Nader Abou Shahin

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THE IMPACT AND DEVELOPMENT OF THE CONCEPT OF MODULAR ARCHITECTURE ON HOUSING DESIGN

A THESIS
SUBMITTED TO THE DEPARTMENT OF ARCHITECTURE
AND THE GRADUATE SCHOOL OF ENGINEERING AND SCIENCE
OF ABDULLAH GUL UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
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Name-Surname: Nader Abou Shahin

Signature :

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M.Sc. thesis titled "The Impact And Development Of The Concept Of Modular Architecture On Housing Design" has been prepared in accordance with the Thesis Writing Guidelines of the Abdullah Gül University, Graduate School of Engineering & Science.

Prepared By	Advisor
Nader Abou Shahin	Dr. Öğr. Üyesi Ömer Devrim AKSOYAK

Head of the Architecture Program

Assist. Prof. Buket METIN

Signature

ACCEPTANCE AND APPROVAL

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JURY:

Advisor : Dr. Öğr. Üyesi Ömer Devrim Aksoyak

Member : Prof. Dr. Burak Asiliskender

Member : Doç. Dr. Güldehan Fatma Atay

APPROVAL:

The acceptance of this M.Sc. thesis has been approved by the decision of the Abdullah Gül University, Graduate School of Engineering & Science, Executive Board dated ….. /….. / ……….. and numbered ………….……. .

……….. /……….. / ………..

(Date)

Graduate School Dean
Prof. Dr. İrfan ALAN

ABSTRACT

THE IMPACT AND DEVELOPMENT OF THE CONCEPT OF MODULAR ARCHITECTURE ON HOUSING DESIGN

Nader Abou Shahin
MSc. in Department of Architecture
Advisor: Dr. Öğr. Üyesi Ömer Devrim AKSOYAK

January 2024

Modularity, deeply rooted in ancient art, architecture, and the natural world, has a rich historical legacy. This research endeavours to delineate a historical definition of modularity, objectively compile diverse perspectives and discussions, and explore its modern conceptualization. The primary objective is to cultivate a comprehensive understanding of the term "module" within the context of architectural history. The study explores the various approaches to modularity and prefabrication adopted globally over the last century. The research examines past and present applications in housing projects, conducts a thorough literature review to trace the historical evolution of modular housing, delves into modularity theories in architectural design, and scrutinizes existing case studies. A theoretical framework defines critical concepts of modularity in architectural design and highlights influential architectural theorists and their contributions to modular design. A selection of modular housing projects is then subjected to in-depth case studies, analyzing successful and less successful examples to discern the factors contributing to effective modular design. Through an exhaustive listing and analysis of modular and prefabricated projects, this thesis aims to shed light on the developmental trajectory of the modular approach in terms of construction systems, materials, and dimensions. While revealing notable advancements, the research underscores existing gaps, particularly in customization for future adoption in housing architecture. Against the backdrop of a global housing crisis, modular architecture emerges as a promising solution aligned with the UN's Sustainable Development Goal 11.1—ensuring safe, decent, and affordable housing for all by 2030. This research serves as a foundational exploration into the modular concept in architectural housing, providing insights into its historical evolution and potential future applications.

Keywords: Modularity, Prefabrication, Modular architecture, Housing projects, History of Modularity

ÖZET

MODÜLER MİMARLIK KAVRAMININ KONUT TASARIMI ÜZERİNDEKİ ETKİ VE GELİŞİMİ

Nader Abou Shahin
Mimarlık Anabilim Yüksek Lisans
Tez Yöneticisi: Dr. Öğr. Üyesi Ömer Devrim AKSOYAK

Ocak -2024

Kökleri antik sanat, mimari ve doğal dünyaya dayanan modülerlik, zengin bir tarihsel mirasa sahiptir. Çalışma, modülerliğin tarihsel gelişimine bakarak tanımını yapmaya, modüler kavramı hakkında farklı bakış açılarını ve tartışmaları nesnel bir şekilde derlemeye ve modül kavramının modern anlamı için bir deneme şeklinde hazırlanmıştır. Çalışmanın birincil amacı, mimarlık tarihi bağlamında "modül" teriminin kapsamlı bir şekilde anlaşılmasını sağlamaktır. Çalışma, modülerlik ve prefabrikasyona yönelik olarak geçtiğimiz yüzyıl boyunca küresel ölçekte benimsenen çeşitli yaklaşımları incelemektedir. Çalışmada konut projelerindeki geçmiş ve mevcut uygulamalar incelenmekte, modüler konutların tarihsel gelişiminin anlaşılabilmesi için kapsamlı bir literatür taraması yapılmaktadır.Hazırlanan analizler ile mimari tasarımda modülerlik teorileri araştırılmış ve örnekler üzerinden sentez çalışması hazırlanmıştır. Mimari tasarımda modülerliğin öne çıkan etkileri ortaya konmuş ve modüler tasarım konusunda etkili olan mimarları ve modüler tasarıma katkıları irdelenmiştir. Yapılan literatür araştırması sonucu küresel ölçekte öne çıkan örnekler üzerinden modüler konut projeleri hakkında analiz hazırlanmış ve derinlemesine vaka analizi ve sentezi hazırlanmıştır. Modüler tasarım anlayışı ile hazırlanan projelerin kapsamlı bir listesi ve analizi aracılığıyla bu tez, modüler yaklaşımın inşaat sistemleri, malzemeler ve ölçüler açısından gelişimsel yörüngesine ışık tutmayı amaçlamaktadır. Araştırma, konusundaki ilerlemeleri ortaya koyarken, özellikle konut mimarisinde gelecekte modüler tasarım konusunda mevcut potansiyellerin tartışmasını başlatmaktadır. Küresel konut krizinin arka planında modüler mimari, BM'nin Sürdürülebilir Kalkınma Hedefleri (Hedef 11) ile uyumlu bir çözüm olarak ortaya çıkmaktadır. Çalışma, konut üretiminde mimari tasarım için modüler konseptin temel bir araştırması olarak tarihsel gelişimi ortaya koymakta ve gelecekteki potansiyel modüler tasarım uygulamaları hakkında öngörülerde bulunmaktadır.

Anahtar kelimeler: Modülerlik, Prefabrikasyon, Modüler mimari, Konut projeleri, Modülerliğin Tarihçesi

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I want to express my heartfelt gratitude to my family members, including my father, mother, sister and best friend Haya, and my younger sister and brother. Their unflinching support and endless love have been my anchors throughout my journey of completing this thesis. I would also like to thank my wife for her encouragement and understanding, which has driven my pursuit of academic excellence. To my beloved daughter, Lily, your smile and innocence have inspired me and reminded me of the significance of my work. Thank you for being my motivation and a constant source of joy.

This thesis is not just my achievement; it reflects the collective love and encouragement surrounding me. I am profoundly grateful for the joy and support you all have brought into my life.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

glulam	Glued Laminated Timber
CLT	Cross Laminated Timber
LGS	Light Gauge Steel
MEP	Mechanical, Electrical and Plumbing
MiC	Modular Integrated Construction
PPVC	Prefabricated Prefinished Volumetric Construction
GLS	Government Land Sales
FCS	Frame construction system
PCS	Panel Construction System
RMS	Room Module System
VU	Volumetric Unit
MS	Mixed System

GCHS

For better and affordable home

Chapter 1

Introduction

The idea of modularity has a rich history, evident in ancient art, architecture, and the natural world, as well as in the structure of the human body, botany, and zoology. In modern times, modularity has found its way into various fields, including education, prosthetics, orthopedic implantation, literature, and newspaper and magazine design. Throughout history, humans have been fascinated with the process of construction. The building was not merely a means of shelter but a way to convey the image, growth, and triumph of civilization and immortalize an empire's legacy, and a module was a means used to achieve that. Much of what we know about ancient civilizations such as the Romans, Pharaonic Egyptians, and Greeks comes from the architectural structures they left behind—in his book On Architecture, Vitruvius, a renowned architect, emphasized using modules or measuring tools in Roman architecture (Vitruvius, 2009). This tool was instrumental in ensuring that building elements were harmonious with one another. The use of modules as length-measuring tools was not unique to the Roman Empire but rather was utilized in many civilizations before and after. This thesis aims to provide a historical definition of modularity, gather information and discussions about it, present it unbiasedly, and explore its modern concept.

During the recent history and for over a century, prefabrication and modularity have been used and developed. As the housing crisis escalates, the construction industry must adapt and evolve to meet new demands. Modularity has become increasingly popular in the industrial space due to its ability to offer companies the flexibility to design and provide customers with a wide range of options that will maintain profitable and fast production lines. The origin of modern architecture in the Western world can be traced back to the late 1920s, which coincided with the emergence of prefabrication and modular concepts in construction. Peter Behrens spearheaded this revolution, primarily through his renowned project, The AEG Factory. Behrens mentored several modern architects and prefab influencers, including Le Corbusier, Mies van der Rohe, and Walter Gropius. This thesis research aims to provide a thorough understanding of modules and modularity in architectural housing. Through a combination of theoretical data collection and case studies, this thesis explores the historical use and current approaches to these concepts. The theoretical and literature section provides a chronology of the term and concept of the module. At the same time, the case studies offer examples of how modularity has been utilized in architecture throughout history by various projects, architects, and companies.

The housing crisis is a global issue that has affected many countries, from the richest to the poorest. Researchers have been trying to find solutions to this issue for a long time. While this crisis has many reasons, this research will focus on the construction method. (Luther, 2009) Highlighted how this crisis affects newer generations and society. (Bayliss & Rory, 2020) Traced the cause of the crisis back to the 1980s when the state stopped providing housing and handed it over to the private sector. However, the private sector's main concern was generating revenue, and the quality of buildings suffered since designers' and architects' roles were concealed from construction projects. Prefabricated and modular homes offer a potential solution to this problem, in line with the United Nations' Sustainable Development Goal 11.1, which aims to ensure safe, decent, and affordable housing for all by 2030, and Goal 12, Responsible Consumption and Production, as prefabrication and modularity use resources and materials more efficiently, reducing waste from construction sites.

Nevertheless, it remains challenging to demonstrate their effectiveness, given the slow pace of change in the construction industry over the past 150 years. Sandy Hirshen suggests that the private sector, banks, and other construction companies have been resistant to change, citing the reluctance of unions and banks to associate themselves with housing not attached to the ground. Developers are also driven by densifying the land and securing low-interest rates rather than constructing the structures themselves (Smith, 2011).

The objective of this research is to provide a comprehensive understanding of the term "module" in the context of architectural history. The study will investigate the diverse approaches to modularity and prefabrication adopted by architects and explore their current application in projects. The primary research question, "What is the significance of modularity in the history of architectural housing, and how has the idea of modularity evolved over time?" will guide the research, along with the secondary question, "How is modularity utilized in today's construction industry?" This thesis will trace the module's evolution from its early form and definition to its evolution during the Industrial Revolution in the 19th century, culminating in its current application and construction methodology using modularity. This research employs a mixed-methods approach, which includes a theoretical framework, in-depth case studies of modular and prefabricated projects, and Architectural Analysis. The project begins with a thorough literature review to understand the historical evolution of modular housing, theories of modularity in architectural design, and existing case studies. Following that, a theoretical framework defines the fundamental concepts of modularity in architectural design, including essential contributions from influential architectural theorists. Then, a selection of modular housing projects will be analyzed in-depth to understand what factors contribute to effective modular design. By thoroughly examining modular and prefabricated projects, this research aims to illuminate the developmental trajectory of the modular approach in terms of construction systems, materials, and dimensions. While highlighting notable advancements, the research also points out existing gaps, particularly in customization, that need to be addressed for future adoption in housing architecture.

As a personal interest, the opportunity to move from one residence to another and even from one country to another made understanding the importance of owning a home that is both affordable and meets the needs of its residents easy because of these experiences. This research seeks to uncover how prefabrication and modularity can solve this need.

To comprehensively explore the development of modular design, this thesis research follows this structured approach;

The second chapter delves into the historical roots of modularity, connecting it to the Fibonacci Series and examining its origins with Vitruvius and Leon Battista Alberti. It then delves into the influence of modularity during the Industrial Revolution, analyzing the contributions of key figures such as Bauhaus, Le Corbusier, and Bemis. By showcasing the diverse impact of modular concepts in architectural evolution, this chapter provides a thorough narrative that spans mathematical principles, historical contexts, and revolutionary industrial applications.

Within the third chapter, the thesis explores the fundamentals of prefabrication and modularity. This includes exploring various types of systems, dimensions, and levels of prefabrication. The chapter culminates with an emphasis on the significance of lean production and an overview of seismic performance in modular construction. Overall, this provides a comprehensive comprehension of modularity within architectural design.

Chapter four thoroughly examines the modern utilization of modularity in architecture, featuring more than 50 case studies from North America, Europe, and East Asia. The chapter showcases various modular designs, including famous North American projects such as Habitat 67, pioneering European examples, and innovative structures from East Asia. This comprehensive exploration provides insight into the varied applications of modular design across three continents.

Ultimately, the fifth Chapter serves as the concluding chapter, summarising the crucial discoveries and insights from the research.

Architects such as Vitruvius, Bemis, Le Corbusier, Buckminster Fuller, and Walter Gropius have created designs and techniques for utilizing modularity in architecture to enhance the construction industry. It is essential to prioritize better construction methods by exploring all available options. Joe Tanney (Smith, 2011) raises a valid concern that the primary focus of architecture is shifting towards speedy production rather than quality, which might result in future projects being created quickly but not necessarily better. The following sections of the thesis will further investigate these principles and techniques, delving into the modular concept in housing architecture to gain a deeper understanding.

Chapter 2

Development of Modular Design idea

Modularity, which refers to the arrangement of independent but interconnected units, has been a crucial concept in various fields throughout history. This chapter explores the rich history of modularity by examining its roots, manifestations in nature and architecture, and evolution through significant eras. From the mathematical elegance of the Fibonacci series to the precision of ancient architectural designs and the transformative period of the Industrial Revolution, the history of modularity reveals a narrative that transcends disciplinary boundaries.

Modularity has recently emerged as a focal point of attention within the construction sector; however, it is essential to acknowledge that this concept has a profound historical lineage. The historical roots of modularity, modules, and proportion are not confined solely to the Roman Empire; they have also imprinted on diverse architectural traditions, including Mesopotamian, Egyptian, Anatolian, Greek, Etruscan, Early Christianity, and Byzantine periods. Moreover, modularity finds expression in natural phenomena, art, the human body, and mathematics, particularly about the Fibonacci numbers and the golden ratio (BOMBA, 2006). The early development and utilization of the term "module" can be attributed to mathematicians and ancient architects, who derived it from the Latin word "modulus." The module, regarded as a length-measuring tool, sought to achieve harmonious proportions inspired by observations of nature and the human body, particularly the golden ratio and the Fibonacci series. These ancient thinkers perceived these mathematical principles as inherent in the universe's structure. They sought to integrate them into their architectural and artistic endeavors to evoke a sense of aesthetic balance and beauty. Several millennia ago, the concept of the term module was found in movable modular homes of Nomadic tribes has been prevalent. Nomadic tribes used to gather light materials to build simple homes that could be effortlessly assembled, dismantled, and transported to a new location. They would then reconstruct the same home in its new spot (Staib et al., 2008).

2.1 Significance of the Fibonacci Series for Modularity

The concept of modularity holds deep historical roots, permeating various disciplines, including ancient art, architecture, and natural sciences. The exploration of modularity in nature, particularly in the human body, botany, and zoology, is exemplified by the presence of the Fibonacci sequence, golden ratio, and spirals, which are omnipresent in the world around us. The inception of the Fibonacci sequence can be traced back to the works of the Indian mathematician Pingala during the period of 300–200 B.C.E., where he initially identified this numerical sequence within his published work, the Chandastra (Persaud & O'Leary, 2015). Evidencing its pervasive nature, the Fibonacci sequence extends its influence across diverse aspects of existence, including the intricate patterns of fern leaves, architectural designs, and even artistic compositions, thus revealing an overarching universal architecture that surpasses imagination.

The development and propagation of the Fibonacci sequence in the Western world can be attributed to Leonardo Pisano, who expounded upon this numerical series in his seminal work "Liber Abaci" (Book of Calculations). Pisano's in-depth study of the Hindu-Arabic numeral system contributed significantly to the understanding and popularizing the Fibonacci sequence (Persaud & O'Leary, 2015). Nevertheless, Edouard Lucas, a French Mathematician in 1877, bestowed the term "Fibonacci sequences" on this phenomenon as a tribute to Leonardo Pisano (Persaud & O'Leary, 2015).

The Fibonacci series is a set of numbers where each term is the sum of the two preceding terms, starting with the first two terms being "1". As the series progresses, the ratio between consecutive numbers gradually approaches the golden ratio, which is significant in forming non-linear shapes observed in various aspects of life. Here is a sample of the Fibonacci sequence: 0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, and so on. This mathematical sequence provides a profound explanation for the emergence of non-linear forms found ubiquitously in natural phenomena. For instance, the iconic spiral depicted in (Figure 2.1.1) below can be quickly drawn following the Fibonacci sequence numbers precisely inscribed within a golden rectangle.

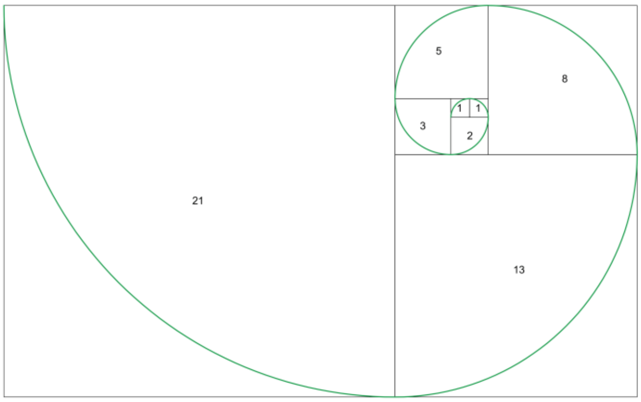


Figure 2.1.1 Golden rectangle and a golden spiral, drawn by the author

Such spirals are prominently observed in nature, appearing in natural occurrences like the human ear and hand, as exemplified in the illustration (Figure 2.1.2). The early artists, sculptors, and architects keenly observed the harmonious proportions in the human body, as outlined in later chapters, which contributed to the integration of beauty and aesthetic appeal into their works. Moreover, the Fibonacci sequence and the golden ratio have been more recently used to define anatomical beauty, particularly in facial aesthetics (Persaud & O'Leary, 2015).

