacked Parking

FAR 4.5: 281,670 sq. ft. (Total Lot size: 62,595 sq. ft.)
Open Space at 35%: 21,900 sq. ft.
Buildable Lot Area at: 40,695 Sq. Ft./ per floor
40,695 / 400 = 101 parking stalls per floor 40,695 x .15 = 6,105 sq. ft. Mech/Circ per floor at 15%
34,590 / 2900 (one dwelling unit type each) = 11.93 units each, 47.72 units total ~ 47 units per floor
180’ height limit 15’ commercial ground floor 15’ per parking floor 12’ per residential floor
1 parking stall per dwelling unit 1 parking stall per 500 sq. ft. average of commercial space 40,695 / 500 = 82 parking stalls per commercial ground floor area
281,670 / 40,695 = 6.9 floors = 1 floor commercial, 5 floors residential = 235 parking stalls needed~ 3 floors of parking
= 9 stories, 120’ = 244,170 floor area + parking

Table 26. FAR 4.5 and 50% Open Space Scenario with Stacked Parking

FAR 4.5: 281,670 sq. ft. (Total Lot size: 62,595 sq. ft.) **+46,990 sq. ft. open space bonus =** **FAR 4.5=328,660**
Open Space at 50%: **31,298 sq. ft.**
Buildable Lot Area at: 31,297 Sq. Ft./ per floor
31,297 / 400 = 78.25 parking stalls per floor 31,297 x .15 = 4,695 sq. ft. Mech/Circ per floor at 15%
26,602 / 2900 (one dwelling unit type each) = 9.17 units each, 36.68 units total ~ 36 units per floor
180’ height limit 15’ commercial ground floor 15’ per parking floor 12’ per residential floor
1 parking stall per dwelling unit 1 parking stall per 500 sq. ft. average of commercial space 31,297 / 500 = 63 parking stalls per commercial ground floor area
328,660 / 31,297 = 10.5 floors = 1 floor commercial, 7 floors residential = 315 parking stalls needed~ 4 floors of parking
= 12 stories, 159’ = 250,376 floor area + parking

Table 27. FAR 4.5 and 75% Open Space Scenario with Stacked Parking

FAR 4.5: 281,670 sq. ft. (Total Lot size: 62,595 sq. ft.) **+125,200 sq. ft. open space bonus =** **FAR 4.5= 406,870**
Open Space at 75%: 46,940 sq. ft.
Buildable Lot Area at: 15,655 sq. ft./ per floor
15,655 / 400 = 39.14 parking stalls per floor 15,655 x .15 = 2,348 sq. ft. Mech/Circ per floor at 15%
13,307 / 2900 (one dwelling unit type each) = 4.6 units each, 18.4 units total ~ 18 total units per floor
180’ height limit 15’ commercial ground floor 15’ per parking floor 12’ per residential floor
1 parking stall per dwelling unit 1 parking stall per 500 sq. ft. average of commercial space 15,655 / 500 = 32 parking stalls per commercial ground floor area
406,870 / 15,655 = 26 floors~ 13 stories allowable = 1 floor commercial, 7 floors residential = 158 parking stalls needed~ 4 floors of parking
= 12 stories, 159’ = 125,240 floor area + parking

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