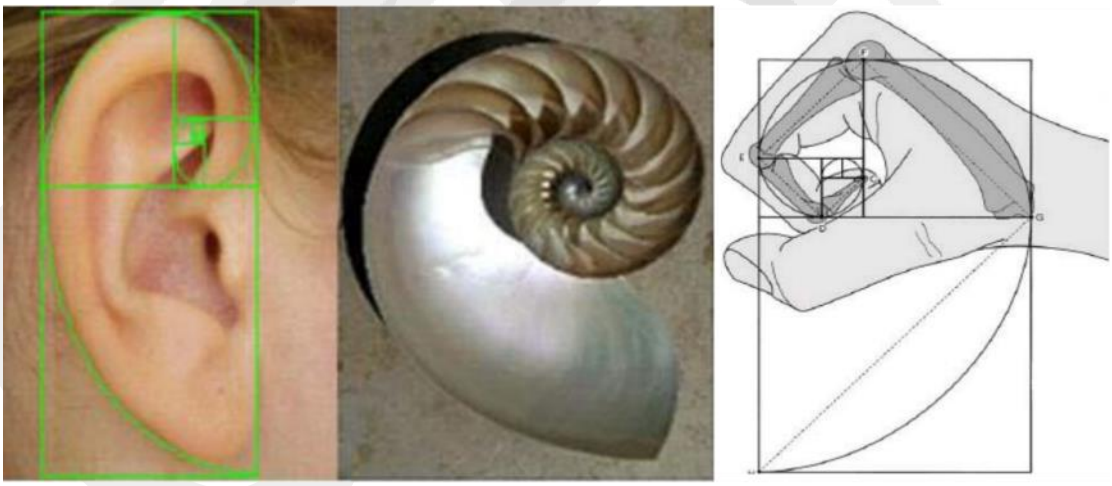


Figure 2.1.2 Golden spiral in nature, human ears, and hands, by (Persaud & O'Leary, 2015)

In his book "De Pictura," Leon Battista Alberti profoundly captures the essence of the Fibonacci sequence's significance by advocating for the seeking of all learning from nature itself. This notion underscores the idea that the Fibonacci sequence and its manifestation in various natural forms offer profound insights into the principles of modularity and aesthetics. By elucidating the historical prominence of the Fibonacci series and its widespread implications across various disciplines, this chapter delves into the fundamental principles of modularity and its significance in understanding the intricate patterns and structures that define our world.

2.2 Modularity in Architecture History

Modularity and the module concept have long existed in architectural history through great civilizations such as the Egyptians, Greeks, and Romans. Many architects have pointed out in some or another the idea of module and proportion, and maybe one of the first architects to mention it is Vitruvius in the book De Architectura, followed by many inspired architects from his writings until today.

2.2.1 Vitruvius

In the first century B.C., Vitruvius laid down the fundamental construction principles through his seminal work, The Ten Books on Architecture. He detailed methods for building modular systems using stone elements and defined a *module unit* as a measuring tool. Vitruvius also expressed his deep admiration for Julius Caesar, the supreme ruler of Rome, his methods of governance and conquest, and the remarkable architecture behind his reign. In The Ten Books, Vitruvius began by defining the architect, their education, and the principles of architecture before elaborating on the concept of proportion in ancient temples and the human body. He discussed the meaning of modularity in ancient times, including their practice of measuring parts of the human body and the fact that the human body has a system of proportions found in the head, the navel, and other areas. In essence, modularity in the Roman Empire was measured using Modulus (Vitruvius, 2009).

The first chapter of Vitruvius' book delves into the architect's profession and the necessary skills, knowledge, and expertise required for an architect to excel. The chapter on the education of the architect is delightful and enlightening. Vitruvius emphasizes that an architect must be talented and possess the ability to learn. While it is not necessary to master all fields, an architect should have a working knowledge of various fields, such as history, which is crucial in providing context and meaning to the decorations and designs used in their work.

In Book 3, Vitruvius expands on proportion in ancient temples and the human body. The chapter highlights the importance of modularity in ancient times when they used the human body as a model for proportion. The human body has a system of proportions found in the head and the navel, and the concept of the perfect number ten comes from human fingers. Vitruvius also mentions that mathematicians consider six the perfect number, and when combined with ten, they get sixteen as the absolute number. These figures perfectly harmonize with the proportions used in the temples they built.

In Book 4, Vitruvius describes the method and principles of building a Doric temple, particularly the façade and columns' design. The chapter emphasizes the importance of the module unit and its proportions, specifying the order and measurement for each part of the temple's façade.

Finally, in Book 6, Vitruvius emphasizes the need for harmonious design and styling. Every location requires a different design, and modularity is crucial in achieving optical harmony. Since the human eye sees objects differently, the importance of modular construction in absolute harmony cannot be overstated.

2.2.2 Leon battista alberti

Leon Battista Alberti was a renowned architect from Genoa, Italy, born in 1404. Alberti's works are primarily influenced by Vitruvius's writings, as evidenced in his ten books on the art of building (De Re Aedificatoria), where he discusses proportions in the human body and the methods of creating statues based on numerical measurements. In his book, De Pictura, Alberti emphasizes the importance of the relationship between nature, beauty, and artistic principles, stating that learning should always be derived from nature. He uses the term "module" as a measuring tool inspired by the human body. One of them is Exempeda, a six-part modular ruler, which is divided into six pedes (feet), sixty unceolae (inches), and six hundred minuta (minutes). Alberti also introduces the term "Braccio," which means "arm" in Italian. These measuring terms and proportions are discussed in his books, De Pictura and De Statua. (Aiken, 1980)

2.3 Modularity in the Industrial Revolution

Modularity has become increasingly popular in the industrial space due to its ability to offer companies the flexibility to design and provide customers with a wide range of options that will maintain profitable and fast production lines. This has resulted in several benefits, such as increased production efficiency, improved quality control, and reduced operational costs. The industry primarily adopts modularity to diversify the manufactured products while exploiting similarities in the production process to enhance efficiency and reduce complexity. Companies can customize their products without redesigning the entire process when the production process is broken down into smaller, interchangeable modules. Utilizing modularity results in time and resource savings and enables companies to promptly respond to market fluctuations, giving them a competitive advantage in the industry. Modularity has revolutionized the industrial space by enabling companies to remain ahead of the curve and cater to their clients' changing requirements. However, the construction sector needed more modularity than other industries, prompting architects and designers to establish new ideas addressing this shortcoming. (Miller, 1998).

2.3.1 Modernity and Modularity

The origin of modern architecture in the Western world can be traced back to the late 1920s, which coincided with the emergence of prefabrication and modular concepts in construction. Peter Behrens spearheaded this revolution, primarily through his renowned project, The AEG Factory. Behrens mentored several modern architects and prefab influencers, including Le Corbusier, Mies van der Rohe, and Walter Gropius. It is widely considered his most significant accomplishment (Smith, 2011).

Modularity has been a significant area of interest for architects throughout history. The integration of proportion and defined design measures has been associated with beauty and symmetry. This concept has been evident in ancient and modern architecture, with examples ranging from prefabrication to modules. The primary motivation for modular design is the human eye's natural inclination towards beauty, as ancient Roman architect Vitruvius and modern architect Le Corbusier noted. The ancient builders discovered the proportion in and between human extremities, creating the first Doric column. The column reflected the strength and beauty of the human form. This innovation was born out of necessity, symmetry, and observation and continued to be as such with architects centuries later.

2.3.2 Bauhaus

Bauhaus (meaning Building house in Germany) is a German art school founded by Walter Gropius from 1919 to 1933. It has a significant influence on Modern design, Modern architecture, and other fields. The desire for art education rehabilitation in Germany was the main driver for the Bauhaus movement before it was established in 1919 by Walter Gropius. The reform of art education started by forming a German workshop (Deutsche werkstätten) by Karl Schmidt in 1898, then the influence of Hans Poelzig and Peter Behrens as directorships of art schools in 1903, and then with Henry van de Velde’s Grand Ducal School of Arts and Crafts in 1906 (Frampton, 1992).

According to a letter written by Oskar Schlemmer in 1922, Walter Gropius chose the name Bauhaus from the term (Bauhütte) meaning (Building hut) as a title for the new institution he was establishing to be a reminder of the medieval term (Bauhütte) and convinced the government to approve it.

Oskar Schlemmer's letter (Frampton, 1992) “Originally the Bauhaus was founded with visions of erecting the cathedral of socialism and the workshops were established in the manner of the cathedral building lodges *[Dombauhütten]*. For the time being, the idea of the cathedral has receded into the background and, with it, certain definite ideas of an artistic nature. Today, we must think at best in terms of the house. Perhaps even only think so in the face of the economic plight. Our task is to become pioneers of simplicity, that is, to find a simple form for all life’s necessities. Which is respectable and genuine at the same time.”

Several known names were part of the Bauhaus period, in addition to the founder Walter Gropius, according to chapter 14 of the book (Frampton, 1992). Throughout its existence, Bauhaus had three directors: Walter Gropius from 1919 to 1928, Hannes Meyer from 1928 to 1930, and Ludwig Mies Van der Rohe from 1930 – 1933. Other figures like Johannes Itten, a Swiss painter, and a teacher, were in charge for the first three years; the Dutch artist Theo van Doesburg had a significant influence in teaching and even in the furniture of the school's offices like Gropius's office himself. In early Bauhaus 1922, Moholy-Nagy, a Hungarian artist, was also an important figure.

Bauhaus art schools started in Weimar in 1919 but did not stay there for long for many reasons, most related to politics. In 1925, Bauhaus moved to Dessau and stayed there for almost seven years; in 1932, Bauhaus moved again to the outskirts of Berlin, ending nine months later in 1933.

Throughout the history of building construction, advancements in building materials, techniques, and technologies have played a significant role in improving methods and enhancing the quality of structures. As Walter Gropius explains in his book, The New Architecture and the Bauhaus (Gropius, 1965), these advancements have transformed the role of walls from a structural load-bearing component to a partition between enclosed spaces, offering protection against elements such as wind, heat, and noise. Furthermore, the evolution of bigger windows and the adoption of flat roof designs have provided functional benefits such as increased space and improved living conditions for upper rooms.

Standardization and consistent design elements have been crucial in promoting civilized societies. Walter Gropius (Gropius, 1965) recognized the value of standardization in improving the quality and affordability of housing. By stacking these small living spaces together, a street unit is formed, which can ultimately contribute to the overall image of a city. The most impressive cities throughout history have been defined by their repeated use of structural elements and traditional building styles, resulting in a majestic sense of symmetry. We can create stunning and harmonious cities by adopting a unified approach to architecture while still allowing for individual expression. This approach can elevate the social level of an entire city and help us create a brighter future with a distinctive mark of greatness.

Under the leadership of Walter Gropius, the Bauhaus School established a pragmatic approach that fostered collaboration between artists, designers, and industrial production lines, enabling each group to understand the other's craft better (Gropius, 1965). Between 1922 and 1925, several household items (as shown in Figure 2.3.1) were developed using this methodology, serving as prototypes for mass production in factories within and outside Germany.

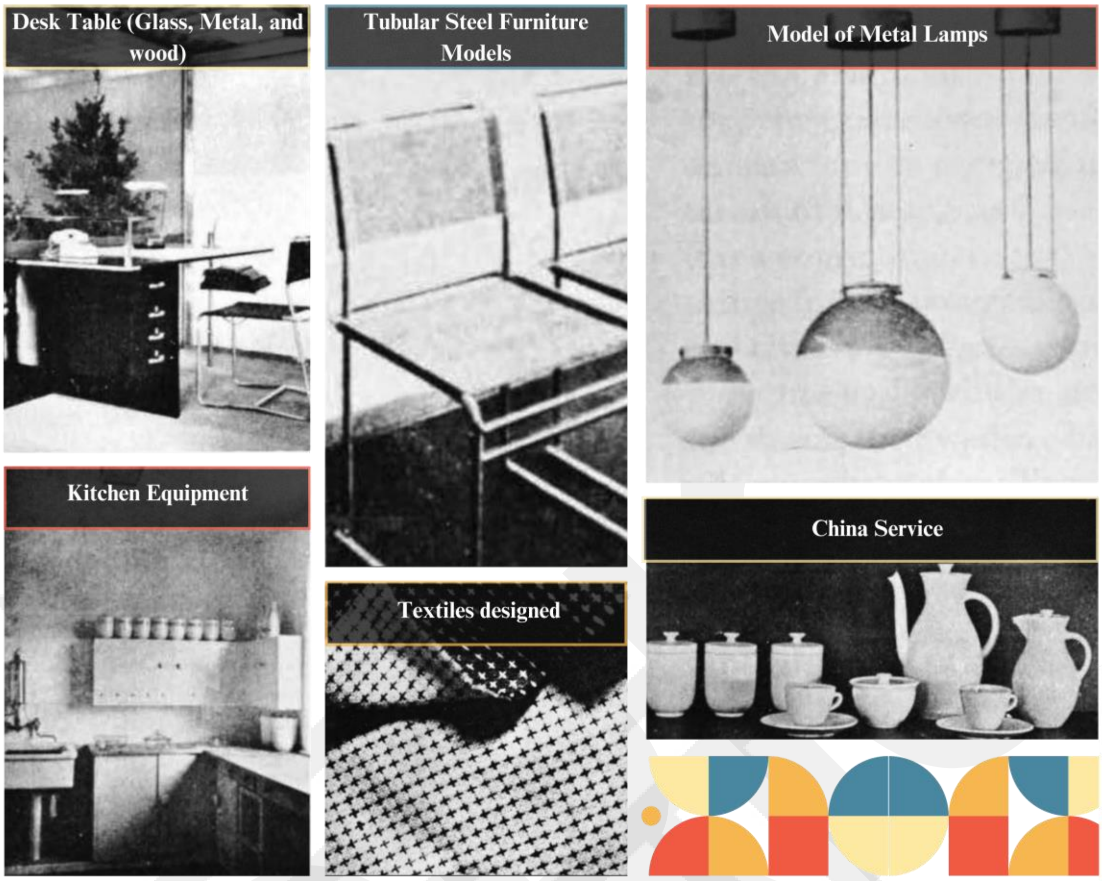


Figure 2.3.1 Products for mass production by Bauhaus, made by the author using (Gropius, 1965)

Rationalization, as Walter Gropius believed, is the key to quality in future houses, achieved by technical proficiency that allows house structures to be dismantled into parts for mass production in a factory. The future of house construction with technology will be through prefabrication and mass production in factories by norming every part of the house. The quality of future houses is the ability to deliver ready-constructed house units built inside a dry and controlled factory. As Van de Velde and other artists were concerned about the freedom of creativity for architects or artists, Walter Gropius also raised the same concern but with a different opinion over using Standardization and Rationalization. Repetition and standardization of the house parts will not affect the freedom of architecture, as Gropius describes. Each unit has a unique expression according to the individual personality, producing a mix of maximum standardization and maximum variety (Gropius, 1965).

Gropius offered another critique of architecture under rationalization, highlighting the beauty that arises from the simplicity of module designs that can be easily assembled to meet our needs without weighing heavily on the ground. According to Gropius, the benefits of prefabricated homes constructed from these modules are primarily economic. They can elevate living standards, making many of today's luxury features standard fare in future homes.

Walter Gropius envisioned the Bauhaus school to revolutionize the design industry. His goal was to merge the talents of artists and craftsmen with industrial training, creating a new breed of skilled and knowledgeable graduates capable of anything. He famously described these students as possessing the ability to introduce innovative ideas to the industry and use machinery to bring those ideas to life (Gropius, 1965). As a prominent figure in the Bauhaus movement, Gropius aimed to become the Henry Ford of housing. His first project after leaving the school was the Copper House, which incorporated the principles of Bauhaus architecture and design.

2.3.3 The Hirsch Copper House

The Hirsch Copper House (P-30, Tables 4.1.1 & 4.1.2) is an example of a saga project that Walter Gropius was a part of in the 1930s after he left the director position at Bauhaus resembling the first prefabricated house project that he was visioning through the years in Bauhaus. The company (Hirsch Kupfer-und Messingwerke) (Hirsch copper and brass works) is one of the major leading companies in Germany in the 1900s beginnings, with various copper products like tubing, sheeting, and roofing. Hirsch took the idea of Förster and Krafft and made a production line for the element of the house under an entirely specific department in the factory (the Copper House Department). Houses examples (six houses) were erected for exhibitions like the Paris International Colonial Exhibition in 1931 and the Berlin Exhibition (Figure 2.3.2) (Gropius & Wachsmann, 2021).

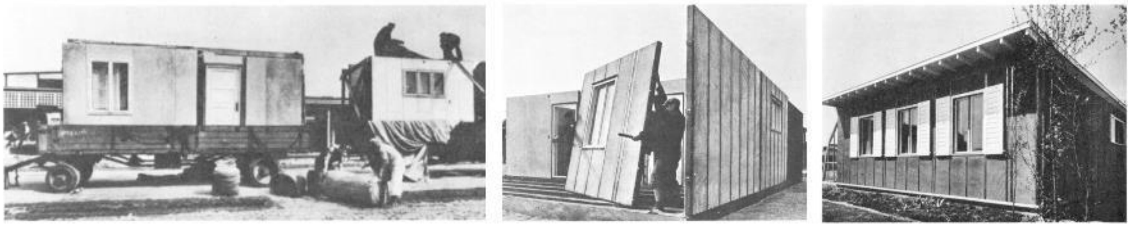


Figure 2.3.2 Process of erecting a house in Berlin exhibition 1932 (Gropius & Wachsmann, 2021).

Walter Gropius was impressed with the copper house concept in general, but he had, of course, his ideas and plans to enhance some of the technical and architectural details of the house. In June 1931, the official relationship between Gropius and Hersch on the Copper House began. Gropius immediately took responsibilities off Hirsch's back, such as design, research, development, and marketing (Gropius & Wachsmann, 2021). The Copper House as a prefabricated dwelling had advantages that made it famous in Germany, other countries, and the United States. Some of these advantages are noted in the Copper House as building accuracy, mechanical assembling, Healthy standards, excellent level of thermal insulation, and fire resistance, in addition to resistance to lightning and earthquakes, freely movable internal space, and all that can be assembled in 24 hours. Wall panels were finished inside a factory with aluminium coating and sanitary and electrical installations. Panels were manufactured with openings with mainly four types, as shown in (Figure 2.3.3) (Gropius & Wachsmann, 2021).

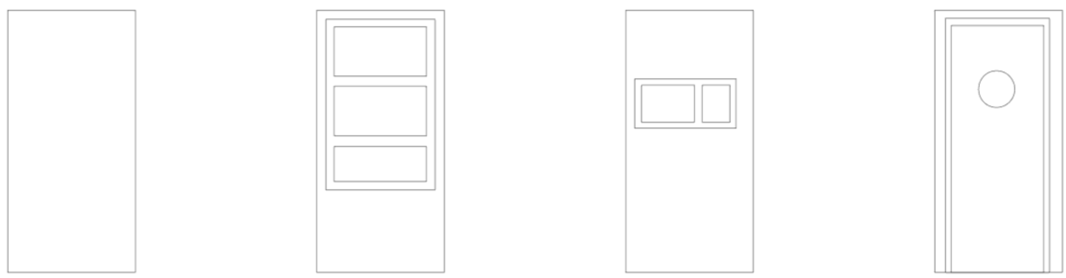


Figure 2.3.3 Copper house components, redrawn by the author using (Gropius & Wachsmann, 2021).

Although Gropius was impressed by the idea of the copper house and its advantages, he still criticised the design, structure safety, detail drawings, the noise caused by weather conditions like rain or hail on the copper sheets, and other service installation issues. The main question that concerns Gropius and is constantly debated is the necessity of designing under standardisation but keeping a certain level of variety for the buildings.

Standardized panel and part designs were manufactured within several options, such as the variety of colors for the interior walls and finish patterns, as shown in (Figure 2.3.4). The panels were delivered to the site fully completed and ready to be assembled in four basic types: wall panel, sliding window panel, small window panel, and door panel, as illustrated in (Figure 2.3.3).

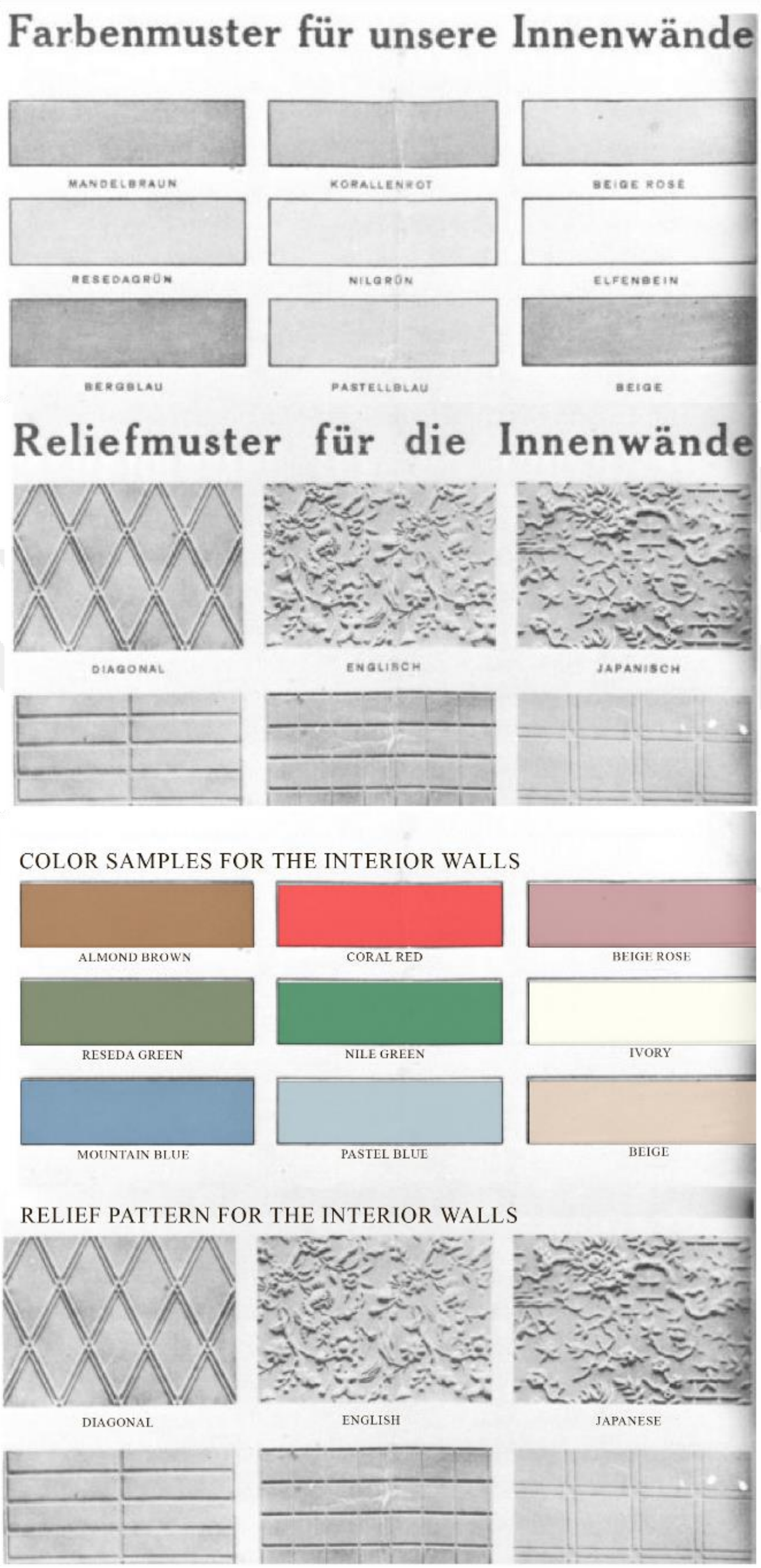


Figure 2.3.4 Wall samples, colors & patterns, in German, translated and made by the author using (Gropius & Wachsmann, 2021)

Marketing and advertisement of this new housing concept was a significant sector of the department in which flyers and brochures were carefully designed and drawn to show an example of a Copper House and the process of assembling, as shown in (Figure 2.3.4) & (Figure 2.3.5) for a type of the houses as well as other types published like (Haus Kupfercastell) CopperCastell 1931.

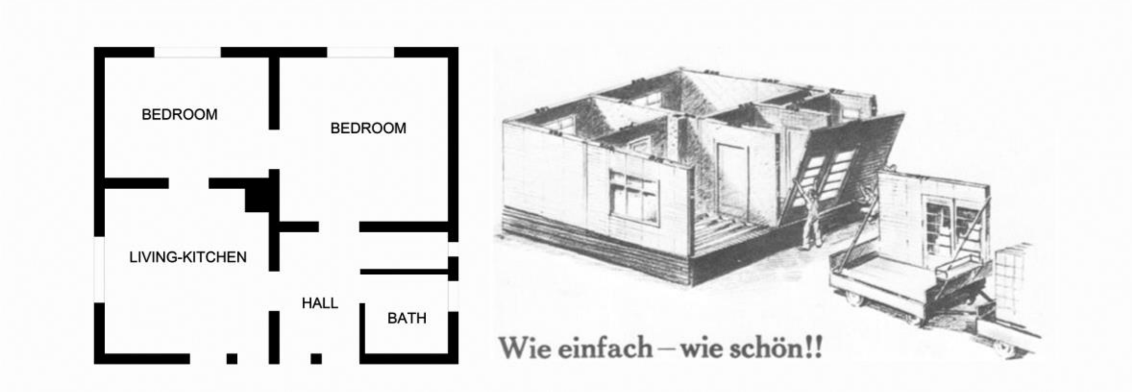


Figure 2.3.5 Copper house assembling process ad in 1931, Saying: "How simple - how beautiful !!" with a floor plan redrawn by the author using (Gropius & Wachsmann, 2021).

The Copper House improvement and refining continued, particularly for the aesthetic and technical aspects, in addition to testing all house components and parts like the copper sheets and the jointing system for better options and methods. Gropius implemented the idea of continuous work and collaboration between the factory and designers from the Bauhaus school program, keeping the importance of creating a system of modularity and standardization. In doing so, Gropius improved and designed new types of copper houses (Figure 2.3.6). There were nine types of houses mentioned (Gropius & Wachsmann, 2021) ranging from expensive to affordable:

a- The Copper Castell (Kupfercastell) is a 100 m^2 two-floor house costing 10900 RM (Reichsmark, equal to 2595 US dollars at the time 1931). The Copper Castell house was one of three houses shipped to the United States in 34 packages.

b- Eigen Scholle, a 56.6 m^2 house for 6300 RM (equal to 1500 US dollars).

c- Type K, a 37 m^2 house costs 4200 RM (equal to 1000 US dollars) with three rooms, an open kitchen, and a bathroom.

d- Type K1 is a 62 m2 house that is bigger with two more rooms than type K.

e- Type K0 and K2, as slightly different models.

f- Type M is a basic model house of 49 m^2.

g- Type R, a large model seven rooms house villa of 167 m2 and cost 13600 RM (3238 US dollars)

Figure 2.3.6 Copper house types (Gropius & Wachsmann, 2021).

The goal set by Gropius was to manufacture around ten houses each month. However, exact and specific numbers of the Copper House production are not available other than that about 30 houses were produced at the end of 1931. In addition to working with his office on the design of Copper Houses, Gropius also worked on their catalog and marketing by listing and highlighting the house advantages such as quality, economical prices, lightness, easy transportation, and quick delivery (2 – 3 months). Gropius's efforts to promote the houses paid off in drawing the attention of the Russians; they were particularly interested in the houses' quick production and building period. The United States also was interested in the Copper House, and the records show three houses shipped to New York, Los Angeles, and Houston.

As the Copper House represents a new idea, one of its greatest successes was at Competitions like the Wachsende Haus exhibition in Berlin in 1932, where two houses were erected at an astonishing speed according to Gropius's detailed working schedule (Figure 2.3.7). The two houses were a great success at the exhibition and were among the best examples resembling successfully the advantages Gropius listed as easily transported, adaptable, and flexible (Gropius & Wachsmann, 2021).

Figure 2.3.7 Copper house erection speed process, Berlin exhibition 1932 (Gropius & Wachsmann, 2021).

While Gropius was not the one who patented the idea of the Copper House, he improved many of its aspects and advantages, and it can be considered that he was the reason for its success. For example, Gropius used different materials, steel, and aluminum, for the interior walls, enhancing thermal and acoustic performance and other safety properties. He also improved the design using horizontal copper sheets for exterior walls and replaced the pitched roof with a flat roof. Basically, he turned the Hirsch type into a modular prefabricated house. For Gropius, it was not just a passing project but rather represented the idea that he had always been interested in since 1910: prefabrication. To actually put it into action was an essential step for him. The idea of prefabrication balances maximum standardization with controlled diversity simultaneously. However, it was just a start, and the Hirsch prototype that Gropius worked on was still limited. One of the most critical aspects of the shortcomings and limitations of the Hirsch system is its great freedom for diversity in the planning stage. However, this freedom is limited and decreases during and after construction, which makes it a preliminary idea that is still far from the optimal use of prefabrication and Modularity (Gropius & Wachsmann, 2021).

Despite some success achieved by the short life of the Copper House, Gropius did not feel it was the success he had always dreamed of building a house in a factory for mass production. Gropius's journey with the Copper House ended in 1932 because of differences between him and Hirsch. However, almost simultaneously, the Copper House failed to be profitable as their cost was not cheaper than the traditional method, and they stopped production. Financial issues and the crisis and deflation in the years 1930 - 1933 played a significant role in the failure of the Copper House and not the personal relationship between Gropius and Hirsch or the design and beauty of the house (Gropius & Wachsmann, 2021). Another example by Gropius for the prefabrication concept will be illustrated in Chapter 4.

2.3.4 Le Corbusier & The Citroen House

A captivating floor in the history of modular discourse revolves around one of the most intriguing personalities in 20th-century architecture, Charles-Edouard Jeanneret, popularly known as Le Corbusier, a Swiss-born French artist who excelled in various disciplines, such as architecture, urban planning, painting, sculpture, and design. He was among the first architects to incorporate the concept of modules in architecture by using human body measurements (Anthropometry) to create harmonious spaces in buildings. Le Corbusier debated this subject with other architects of his time. His work was developed through collaboration with many architects, designers, and painters. To write his book "The Modulor," he worked on proportion for several years and met many architects, providing one of the essential sources. Le Corbusier believed that modularity represents beauty and aesthetics, similar to ancient beliefs (Cohen, 2014). In "The Modulor," he envisioned a proportioning system in building sites to quickly join the elements of prefabricated projects and ensure harmonious planning and installation of rooms, doors, and windows.

During his visit to New York in 1945, Le Corbusier introduced the idea of Modulor to the renowned physicist Einstein (Figure 2.3.8), who later commented in a letter to Le Corbusier that "it is a scale of proportions which makes the bad difficult and the good easy" (Corbusier, 2021). Einstein's comment highlights the importance of "The Modulor" as a significant development in architecture, as it shows the negative impact of industrialization on our physical life, causing a separation between our bodies and our surroundings. The industrial standardization approach aims to achieve uniformity, which reflects our need to find standard products that bring everyone's needs together (Figure 2.3.9).

The explanation of modularity and prefabrication by Le Corbusier, as presented in Chapter 3 of The Modulor (Corbusier, 2021), is both straightforward and compelling. He states, "Order is the very key of life." While his ideas are subject to more detailed research and analysis, they can provide a valuable framework for comprehending the concept. To illustrate his statement further, Le Corbusier used the alphabet as an analogy, with 26 letters representing modules that can be combined to create countless words (or buildings), each with its unique form and function. This approach's possibilities of order are infinite, but the challenge lies in designing a practical set of modules to realize it. Creating a modular, efficient, and aesthetically pleasing modular design remains a crucial objective in contemporary architecture.

Figure 2.3.8 Le Corbusier and Albert Einstein meeting in 1946 (Basulto, 2011)

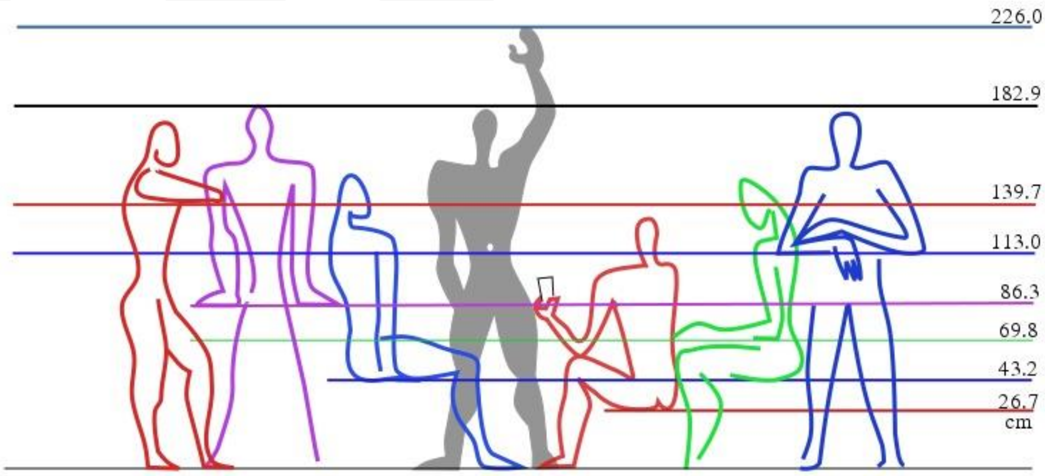


Figure 2.3.9 Le Corbusier's Modular man (Arellano, 2018)

Le Corbusier's impact on modernism during the 20th century was significant, and his ideas for standardization in the construction industry began in the 1920s with the Citroen house he designed (P-32, Tables 4.1.1 & 4.1.2). The Citroen House, also known as the Maison Citrohan (Figure 2.3.10), was created to support his statement that "a house is a machine for living." This statement reflects his admiration for the technology behind the perfection of automobiles, aeroplanes, and ships, which he considered the Greek Temples of today (Smith, 2011).

Figure 2.3.10 a Sketch of a pre-constructed version of the 1927 (Maison Citröhan, n.d.)

The Maison Citrohan is a prime example of Le Corbusier's principles of functionality, efficiency, and a break from traditional architectural norms. Le Corbusier's vision for the Maison Citrohan was to produce a prototype for mass-produced housing that could solve the housing crisis in post-World War I Europe. The house was designed to be easily replicable, utilizing standardized components that could be mass-produced and assembled quickly and economically. He famously coined the house concept as a "machine for living," and the Maison Citrohan exemplifies this idea (Smith, 2011). Le Corbusier designed five prototypes of the Maison Citrohan from 1920 to 1927, each version more refined than the previous one (*Maison Citröhan*, n.d.). The design of the house is an open plan floor, flat roof, and horizontal windows, using industrial materials such as steel and glass and prefabricated doors and windows to reflect the influence of the machine age on architecture (Figure 2.3.11) & (Figure 2.3.12). Although the Maison Citrohan was never constructed on a large scale, it played a significant role in shaping modernist architecture. The house's modular design, interchangeable walls, andadaptability showcased Le Corbusier's vision for addressing evolving human needs over time (Smith, 2011).

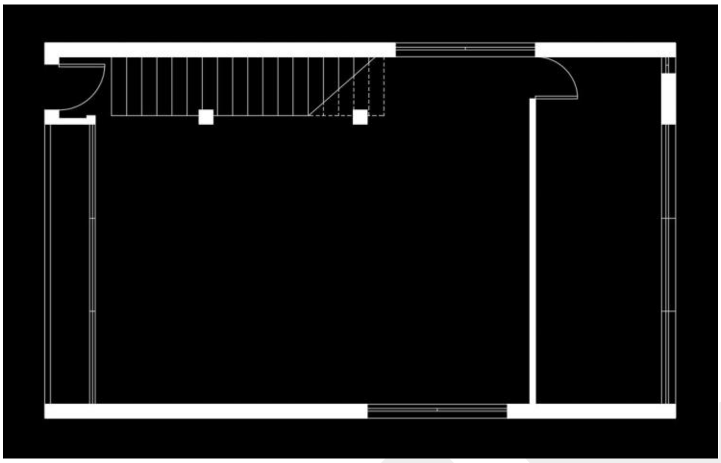


Figure 2.3.11 Citroen house first floor plan redrawn by the author (P-32, Tables 4.1.1 & 4.1.2)

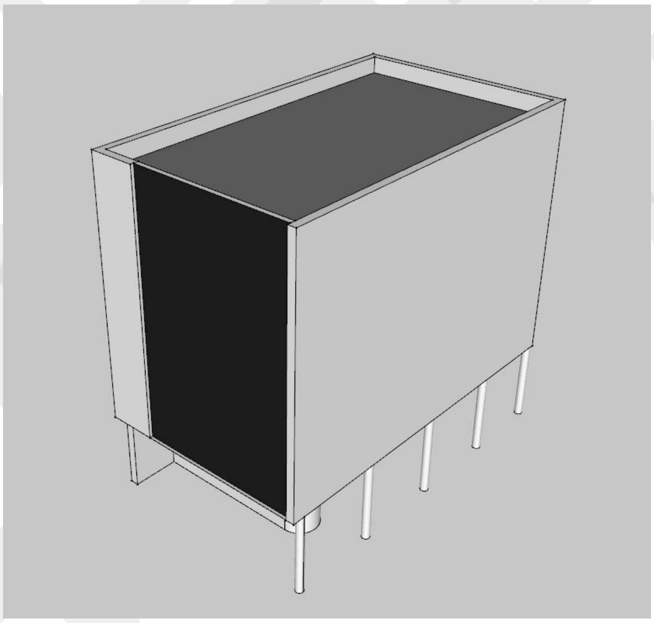


Figure 2.3.12 Citroen house 3D model made by the author (P-32, Tables 4.1.1 & 4.1.2)

2.3.5 Bemis and the Cubical Modular

The modular design has been applied in diverse ways throughout history and in various fields. In the field of architecture, one of the key figures who adopted this principle was Albert Farwell Bemis, a prominent figure in the mid-century American housing and construction industry. According to (Russell, 2012), Bemis's Cubical Modular Concept, which he proposed in the 1930s for mass production, has been a topic of debate, especially when compared to Le Corbusier's Modulor. In fact, Bemis and Le Corbusier had some conflict over the originality and method of their respective modules.

Bemis's module was essentially a unit of measurement, similar to an ancient concept. He extended his module in three dimensions, adding practical utility to the concept. The cubic shape of 10 cm (4 inches) was based on the American wood-frame house (Figure 2.3.13). Bemis believed the cubic module would provide a certain quality, unity, variety, and symmetry for design criteria. In short, Bemis's cubical modular concept operated at a basic level of dimensional coordination for every building component and at a higher level of abstraction and ambition. However, there are limited articles on his cubic modular concept and use, with only a few publications available.

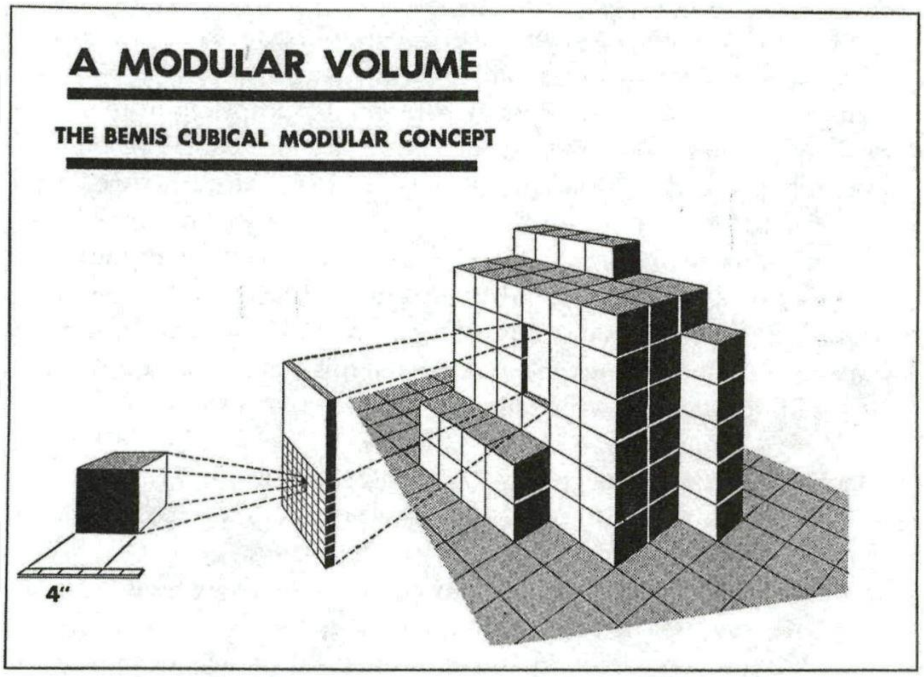


Figure 2.3.13 Bemis cubical modular concept (Russell, 2012)

This chapter has shed light on the widespread presence of proportions in nature, as evidenced by the Fibonacci sequence, golden ratio, and spirals. Looking back at ancient Roman architecture, we see the emergence of the "module" as a crucial tool for achieving harmonious structures, first mentioned by Vitruvius and later endorsed by Leon Battista Alberti. During the Industrial Revolution, modularity gained popularity in the industrial sector, but its limited integration into construction prompted architects and designers to find innovative solutions. The contributions of figures like Peter Behrens, Walter Gropius, and the Bauhaus movement were instrumental, with Gropius's groundbreaking prefabrication ideas exemplified in The Hirsch Copper House project. Le Corbusier's visionary designs, such as The Citroen House project and The Modulor book, also cemented his legacy as a significant figure in the history of modularity. Finally, Bemis's Cubical Modular idea, featuring a compact module of 10 cm, adds to our understanding of modularity's evolution. These historical milestones provide a foundation for exploring contemporary applications and considerations in subsequent chapters. The third chapter offers a comprehensive introduction to prefabrication and modularity. It establishes foundational concepts and explores the utilization of modules, providing insights into the diverse types of prefabrication systems and dimensions that characterize modular construction. A brief examination of the level of prefabrication introduces nuanced perspectives on assembly and construction processes. In addition, the chapter emphasizes the significance of lean production in modularity, highlighting the efficiency and resource optimization. The chapter concludes with an overview of modular construction's seismic performance and resistance, underscoring modular architectural designs' structural robustness and resilience. Collectively, these subtopics provide a thorough understanding of modularity's practical applications and considerations in architectural design.

Chapter 3

Modularity in Architectural Design

Thomas Hardiman from the Modular Building Institute (MBI), founded in 1983, defines *modular architecture* as “An off-site project delivery method used to construct code-compliant buildings in a quality-controlled setting in less time and with less material waste.” (Smith, 2011).

The definition of "module" in modern literature is not always clear or consistent across sources. It can refer to either physical building blocks or non-physical software components. Some have categorized modules based on their functionality to define the term better, such as primary, auxiliary, unique, and adaptive (Miller, 1998). In the mid-1970s, the term "module" was varied - some focused on producing affordable and efficient products for profit, while others used it to describe innovative and fashionable design (Russell, 2012).

Throughout the literature, many artists and architects have rejected concepts that limit their creativity, such as Van de Velde's rejection of type and standardization. It is essential to consider both the advantages and disadvantages of modular construction. While the benefits of modular construction are widely recognized, it is essential to recognize the obstacles that prevent its widespread use. Advanced planning and engineering are necessary for every step of a modular project, and the financial power of large contractors can be a barrier. Additionally, some architects may resist limitations (Ap, 2017). Since the 1970s, there have been two interpretations of the term "module." One has focused on profit, denoting cheap and efficient construction, while the other has emphasized creative and stylish design (Russell, 2012).

3.1 Prefabrication & Modularity

The prefabrication construction method has a long history, with evidence dating back to 1624 in English houses and in the late 1700s in hospitals and warehouses. It is often confused with modularity, which is a separate concept. However, large industrial companies use both methods together in mass customization projects. Notably, projects like Habitat 67, The MDU house, and the EX's Nine-level shipping mall have successfully utilized both modularity and prefabrication during the production and construction processes (Kotas et al., 2001). A wooden housing project in Amsterdam-Netherlands is another example of these concepts working together, with modules prefabricated in a factory and then transported to the location for assembly. Prefabrication is a technique that is primarily used in industrial work, where building components are manufactured in a controlled environment free from production obstacles like inclement weather (Staib et al., 2008). While prefabrication and modularity are distinct systems, they are nevertheless closely related. These systems can be classified based on the level of prefabrication that a product possesses when it leaves the factory. Essentially, any material manufactured on a mass production line is considered prefabricated. However, if a product has a prefabrication percentage that exceeds 90%, it falls under the modular category. Consequently, modularity refers to producing project components mostly in factories, requiring minimal on-site work. Prefabrication offers several advantages, including high precision and predictability regarding both time and cost and easy site access. This is particularly valuable for all stakeholders involved in a project, including project owners, architects, and builders. However, it is essential to note that there are also some drawbacks, the primary one being the cost. Prefabrication projects can be expensive due to the need for specialized equipment and materials, making them less accessible for those on a tight budget.

3.2 Modules

In the early days of the modular architecture movement, which began to gain popularity in the mid-20th century, the focus was on futuristic designs that utilized new methods of structure, materials, layout, and finishes. Examples included Buckminster Fuller's Dymaxion House in 1927, Moshe Safdie's Habitat 67, and the Nakagin Capsule

Tower in 1972. However, today's modular design focuses on delivering fast projects with high-quality outcomes, allowing for faster construction times than traditional on-site construction. Later in this thesis, we will delve more deeply into these projects and others. The term "module" has its origins in an ancient measuring tool. However, modern modular design refers to units of a particular scale or dimension that can be prefabricated and assembled on-site. Modular architectural projects can be divided into two types: residential and commercial. Within each type, projects can be temporary or permanent, and building materials can vary from timber to steel or concrete, depending on the location and required structure.

Regarding prefabricated construction, there are typically three systems commonly used: frame construction, panel construction, and room module construction (often called volumetric construction). Frame construction involves assembling a structure using pre-made frames that are then connected. Panel construction involves using pre-made panels assembled on-site to form the structure. Room module construction involves fully assembling rooms or sections of a building off-site and then transporting them to the construction site for installation. These construction methods have unique advantages and disadvantages and can vary in cost and complexity depending on the specific project requirements.

3.3 Types of prefabricated systems

Comprehending the various forms of prefabrication and modules is an extensive topic, as various systems exist, some exclusive to each project. This research will condense the topic into three principal system types of construction: Frame construction system (FCS), Panel construction system (PCS), and Room module system (Volumetric units) (RMS) (VU). These systems can be composed of different materials, such as Timber, Steel, or Concrete, depending on the specific project requirements (Smith, 2011) (Staib et al., 2008) (Lawson et al., 2014).

The dissimilarities among various construction systems can be characterized by their level of flexibility and degree of prefabrication, as illustrated in (Figure 3.3.1). The Frame system is the most flexible and the least prefabricated, while Room module units are the most prefabricated and the least flexible. The Panel system falls between the two and can be considered a moderate option (Staib et al., 2008).

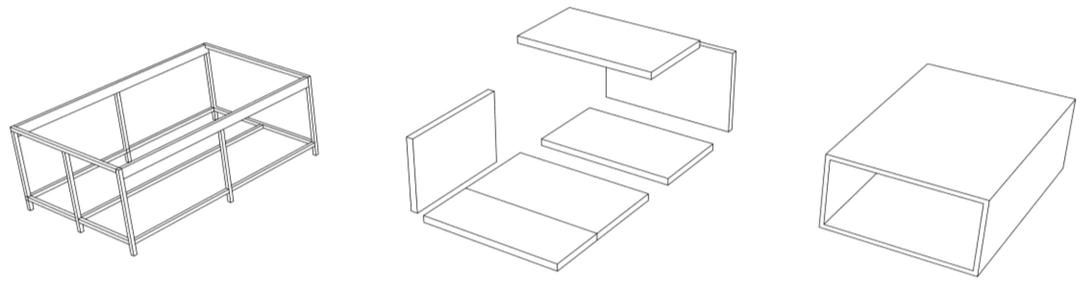


Figure 3.3.1 Prefabricated building systems (left to right) Frame, Panel, and Room unit drawn by the author

3.3.1 Frame & Panel Construction System

Frame and Panel are the most widely used systems for prefabrication projects (Bayliss & Rory, 2020). The frame system is constructed from linear elements such as columns and beams supported with other elements to achieve more stability and resist loads (Staib et al., 2008). Depending on the project type, location, and requirements, this system can be constructed from timber, steel, or concrete.

Timber frames are used to build Schools, houses, and hotel projects; However, Timber is less common than steel and concrete for modular projects. Usually, for housing projects, Timber modules are constructed with a maximum height of 2 floors; the house will be erected using timber studs with a particular dimension and then fitted with insulation materials, boards, and interior equipment (Lawson et al., 2014). Various construction methods use timber; the difference is mainly based on how columns and beams are built and the type of connection used (Figure 3.3.2). There are types such as Solid timber, Glued laminated timber (glulam), and Cross laminated timber (CLT) (Staib et al., 2008) (Bayliss & Rory, 2020). The timber frame construction system is today's primary and simplest offsite construction method (Bayliss & Rory, 2020).

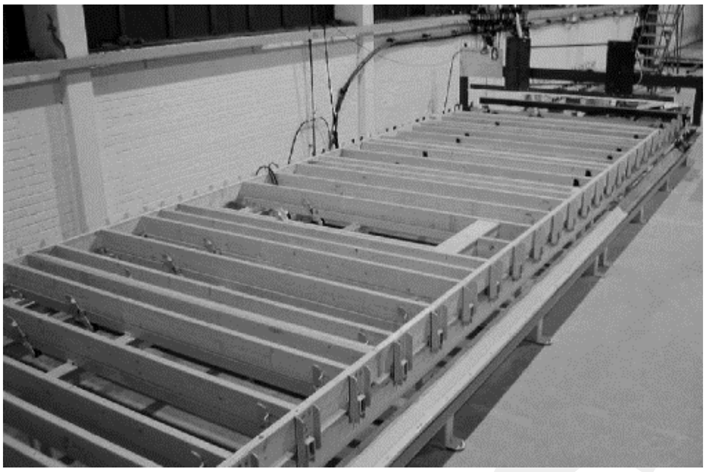


Figure 3.3.2 Manufacturing a timber floor (Lawson et al., 2014)

The steel frame has the same principle, but columns and beams made out of steel have a high load-resisting ability while keeping a minimum weight. Since the modern steel development, there have been a variety of building applications using steel frames; a popular type of steel frame construction for houses is (LGS) Light Gauge Steel (Staib et al., 2008) (Bayliss & Rory, 2020). Concrete frame construction, on the other hand, since they have high dead loads, is mainly limited to buildings with a low height, typically one floor, such as industrial buildings (Lawson et al., 2014) (Staib et al., 2008). (Figure 3.3.3) represents the construction process of a concrete frame for a house in Germany 1995.

Figure 3.3.3 Concrete frame construction, House in Germany, 1995 (Staib et al., 2008)

Panel systems are 2D panels that are prefabricated and manufactured inside factories with all necessary boards and insulations and then delivered to the site (Lawson et al., 2014). These panels are used mainly to build walls but also for floors and roofs, and they can be either load- or non-load-bearing elements (Smith, 2011). Like frame construction, Panels are made of Timber, Steel, or Concrete. However, panels are also available from masonry for some special projects and requests (Staib et al., 2008). The construction method for panels is divided into three main types: small panels, large panels, and Cross wall panels, as shown in (Figure 3.3.4). Each type has a different use and dimension based on the project type and elements. Out of the three materials for panels (Timber, Steel, and Concrete), concrete panels are the most used type, suitable for multi-floor houses, and the thickness of concrete panels gives an advantage of good sound and fire insulations (Staib et al., 2008).

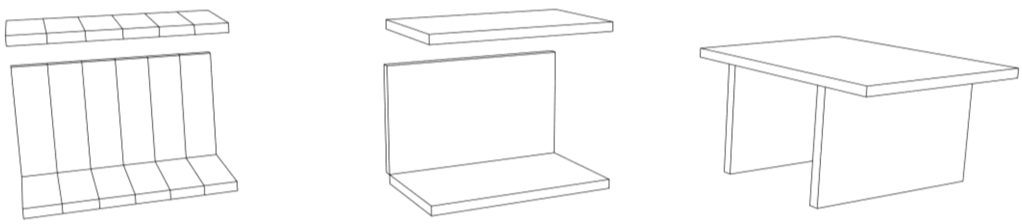


Figure 3.3.4 Construction panel system types (left to right) small, large, cross wall panels drawn by the author using (Staib et al., 2008)

3.3.2 Room module system (Volumetric unit)

Room module construction system or Volumetric unit construction is a Three-dimensional unit manufactured to the highest level of completion required for the project. While the two systems, Frame and Panel, are the most widely used for projects, they are not the ideal option for capturing the benefits of the prefabrication concept (Bayliss & Rory, 2020). Volumetric construction is the main focus of information and project case study types this research is conducted around as they are the highest-level offsite construction can reach as of current techniques. For comparison, the Automobile industry manufactures products that are 100% prefabricated; volumetric room units can be manufactured inside factories up to 95% prefabricated, leaving only the minimum percentage of work to the assembly process on site (Staib et al., 2008). Modular projects, as illustrated in the history section of the research, mainly were about utopian futuristic ideas back in the 1960s and 1970s; however, currently, most of the projects use this concept to erect buildings as fast as possible (Smith, 2011). The massive advantage of volumetric units for these interested parties is the ability to modify, produce, and customize room units to fit any project, whether temporary or permanent buildings and horizontal or vertical (Staib et al., 2008).

Modular units, as the other two systems, can be manufactured from Timber, Steel, or Concrete with dimensions limited to transportation requirements. In addition to the material used, these room units are available in various forms: partially open-side modules, fully open-side modules, or all closed modules, depending on the type and design of the project (Figure 3.3.5). These forms give freedom to the architect to use multiple modules to design one-, two-, or three-room apartments (Staib et al., 2008).

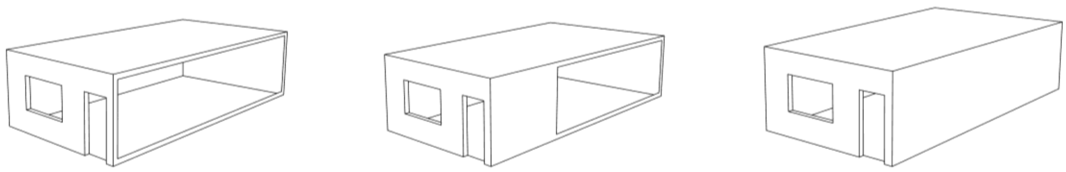


Figure 3.3.5 Volumetric module types (left to right) Fully opened, Partially opened, Fully closed, drawn by the author using (Staib et al., 2008)

Timber modules (Figure 3.3.6) are a popular material used for the modular construction method. However, this material is considered efficient when designing a house with a maximum three-floor height. Any higher than that, switching to different materials such as Concrete or steel is more economical. LAKE TAHOE HOUSE in Irontown, built by Michelle Kaufman and Paul Warner, is a timber module house of 325 m2 that was finished in about five months, more than three months of prefab work inside a factory and then shipped to the location for assembling in two days (Smith, 2011). Kam Valgardsen from The Irontown Homebuilding Company, after years of doing a handful of housing projects, believes that the absolute best advantage of modular construction is the ability to follow time and budget schedules with high accuracy. The eminent disadvantage is the limitation on the design and dimension restriction that the transportation required.

Figure 3.3.6 Timber module assembly process (Staib et al., 2008)

Steel modules (Figure 3.3.7) are mainly for commercial modular projects since these projects tend to require a sturdier structural system. One of the famous companies working with Steel modules is Kullman Buildings Corporation. The modules built from steel can be six floors high. The steel modules can be 3 by 8 meters or even 6 by 20 meters with a height of 3.2 m, completed in a factor and infilled with the necessary layers and insulation (Smith, 2011).

Figure 3.3.7 Modular housing project, Germany 1997, Steel room modules (P-10, Tables 4.1.1 & 4.1.2)

Shipping containers are a well-known example of utilizing steel modules. These containers are designed to have structural solid properties and can be transported with standard dimensions of 2.42 meters in width and up to 12.19 meters in length, with a height of 2.59 meters (Lawson et al., 2014). With over 800,000 unused shipping containers stored in ports throughout the United States and Britain, they can be repurposed as a cost-effective source of steel modules for housing projects. It is important to note that these containers meet most building codes and can withstand up to 15 floors (Smith, 2011). A great example of a housing project using shipping containers is the Keetwonen Amsterdam student dormitory (P-34, Tables 4.1.1 & 4.1.2), designed by Architectenburo JMW. It is the largest shipping container housing project globally, providing approximately 1034 modules and offering a thousand student units (Figure 3.3.8). Although initially designed as temporary housing, its popularity has led to its continued use.

Figure 3.3.8 Keetwonen Amsterdam, reused shipping containers modules (P-34, Tables 4.1.1 & 4.1.2)

Concrete modules (Figure 3.3.9) are made from any concrete desired, either regular or lightweight. However, the process should be inside factories to achieve high-quality modules produced. Restrictions for building concrete modules should be followed depending on the project's location; for example, the thickness of the module walls should be at least 5 cm (Staib et al., 2008). The fact that the walls and floors of the module are all concrete increases its structural strength and enables the modules to be stacked for a multi-floor building.

Figure 3.3.9 Habitat 67 by Moshe Safdie, Reinforced Concrete modules (Habitat ’67, n.d.)

The process of renovating old buildings can pose significant challenges, particularly when it comes to preserving their original form and quality. In such cases, room module units provide a viable solution. Specifically designed to blend seamlessly into existing structures, these units enable the creation of a functional living area while maintaining the building's timeless character. Utilizing room module units makes it effortlessly possible to add a comfortable living space without sacrificing the underlying structure's unique form and integrity (Lawson et al., 2014).

3.3.3 3D Printing

The global 3D construction market is set to experience extraordinary growth, projected to rise by an impressive 91% between 2021 and 2028 (Gemma Falconer Da Silva, n.d.). This progress can provide economical housing, disaster relief shelters, and a sustainable construction solution. An advantage is the reduced construction costs associated with this approach. The efficiency of 3D printing technology has advanced to the point where entire building units can now be printed within 24 hours. An essential benefit of the 3D-printed architecture is its capability to offer a more sustainable construction method using local materials. Experts are actively researching alternatives to traditional materials, such as clay, as evidenced by the testing home TECLA conducted by architects WASP and Mario Cucinella in Italy (Figure 3.3.10).

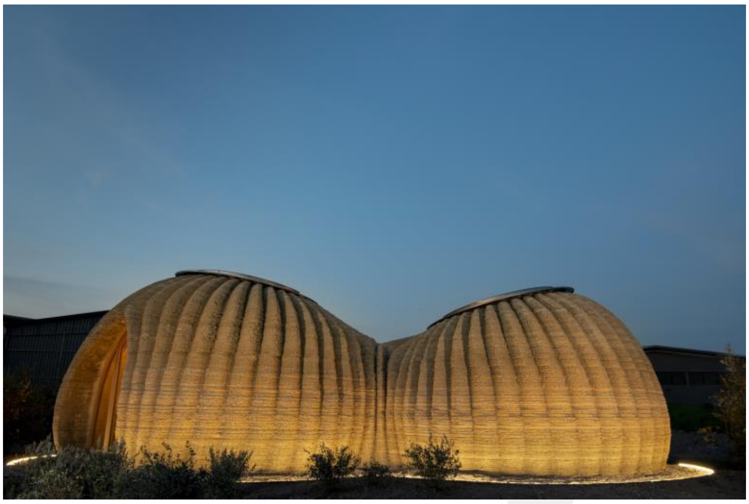


Figure 3.3.10 Clay 3D printed house (Paula Pintos, n.d.)

In California, USA, Mighty Buildings is a recent entrant in the field, utilizing 3D printing and robotic automation to realize the vision of constructing affordable and sustainable homes. The company has completed a two-bedroom house using its innovative system (P-55, Tables 4.1.1 & 4.1.2), which involves printing 22 panels through a combination of 3D printing, robotics, and automation. Essentially utilizing a panel construction system, this method boasts a claimed 99% reduction in waste and a lower carbon footprint than conventionally built homes (Figure 3.3.11).

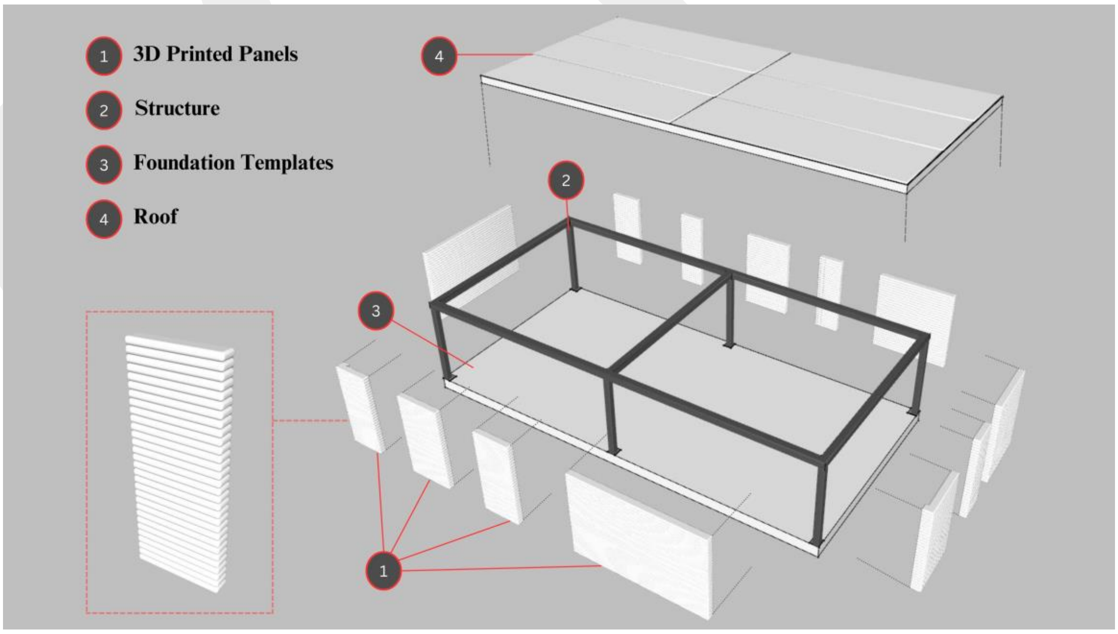


Figure 3.3.11 Mighty Building 3D printed house model made by the author (P-55, Tables 4.1.1 & 4.1.2)

3.3.4 Modules dimension

According to (Smith, 2011), the current dimensions for modules are restricted to 4-4.9m in width, 15.8-18.2m in length, and 3.6m in height due to transportation constraints. However, some companies, such as Boxabl in the United States, have developed foldable or pull-to-open modules to expand the range of sizes available. (Figure 3.3.12) and (Figure 3.3.13) showcase a 2D plan and 3D model for a module utilized in the construction of the Greenford Quay project in West London in 2020 by HTA Design LLP architect. The project incorporated various module dimensions. (Bayliss & Rory, 2020).

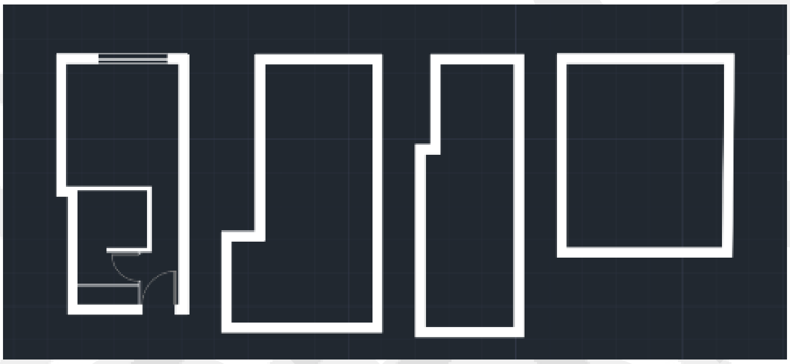


Figure 3.3.12 2D Modules plans drawn by the author using (Bayliss & Rory, 2020)

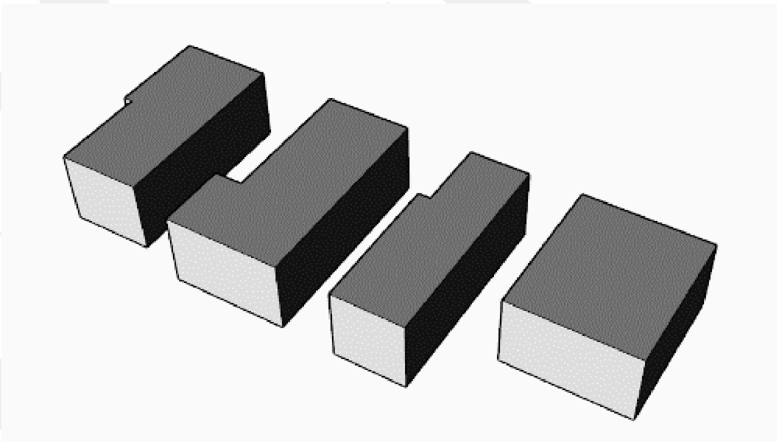


Figure 3.3.13 3D models made by the author using (Bayliss & Rory, 2020)

3.4 Level of Prefabrication

Prefabricated building parts and modules are manufactured in factories with varying levels of completion. These levels start from raw materials and progress to fully finished modules (as illustrated in Figure 3.4.1). The level of prefabrication for modules typically ranges from 60% to 95%, with some factories producing modules that are almost complete before they leave the factory. This means that the work required on-site is significantly reduced, making the construction process more efficient and cost-effective. (Smith, 2011).

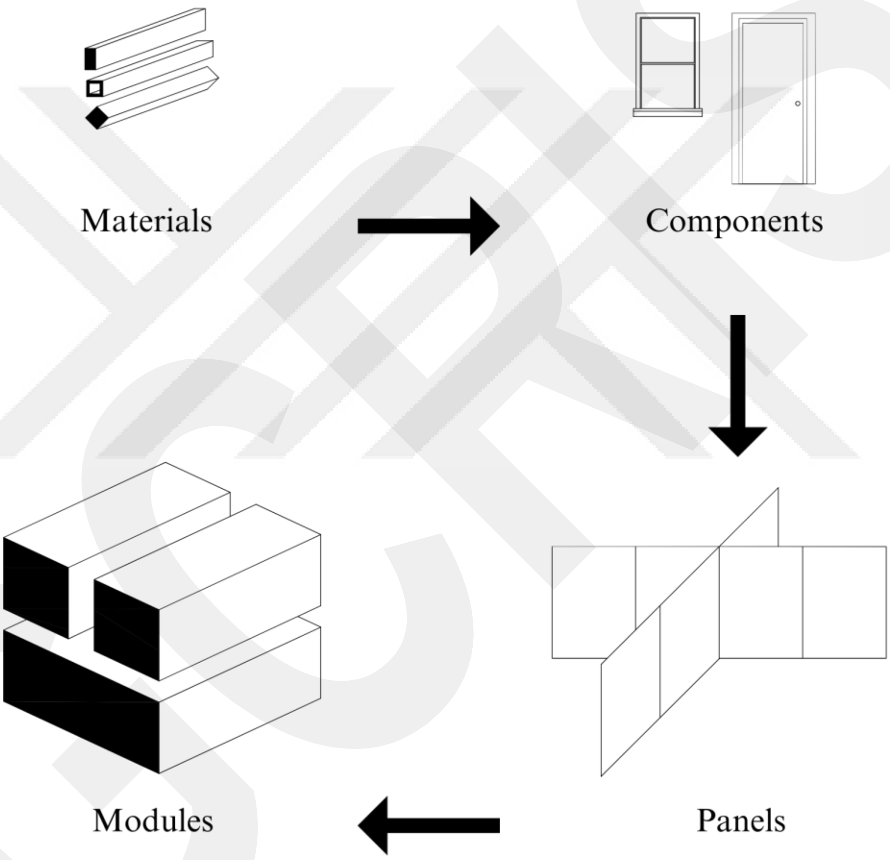


Figure 3.4.1 Level of prefabrication, Materials being the least and Modules the most, drawn by the author using (Smith, 2011)

3.5 Lean Production

The lean concept in manufacturing mainly aims to reduce production time to the minimum and respond to the consumers. This concept is well known in the automobile sector, especially by Henry Ford. The Japanese car company Toyota uses this concept for building prefab houses with five principles borrowed from the company's lean production line it from its car production line (Just in Time, Jidoka, Heijunks, Standard Work, Kaizen). The houses are built with modules that are 85% completed, with most of the elements installed before being sent to the site. Toyota is not the only manufacturer to use this concept. Many other companies are also trying; however, the construction sector is still far behind other industries, such as automobile and aviation. Lean production will be enhanced by adding value and reducing waste of time, cost, and construction material (Figure 3.5.1). Joe Tanney from the prefab housing company 4 Architecture divided the modular construction industry into two main types: The first is companies built inside factories, and the second is companies that use manufacturing processes in building modules (Smith, 2011).

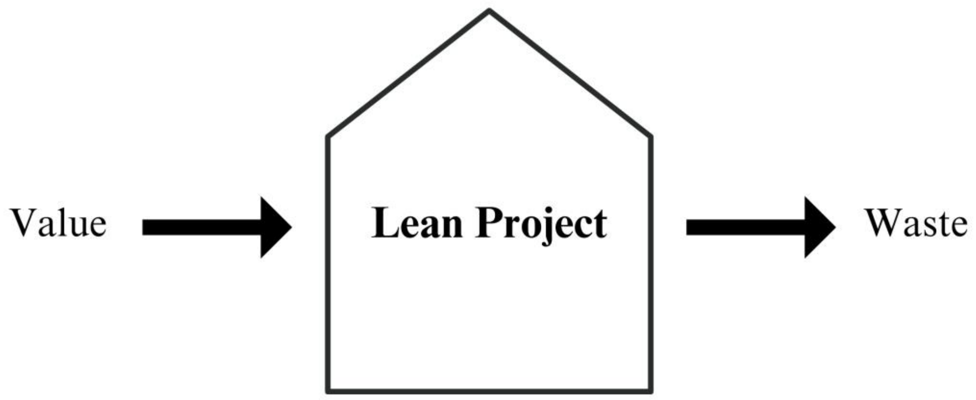


Figure 3.5.1 Benefits of Lean Production in housing construction, made by author using (Smith, 2011)

According to (Lawson et al., 2014), Modular units can be manufactured using one of three central production systems: static, linear, and semi-automated linear production. In static production, the module is built in one position, and materials, services, and personnel are brought to the module, making the process relatively slow. This method can produce 800 to 1200 modules per year. Linear production involves a sequential manufacturing process in discrete stages, similar to an automotive production line. Modules in this system move from one station to another, and the more lines there are, the more modules can be produced. This system can manufacture 3000 modules per year. The semi-automated linear production system is similar to linear production. However, instead of working on the module, it is broken down into elements such as wall, ceiling, and floor panels, which are manufactured in parallel. This system can produce a module every 20 minutes, resulting in about 6000 modules annually. The semi-automated linear production system is three times more productive than traditional on-site construction.

3.6 Modular seismic performance

While assisting the seismic performance and resistance of modular construction is not the primary objective of this research, the prevalence of tragic earthquake hazards worldwide has brought attention to the safety of modular buildings in the face of such disasters. The compact design of volumetric room modules, which combine walls, roofs, and floors into a single piece, provides a certain level of resistance to seismic hazards. However, studies have shown that modular building failures often arise from connection points between modules. For example, a failure at the corner connection on the first floor can cause a chain of other connection failures that affect the entire building (M et al., 2019). The type of connection used for panels or modules is one of the leading design factors for prefabrication and modularity. This has been in development for decades, with the packaged house, for example, having a unique connection system invented and patented by Kaufmann. Modular construction has various connection points, such as module-to-module, inner module, module-to-frame, module-to-core, or module-to-foundation connections (Figure 3.6.1). These connection points significantly affect the seismic performance of a modular building (Deng et al., 2020).

As mid-to-high-rise modular architecture projects become more common, it is crucial to focus on testing and enhancing the seismic performance of these structures. However, this section is not comprehensive enough to cover the seismic performance of all prefabricated module types, as each requires specific testing and data to assist its performance.

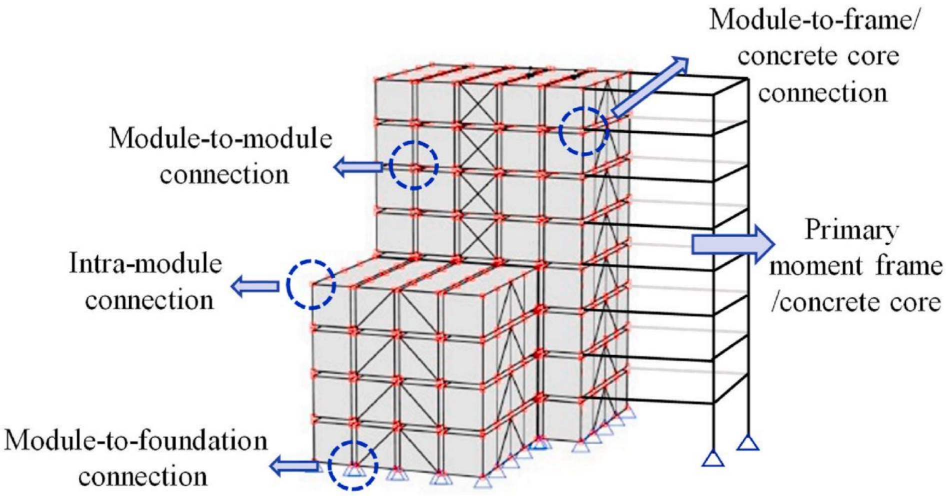


Figure 3.6.1 Connection types in modular construction (Deng et al., 2020)

This chapter has explored prefabrication and modularity, examining the different types of modules and their applications. The study has covered a range of prefabricated systems, from Frame and Panel to Volumetric units. The future of modularity systems and materials includes integrating 3D printing technology. The chapter has emphasized the importance of transportation requirements and the limited dimensions of modules. The study also highlighted how lean production principles have influenced modular construction and helped to streamline production practices. The connection points between modules and the seismic performance of modular projects are crucial considerations for ensuring the overall resilience of modular construction. The fourth chapter delves into the exploration of modularity through an extensive array of case studies that feature over 50 projects from North America, Europe, and East Asia showcasing prefabrication and modularity principles and systems in real projects. The chapter examines the North American origin of modular architecture, showcasing iconic projects such as Habitat 67. The study then transitions to European modularity, including pioneering projects and more. The exploration extends to East Asian modularity, showcasing Japan's capsule tower, Singapore's modular system, and China's rapid construction.

Chapter 4

Contemporary definition and use of modularity in architecture

This chapter will embark on an exciting journey as we explore many module projects representing various architectural styles and design philosophies. We will delve into captivating case studies from various parts of the world, highlighting innovative ideas and solutions that have transformed architecture. Additionally, we will glimpse visionary architects and companies at the forefront of this exciting frontier, pushing the boundaries of what is possible in architecture.

4.1 Case studies

Table 4.1.1 presents a comprehensive collection of projects to provide insight into prefabrication and modular methods. The projects were carefully selected from North America, Europe, and Asia, considered the key regions with the highest involvement in prefabrication and modularity, as shown in the map (Figure 4.1.1). Table 4.1.1 provides details such as the project name, architect, country, year, building material, project module unit dimension or area, and system type, as explained in Chapter Three. The majority of prefabricated projects tend to utilize the Panel Construction System (PCS) and the Room Module System (RMS), which is also referred to as the Volumetric Unit (VU). The Table provides essential details about each project, including its purpose, design philosophy, and distinctive attributes.

Additionally, a drawing code is assigned to facilitate easy tracking of projects across tables, maps, or figures in the text. Moreover, Table 4.1.2 showcases the projects in a visually compelling manner. The thesis author has included 2D plan drawings, 3D models, and actual photos of each project, providing readers with an immersive experience to delve into the nuances of each design. These carefully crafted visual representations seamlessly connect the theoretical aspects of modular design with the practical and spatial reality of these groundbreaking structures. Later, key projects from each region were chosen for more in-depth information about their significance in developing prefabrication and modularity concepts or for their role in introducing building techniques or changes. The projects were selected based on an extensive literature review to identify the primary architectural figures contributing to the development of modularity in housing design. Thus, pioneering figures were chosen, alongside other subsequent projects resembling the modular concept's continuous evolution up until the present day.

Figure 4.1.1 Map, Showing the locations of all the projects in Tables 4.1.1 & 4.1.2 made by the author

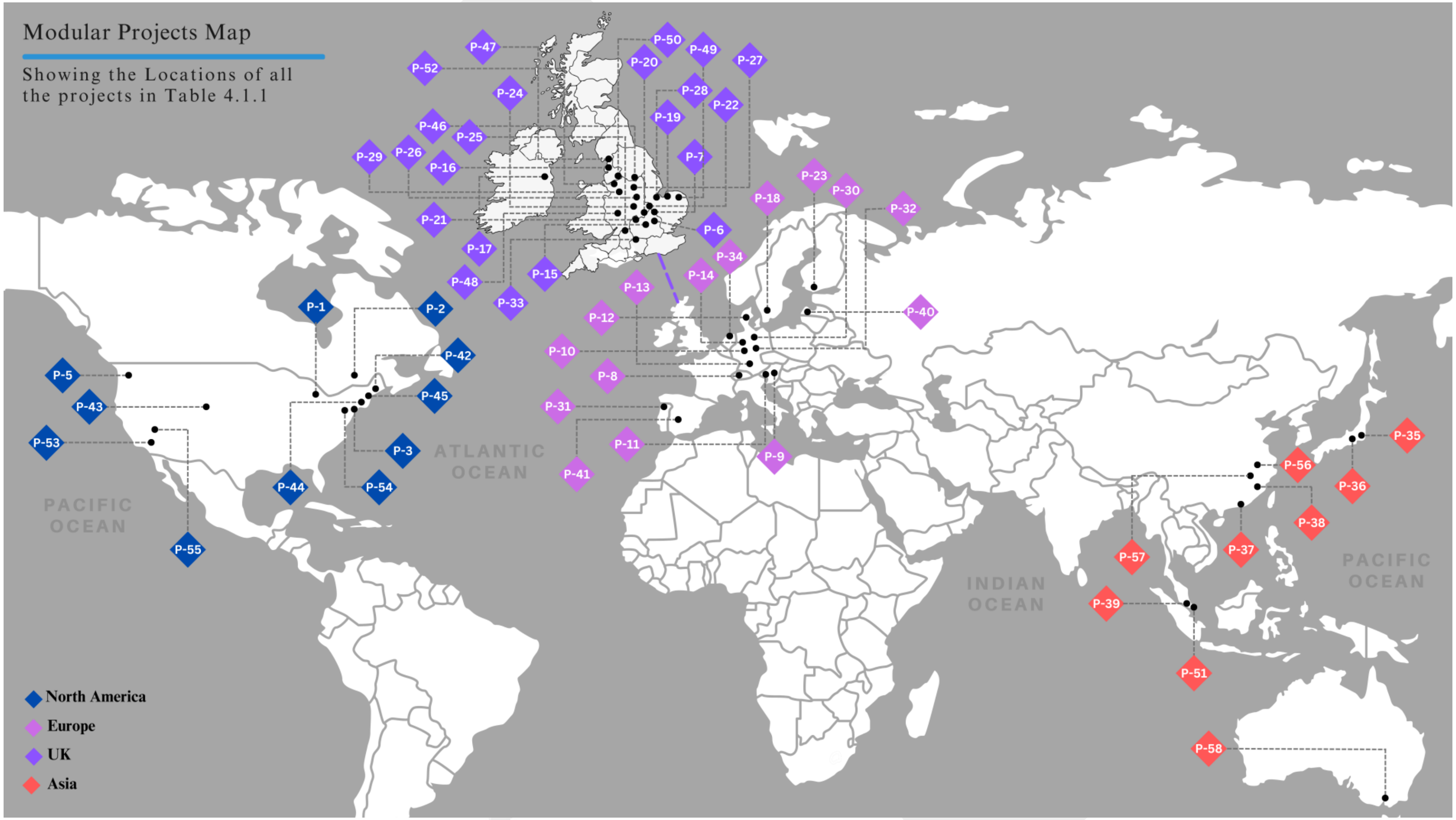


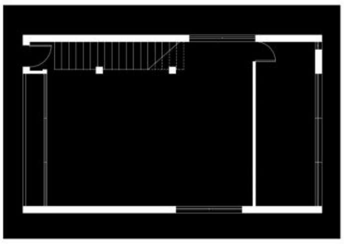
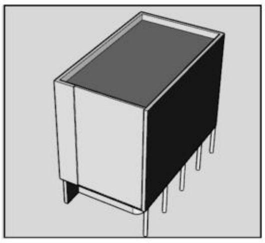
Table 4.1.1 Comprehensive collection of modular projects

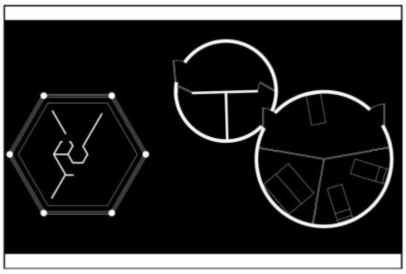
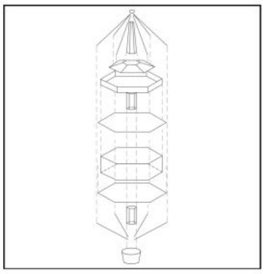
Project Name	Country	Arhictects	System	Year	Material	Module Dim (m)	Code
The Dymaxion house	USA	Buckminster Fuller	PCS	1927	Aluminum	100 m^2	P-43
The Citrohan House	Germany	Le Corbusier	PCS	1927	Concrete, Steel	162 m^2	P-32
The Hirsch Copper House	Germany	Walter Gropius Konrad Wachsmann	PCS	1932	Copper sheets	37 - 167 m^2	P-30
The Packaged House	USA	Walter Gropius Konrad Wachsmann	PCS	1947	Timber	80 m^2	P-42
Habitat 67	Canada	Moshe Safdie	RMS (VU)	1967	Concrete	5.3 x 11.3	P-2
Nakagin Capsule Tower	Japan	Kisho Kurokawa & Associates	RMS (VU) Capsules	1972	Steel	2.3 x 3.8	P-36
Weekend / Furniture House 1	Japan	Shigeru Ban Architects	PCS	1995	Timber	111 m^2	P-35
Bürohaus Rathenow	Germany	Architekten prof. Klaus Sill	RMS (VU) Reinforced Concrete Frame	1997	Steel	2.5 x 3.5	P-10
House in Sumvitg	Switzerland	Bearth & Deplazes Architekten and others	PCS	1998	Timber	220 m^2	P-8
Hotel Extension in Bezau	Austria	Kaufmann 96 GmbH | Dornbirn	RMS (VU)	1998	Timber	4 x 7.5	P-11
Murray Grove UK	England	Cartwright Pickard Yorkon	RMS (VU)	1999	Steel	3.2 x 8	P-6
Camaleon House (Weekend House in Northport)	USA	Anderson Anderson Architecture	PCS	2002	Timber	137 m^2	P-1
LV House	USA	Rocio Romero	PCS (Kit-of-Parts)	2002	Steel	58-135 m^2	P-5
Raines Court UK	England	Allford Hall Monaghan Morris (AHMM)	RMS (VU)	2003	Steel	3.8 x 9.6-11.6	P-7
Open House System	Sweden	Open House AB	RMS (VU)	2004	Steel	3.6 x 7.2-11	P-18
House in Dalaas	Austria	Gohm Hiessberger Architekten	PCS	2005	Timber	311 m^2	P-9
Microcompact Home	Germany	Richard Hordern	RMS (VU)	2005	Timber Aluminum	2.66 cube	P-14
Private Apartments With Integral Balconies	England	Architect ShedKM Yorkon	RMS (VU)	2005	Steel	4.1 x 9.1	P-16
The Loblolly House	USA	KieranTimberlake	MS (Frame & Panel & Room Modules)	2006	Aluminum Timber	204 m^2	P-44
Student Residence	England	Caledonian Modular	RMS (VU) (High Rise Building)	2006	Steel	2.8-4.2 x 12	P-15
Kings Cross Social Housing	England	Caledonian Modular	RMS (VU)	2006	Steel	3.8 x 11	P-24

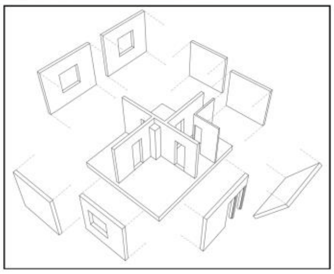
Painter & Peter House Social housing	England	Rollalong	RMS (VU)	2006	Steel	3.6 x 7.7-10.6	P-28
Keetwonen Amsterdam	Netherlands	Architectenburo JMW	RMS (VU) Shipping Containers	2006	Steel	2.4 x 6-12	P-34
Eleven-Storey Apartment Building	England	HTA Architects Vision Modular System	RMS (VU)	2007	Concrete Steel	3-3.6 x 7.2	P-25
House on Sunset Ridge	USA	Resolution: 4 Architecture	RMS (VU)	2008	Timber	5 x 8.2	P-3
Cellophane House	USA	KieranTimberlake	RMS (VU)	2008	Aluminum	6 x 9.1	P-45
LoftCube (Transportable Living Unit)	Germany	Aisslinger + Bracht, and 8, Hamburg	RMS (VU)	2008	Steel Timber	7 x 7	P-13
Futureform Modular Housing	England	Futureform	RMS (VU)	2009	Steel	3.75 x 12	P-19
Cub House	England	Charlie Grieg Futureform	RMS (VU)	2010	Steel	3.5-4 x 7	P-22
High-Quality Housing	England	Caledonian Modular	RMS (VU)	2010	Steel	3.6 x 9	P-26
Student Dormitory	England	O'Connell East Architects	RMS (VU) (High Rise Building)	2010	Steel	4.2 x 7.8	P-33
Tiny House Noa	Estonia	Jaanus Orgusaar	RMS (VU) (Prefab Kit Homes)	2010	Timber	25 m^2 / hexagon	P-40
High-Rise Modular Building	England	O'Connell East Futureform	RMS (VU) (High Rise Building)	2011	Steel	3.8 x 16	P-27
ONV Prefabricated House	Denmark	ONV Architects	RMS (VU)	(2000-2006)	Timber	3.8 x 8	P-12
Modular Apartments	Ireland	Architect HKR Vision Modular System	RMS (VU)	(2000-2014)	Concrete Steel	3.3-4.2 x 6-11	P-17
Tower Hamlets Social Housing	England	Architect Design Buro Rollalong, Rok, Metek	RMS (VU)	(2000-2014)	Steel	3-3.4 x 9-12	P-20
MIMA House	Portugal	MIMA Architects	PCS	2011	Timber	36 m^2	P-31
Seven Modular Housing	Spain	Salgado e Liñares Architects	RMS (VU)	2011	Concrete Timber	5.4 x 7.7	P-41
Olympic Way Mixed Housing And Hotel	England	HTA Architects Vision modular system	RMS (VU)	2013	Concrete Steel	3.8 x 12	P-29
Modular Two-Storey Housing	Finland	NEAPO	RMS (VU) (Large Modules)	(2000-2014)	Steel	5 x 22	P-23
Code Level 5 Social Housing	England	Architect Acanthus Futureform	RMS (VU)	(2009-2011)	Steel	3.6 x 9	P-21
Mini Sky City	China	Broad Sustainable Building Co.	RMS (VU) (High Rise Building) (19 days)	2015	Steel	4.3 x 17	P-57
New Islington Houses	England	Shedkm	RMS (VU)	2016	Timber	5 x 10.55	P-47
B2 Tower	USA	SHoP Architect	RMS (VU) (High Rise Building)	2016	Concrete Steel	4.6 x 15.4	P-54

LA Trobe Tower	Australia	Rothelowman	RMS (VU) (High Rise Building)	2016	Steel	4.2 x 16.4	P-58
Apex House	England	HTA Architects Vision modular system	RMS (VU) (High Rise Building)	2017	Concrete Steel	2.25 x 5.75	P-46
Residential Halls at Nanyang Crescent	Singapore	Santarli Construction Pte Ltd Zheng Keng Engineering & Construction Pte Ltd	RMS (VU) (PPVC)	2017	Steel	3.55 x 11.05	P-39
Casita (Boxabl)	USA	Boxabl Company	RMS (VU) (Foldable)	2017	Concrete Steel	5.91 x 5.91	P-53
Mapleton Crescent	England	Metropolitan Workshop Vision Modular Systems	RMS (VU) (High Rise Building)	2018	Concrete Steel	3.9 x 7.45	P-50
Residential building in Nanjing	China	Local Government Departments	RMS (VU)	2018	Concrete Steel	2-2.9 x 3.8-4.8	P-38
Clement Canopy apartments	Singapore	ADDP Architects LLP	RMS (VU) (High Rise Building) (PPVC)	2019	R.Concrete	4 x 8-11	P-51
Greenford Quay	England	HTA Architects Vision Modular System	RMS (VU) (High Rise Building)	2020	Concrete Steel	3.9 x 8	P-48
George Street London	England	HTA Architects Vision Modular System	RMS (VU) (High Rise Building)	2020	Concrete Steel	4-5.7 x 10	P-52
Garden A-1	China	Broad Sustainable Building Co.	RMS (VU) (High Rise Building) (28 Hours)	2021	Steel	4.8 x 12	P-56
Beechwood West Housing	England	Pollard Thomas Edwards	RMS (VU) (Customizable low-rise houses)	2022	Timber	5.7 x 11.8	P-49
Mighty House (3D Printed)	USA	EYRC Mighty Buildings	PCS (3D Printed Panels)	2022	Recycled composite stone	109 - 296 m^2	P-55
Wong Chuk Hang Student Residence	Hong Kong	AD+RG Architect HTA	RMS (VU) (High Rise Building) (MIC)	2023	Concrete Steel	2.05 x 4.8	P-37

Table 4.1.2 Projects listed with visuals 2D and 3D photos

THE CITROHAN HOUSE			
Project Code	**P-32**	Country	**Germany**
Architect	**Le Corbusier**	Year	**1927**
System	**Panel Construction System**	Material	**Concrete, Steel**
		Details	**3 floors, 162m2**
Visual 2d & 3D			

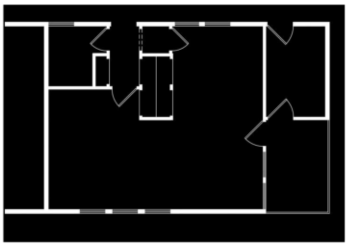
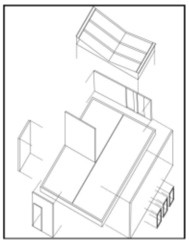
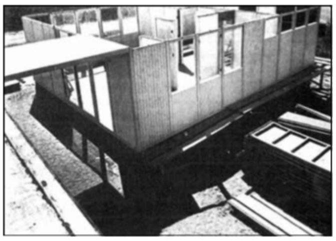
THE DYMAXION HOUSE			
Project Code	**P-43**	Country	**USA**
Architect	**Buckminster Fuller**	Year	**1927**
System	**Panel Construction System**	Material	**Aluminum**
		Details	**Aeroplane-shape, 100m2**
Visual 2d & 3D			

THE HIRSCH COPPER HOUSE			
Project Code	**P-30**	Country	**Germany**
Architect	**Walter Gropius Konrad Wachsmann**	Year	**1932**
		Material	**Copper sheets**
System	**Panel Construction System**	Details	**Nine types, 37 - 167 m2**
Visual 2d & 3D			

THE PACKAGED HOUSE

Project Code	**P-42**	Country	**USA**
Architect	**Walter Gropius** **Konrad Wachsmann**	Year	**1947**
		Material	**Timber**
System	**Panel Construction System**	Details	**Single floor, 80m2**

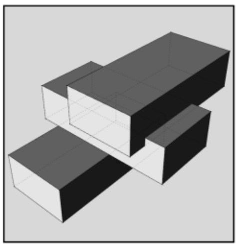
Visual 2d & 3D

HABITAT 67

Project Code	**P-2**	Country	**Canada**
Architect	**Moshe Safdie**	Year	**1967**
System	**Room Module System** **(Volumetric Unit)**	Material	**Concrete**
		Details	**354 modules, 5.3 x 11.3m**

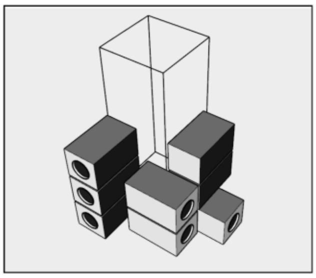
Visual 2d & 3D


NAKAGIN CAPSULE TOWER

Project Code	**P-36**	Country	**Japan**
Architect	**Kisho Kurokawa**	Year	**1972**
System	**Room Module System** **(VU Capsules)**	Material	**Steel**
		Details	**144 capsules, 2.3 x 3.8m**

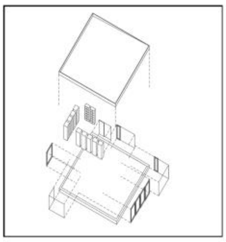
Visual 2d & 3D


WEEKEND / FURNITURE HOUSE 1

Project Code	**P-35**	Country	**Japan**	Year	**1995**
Architect	**Shigeru Ban Architects**	Material	**Timber**		
System	**Panel Construction System**	Details	**Single Person assembly, 111m2 one of three houses built in the late 1990s**		

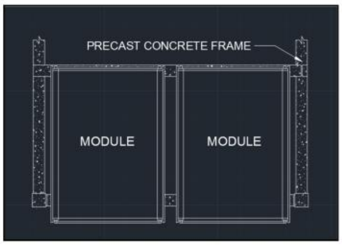
Visual 2d & 3D

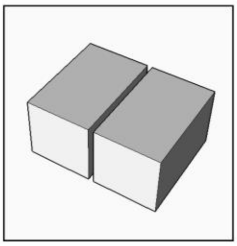


BÜROHAUS RATHENOW

Project Code	**P-10**	Country	**Germany**	Year	**1997**
Architect	**Architekten prof. Klaus Sill**	Material	**Steel**		
System	**Room Module System (VU. R.Concrete Frame)**	Details	**12 modules 2.5 x 3.5m completed in 14 months**		

Visual 2d & 3D

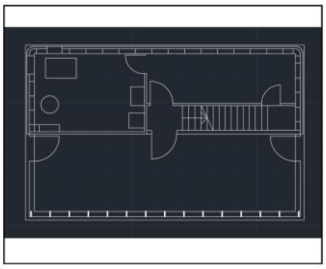


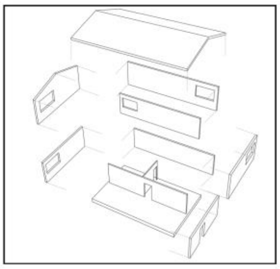


HOUSE IN SUMVITG

Project Code	**P-8**	Country	**Switzerland**	Year	**1998**
Architect	**Bearth & Deplazes Architekten**	Material	**Timber**		
System	**Panel Construction System**	Details	**4 floors Single family house 220 m2, in 7 months**		

Visual 2d & 3D

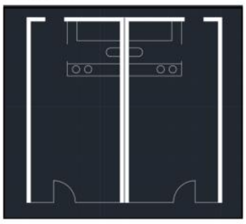
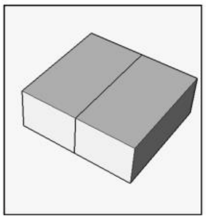




HOTEL EXTENSION IN BEZAU

Project Code	**P-11**	Country	**Austria**	Year	**1998**
Architect	**Kaufmann 96 GmbH**	Material	**Timber**		
System	**Room Module System (Volumetric Unit)**	Details	**10 Modules 4 x 7.5m , built in 5 Weeks**		

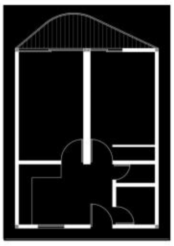
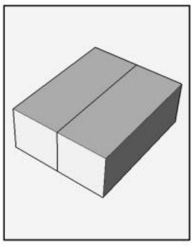
Visual 2d & 3D

MURRAY GROVE UK

Project Code	**P-6**	Country	**England**	Year	**1999**
Architect	**Cartwright Pickard & Yorkon**	Material	**Steel**		
System	**Room Module System (VU. R.Concrete Frame)**	Details	**74-90 Modules 3.2 x 8m 5 floors, 30 homes in 6 months**		

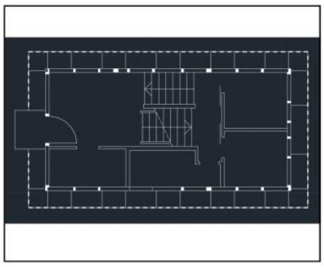
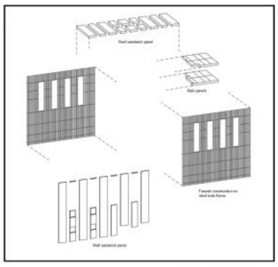
Visual 2d & 3D

CAMALEON HOUSE

Project Code	**P-1**	Country	**USA**	Year	**2002**
Architect	**Anderson Anderson Architecture**	Material	**Timber**		
System	**Panel Construction System**	Details	**4 floors Single Family house 137 m2, built in 2 months**		

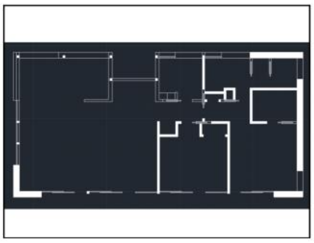
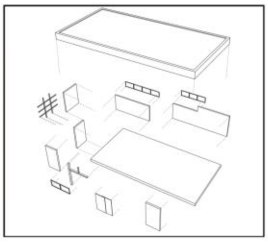
Visual 2d & 3D


LV HOUSE

Project Code	P-5	Country	USA
		Year	2002
Architect	Rocio Romero	Material	Steel
System	Panel Construction System (Kit-of-Parts)	Details	4 types, 58-135 m2 LV-houses built in the USA, Chile, Canada, and France

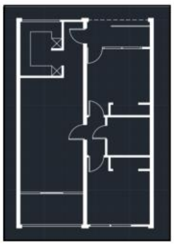
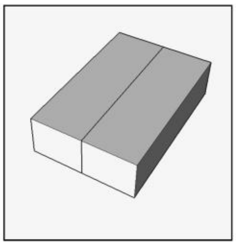
Visual 2d & 3D


RAINES COURT UK

Project Code	P-7	Country	England
		Year	2003
Architect	AHMM & Yorkon	Material	Steel
System	Room Module System (Volumetric Unit)	Details	127 modules 3.8 x 9.6-11.6m 42 one & two bedroom Apt. 11 Three bedrooms Apt.

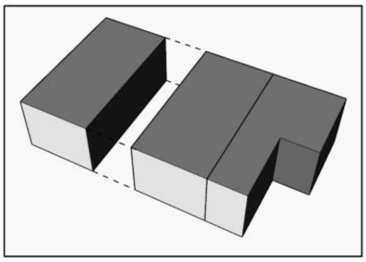
Visual 2d & 3D


OPEN HOUSE SYSTEM

Project Code	P-18	Country	Sweden
		Year	2004
Architect	Open House AB	Material	Steel
System	Room Module System (Volumetric Unit)	Details	L-shaped modules 3.6 x 7.2-11m

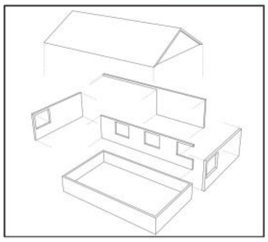
Visual 2d & 3D


HOUSE IN DALAAS

Project Code	**P-9**	Country	**Austria** Year **2005**
Architect	**Gohm Hiessberger Architekten**	Material	**Timber**
System	**Panel Construction System**	Details	**3 floors Single-family house, 311 m2, built in 6 months**

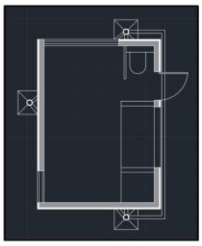
Visual 2d & 3D

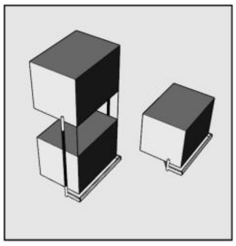


MICROCOMPACT HOME

Project Code	**P-14**	Country	**Germany** Year **2005**
Architect	**Richard Hordern**	Material	**Timber, Aluminum**
System	**Room Module System (Volumetric Unit)**	Details	**2.66m cube shape 7m2 dwelling for one or two people**

Visual 2d & 3D

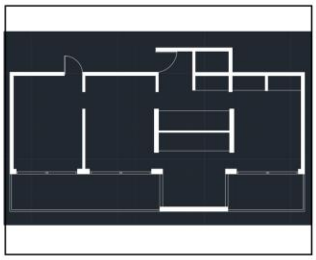


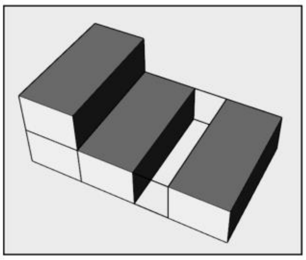


PRIVATE APARTMENTS WITH INTEGRAL BALCONIES

Project Code	**P-16**	Country	**England** Year **2005**
Architect	**ShedKM & Yorkon**	Material	**Steel**
System	**Room Module System (Volumetric Unit)**	Details	**210 Modules 4.1 x 9.1m 7 floors, 102 apartments in 17 months**

Visual 2d & 3D

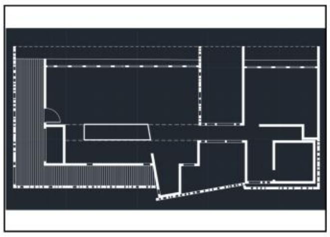


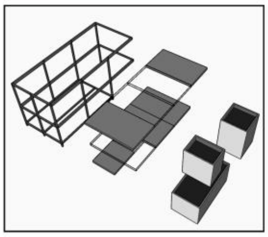


THE LOBLOLLY HOUSE

Project Code	**P-44**	Country	**USA** Year **2006**
Architect	**KieranTimberlake**	Material	**Aluminum, Timber**
System	**Mixed System**	Details	**aluminum frame, prefab modules, and wall panels 204 m2**

Visual 2d & 3D

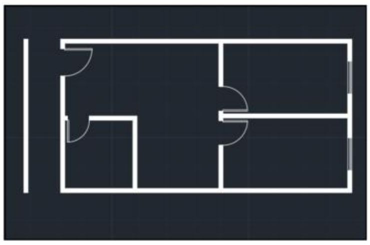


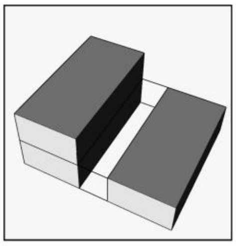


STUDENT RESIDENCE

Project Code	**P-15**	Country	**England** Year **2006**
Architect	**Caledonian Modular**	Material	**Steel**
System	**Room Module System (VU. High Rise Building)**	Details	**413 Modules 2.8-4.2 x 12m 17 Floors finished in 22 months**

Visual 2d & 3D

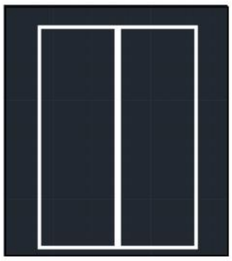


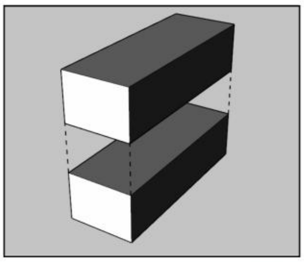


KINGS CROSS SOCIAL HOUSING

Project Code	**P-24**	Country	**England** Year **2006**
Architect	**Caledonian Modular**	Material	**Steel**
System	**Room Module System (Volumetric Unit)**	Details	**73 Modules 3.8 x 11m, 5&6 floors, 23 apartments and 9 town houses**

Visual 2d & 3D

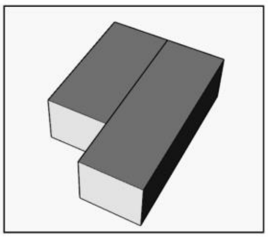




PAINTER & PETER HOUSE SOCIAL HOUSING

Project Code	**P-28**	Country	**England**	Year	**2006**
Architect	**Rollalong**	Material	**Steel**		
System	**Room Module System (Volumetric Unit)**	Details	**76 Modules 3.6 x 7.7-10.6m 38 one & two bedroom apartments**		

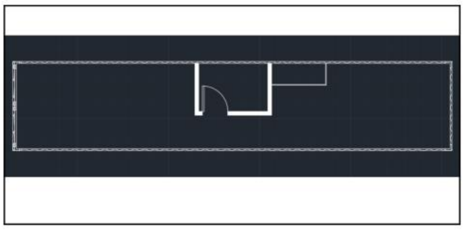
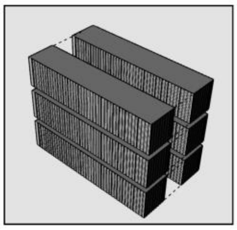
Visual 2d & 3D


KEETWONEN AMSTERDAM

Project Code	**P-34**	Country	**Netherlands**	Year	**2006**
Architect	**Architectenburo JMW**	Material	**Steel**		
System	**Room Module System (VU. Shipping Containers)**	Details	**1034 Modules 2.4 x 6-12m, 1000 student unit, Fast, durable, and cost-efficient**		

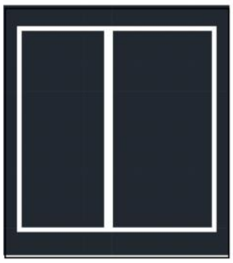
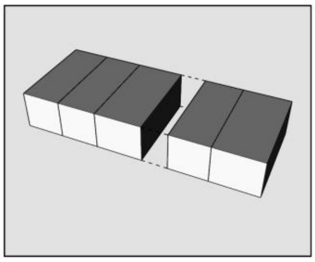
Visual 2d & 3D


ELEVEN-STOREY APARTMENT BUILDING

Project Code	**P-25**	Country	**England**	Year	**2007**
Architect	**HTA&Vision Modular System**	Material	**Concrete, Steel**		
System	**Room Module System (Volumetric Unit)**	Details	**360 Modules 3-3.6 x 7.2m, 3 blocks 6 to 11 floors built in 4 months**		

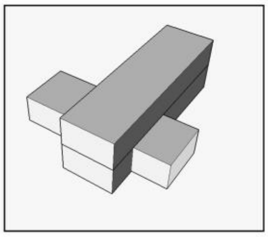
Visual 2d & 3D


HOUSE ON SUNSET RIDGE

Project Code	**P-3**	Country	**USA** Year **2008**
Architect	**Resolution: 4 Architecture**	Material	**Timber**
System	**Room Module System (Volumetric Unit)**	Details	**6 Modules, 5 x 8.2m, LEED Certified prefab house.**

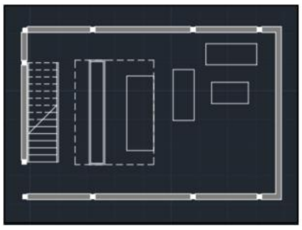
Visual 2d & 3D

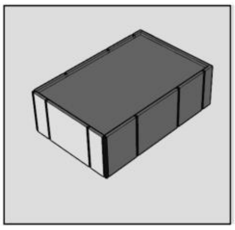


CELLOPHANE HOUSE

Project Code	**P-45**	Country	**USA** Year **2008**
Architect	**KieranTimberlake**	Material	**Aluminum**
System	**Room Module System (Volumetric Unit)**	Details	**6 x 9.1m unit, five floor house, 80% finished in 6 days**

Visual 2d & 3D

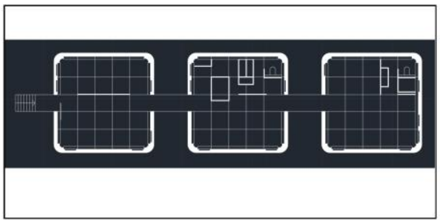


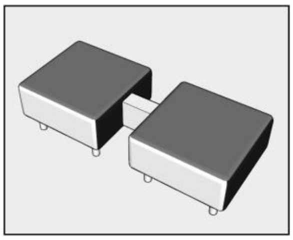


LOFTCUBE (TRANSPORTABLE LIVING UNIT)

Project Code	**P-13**	Country	**Germany** Year **2008**
Architect	**Aisslinger+Bracht, & 8, Hamburg**	Material	**Steel, Timber**
System	**Room Module System (Volumetric Unit)**	Details	**7 x 7m basic unit, dismantled and reassembled in two to three days.**

Visual 2d & 3D

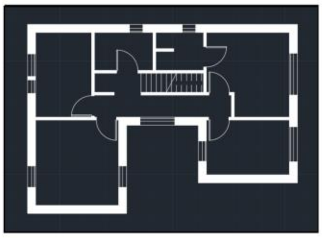


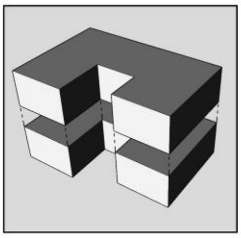


FUTUREFORM MODULAR HOUSING

Project Code	**P-19**	Country	**England**	Year	**2009**
Architect	**Futureform**	Material	**Steel**		
System	**Room Module System (Volumetric Unit)**	Details	**48 Houses, Flexible modules 3.75 x 12m**		

Visual 2d & 3D

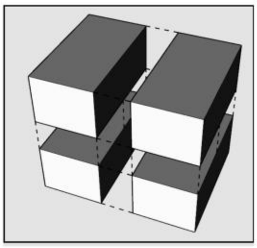




CUB HOUSE

Project Code	**P-22**	Country	**England**	Year	**2010**
Architect	**Charlie Grieg & Futureform**	Material	**Steel**		
System	**Room Module System (Volumetric Unit)**	Details	**Extendable system two modules, four, or more., 3.5-4 x 7m**		

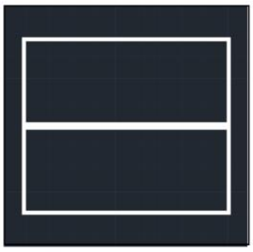
Visual 2d & 3D

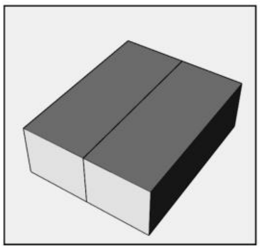


HIGH-QUALITY HOUSING

Project Code	**P-26**	Country	**England**	Year	**2010**
Architect	**Caledonian Modular**	Material	**Steel**		
System	**Room Module System (Volumetric Unit)**	Details	**300 Modules, 3.6 x 9m, 6 floors built in 9 months**		

Visual 2d & 3D

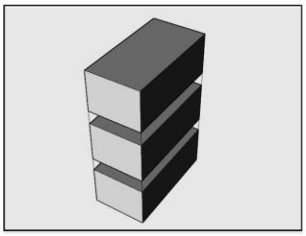




STUDENT DORMITORY

Project Code	**P-33**	Country	**England** Year **2010**
Architect	**O'Connell East Architects**	Material	**Steel**
System	**Room Module System (VU. High Rise Building)**	Details	**805 Module, 24 Floors, built in 7 months, 4.2 x 7.8m**

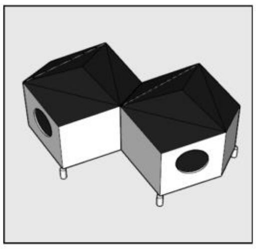
Visual 2d & 3D


TINY HOUSE NOA

Project Code	**P-40**	Country	**Estonia** Year **2010**
Architect	**Jaanus Orgusaar**	Material	**Timber**
System	**Room Module System (VU. Prefab Kit Homes)**	Details	**25 m2, hexagon plan, easily assembled and expanded by adding modules**

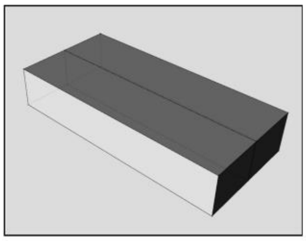
Visual 2d & 3D


HIGH-RISE MODULAR BUILDING

Project Code	**P-27**	Country	**England** Year **2011**
Architect	**O'Connell East & Futureform**	Material	**Steel**
System	**Room Module System (VU. High Rise Building)**	Details	**270 Modules, 3.8 x 16m, 17 Floors, built in 4 months**

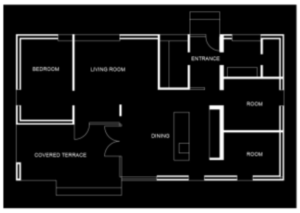
Visual 2d & 3D

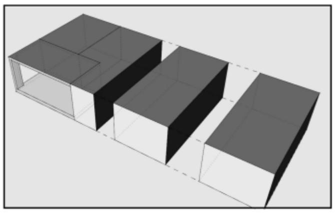




ONV PREFABRICATED HOUSE

Project Code	**P-12**	Country	**Denmark**	Year	**(2000-2006)**
Architect	**ONV Architects**	Material	**Timber**		
System	**Room Module System (Volumetric Unit)**	Details	**3.8 x 8m module, 6 different versions from 60 - 169 m2**		

Visual 2d & 3D

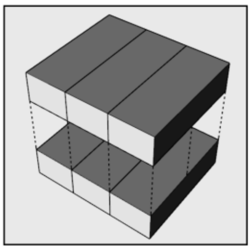




MODULAR APARTMENTS

Project Code	**P-17**	Country	**Ireland**	Year	**(2000-2014)**
Architect	**Architect HKR Vision Modular System**	Material	**Concrete, Steel**		
System	**Room Module System (Volumetric Unit)**	Details	**1515 Modules, 224 apartments, 3.3-4.2 x 6-11m**		

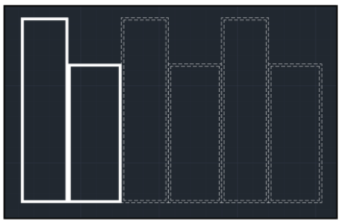
Visual 2d & 3D

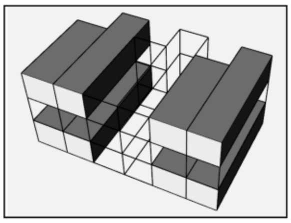


TOWER HAMLETS SOCIAL HOUSING

Project Code	**P-20**	Country	**England**	Year	**(2000-2014)**
Architect	**Architect Design Buro Rollalong, Rok, Metek**	Material	**Steel**		
System	**Room Module System (Volumetric Unit)**	Details	**Three houses, 18 modules, 3-3.4 x 9-12m**		

Visual 2d & 3D

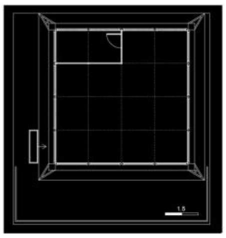
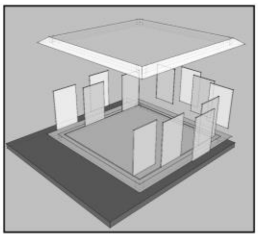




MIMA HOUSE

Project Code	**P-31**	Country	**Portugal**
Architect	**MIMA Architects**	Year	**2011**
System	**Panel Construction System**	Material	**Timber**
		Details	**Low cost, 36 m2**

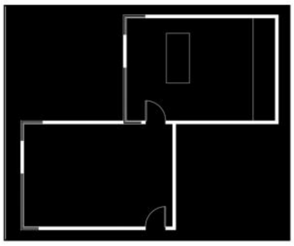
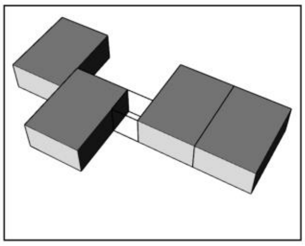
Visual 2d & 3D

SEVEN MODULAR HOUSING

Project Code	**P-41**	Country	**Spain** Year **2011**
Architect	**Salgado e Liñares Architects**	Material	**Concrete, Timber**
System	**Room Module System (Volumetric Unit)**	Details	**5.4 x 7.7m unit, experimental pre-fabricated housing.**

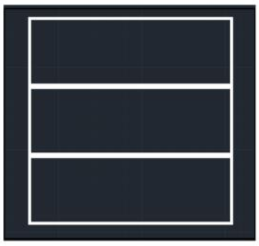
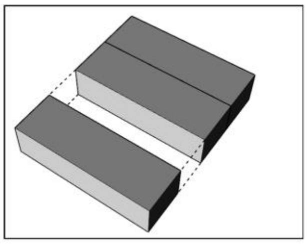
Visual 2d & 3D


OLYMPIC WAY MIXED HOUSING AND HOTEL

Project Code	**P-29**	Country	**England**
Architect	**HTA Architects Vision modular system**	Year	**2013**
System	**Room Module System (Volumetric Unit)**	Material	**Concrete, Steel**
		Details	**700 Modules, 3.8 x 12m**

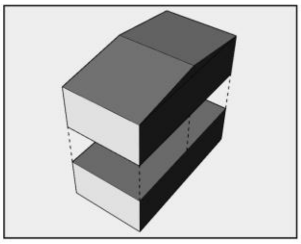
Visual 2d & 3D


MODULAR TWO-STOREY HOUSING

Project Code	**P-23**	Country	**Finland**	Year	**(2000-2014)**
Architect	**NEAPO**	Material	**Steel**		
System	**Room Module System (Volumetric Unit)**	Details	**37 terraced houses of 2 floors, Large module 5 x 22m**		

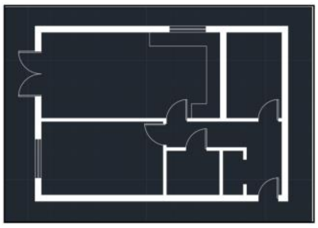
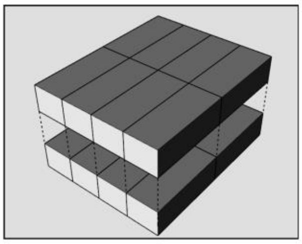
Visual 2d & 3D


CODE LEVEL 5 SOCIAL HOUSING

Project Code	**P-21**	Country	**England**	Year	**(2009-2011)**
Architect	**Architect Acanthus Futureform**	Material	**Steel**		
System	**Room Module System (Volumetric Unit)**	Details	**Five buildings, 5 to 7 modules for each building, 3.6 x 9m**		

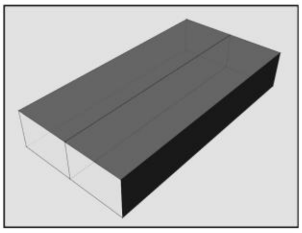
Visual 2d & 3D


MINI SKY CITY

Project Code	**P-57**	Country	**China**	Year	**2016**
Architect	**Broad Sustainable Building Co.**	Material	**Steel**		
System	**Room Module System (VU. High Rise Building)**	Details	**57 Floor in 19 days, 4.3 x 17m**		

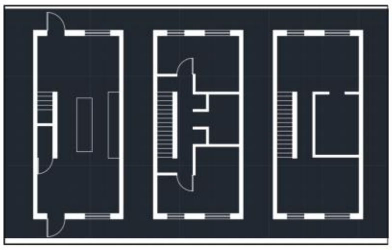
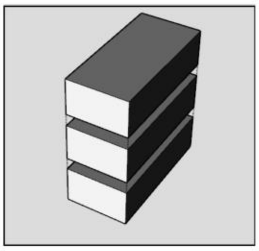
Visual 2d & 3D


NEW ISLINGTON HOUSES

Project Code	**P-47**	Country	**England** Year **2016**
Architect	**Shedkm**	Material	**Timber**
System	**Room Module System (Volumetric Unit)**	Details	**102 Modules, 43 Homes, 5 x 10.55m**

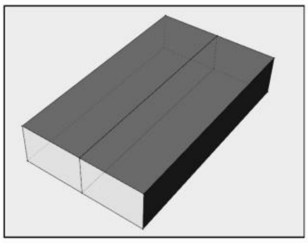
Visual 2d & 3D


B2 TOWER

Project Code	**P-54**	Country	**USA** Year **2016**
Architect	**SHoP Architect**	Material	**Concrete, Steel**
System	**Room Module System (VU. High Rise Building)**	Details	**930 Modules, 32 floors, 363 homes, 4.6 x 15.4m**

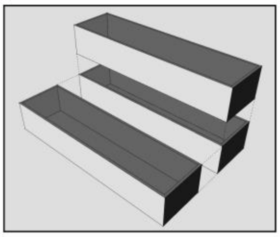
Visual 2d & 3D


LA TROBE TOWER

Project Code	**P-58**	Country	**Australia** Year **2016**
Architect	**Rothelowman & Hickory Group**	Material	**Steel**
System	**Room Module System (VU. High Rise Building)**	Details	**43 Floor, 206 homes, 4.2 x 16.4m modules**

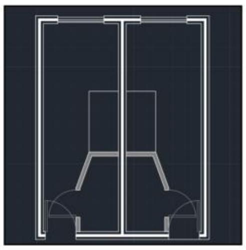
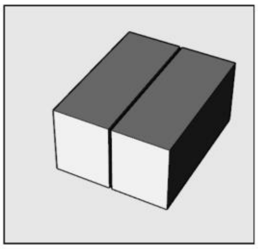
Visual 2d & 3D


APEX HOUSE

Project Code	**P-46**	Country	**England** Year **2017**
Architect	**HTA & Vision modular system**	Material	**Concrete, Steel**
System	**Room Module System (VU. High Rise Building)**	Details	**679 Module, 28 Floor, 558 student rooms, 2.25 x 5.75m**

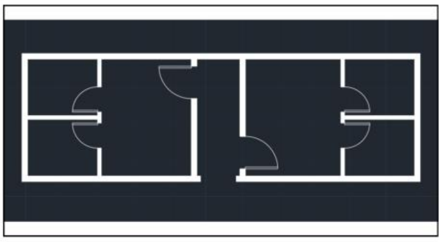
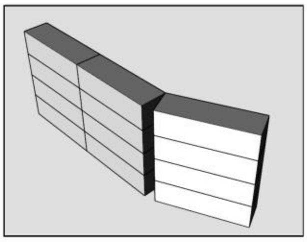
Visual 2d & 3D


RESIDENTIAL HALLS AT NANYANG CRESCENT

Project Code	**P-39**	Country	**Singapore** Year **2017**
Architect	**Santarli Construction Pte Ltd Zheng Keng Engineering**	Material	**Steel**
System	**Room Module System (VU. PPVC)**	Details	**676 Modules and eight types, average 2.97 x 8.1m**

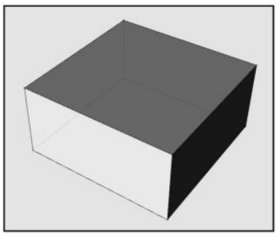
Visual 2d & 3D


CASITA (BOXABL)

Project Code	**P-53**	Country	**USA** Year **2017**
Architect	**Boxabl Company**	Material	**Concrete, Steel**
System	**Room Module System (VU. Foldable)**	Details	**Compact single-bedroom apartment, 5.91 x 5.91m**

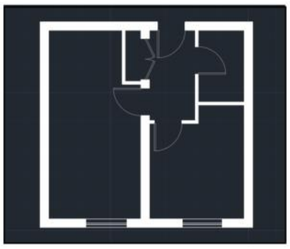
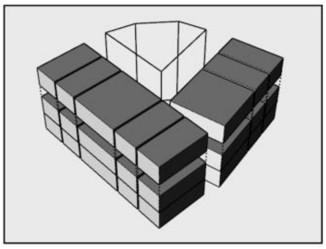
Visual 2d & 3D




MAPLETON CRESCENT

Project Code	**P-50**	Country	**England** Year **2018**
Architect	**Metropolitan Workshop Vision Modular Systems**	Material	**Concrete, Steel**
System	**Room Module System (VU. High Rise Building)**	Details	**243 Module, 27 Floor, 89 home, 3.9 x 7.45m**

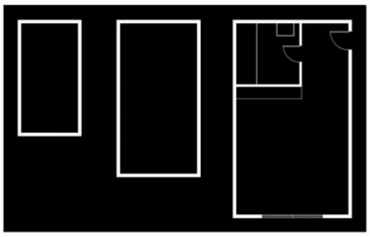
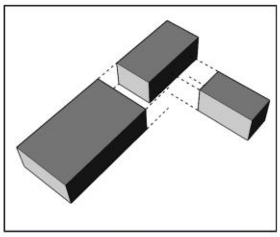
Visual 2d & 3D


RESIDENTIAL BUILDING IN NANJING

Project Code	**P-38**	Country	**China** Year **2018**
Architect	**Local Government Departments**	Material	**Concrete, Steel**
System	**Room Module System (Volumetric Unit)**	Details	**1285 Modules, 10 types, 3 blocks, 2-2.9 x 3.8-4.8m**

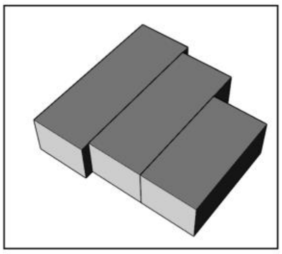
Visual 2d & 3D


CLEMENT CANOPY APARTMENTS

Project Code	**P-51**	Country	**Singapore** Year **2019**
Architect	**ADDP Architects LLP**	Material	**Reinforced Concrete**
System	**Room Module System (VU. High Rise) (PPVC)**	Details	**1899 Modules, 40 Floor, 2 Towers, 505 apartments, 4 x 8-11m**

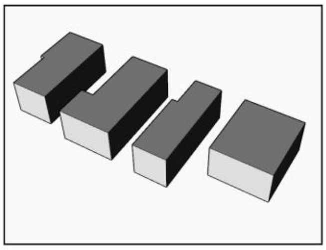
Visual 2d & 3D


GREENFORD QUAY

Project Code	**P-48**	Country	**England** Year **2020**
Architect	**HTA & Vision Modular System**	Material	**Concrete, Steel**
System	**Room Module System (VU. High Rise Building)**	Details	**1180 Modules, 379 homes, 14&6 floors, average 3.9 x 8m**

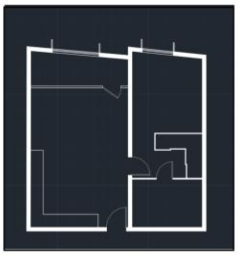
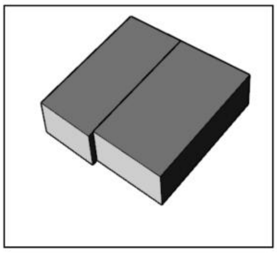
Visual 2d & 3D


GEORGE STREET LONDON

Project Code	**P-51**	Country	**England** Year **2020**
Architect	**HTA & Vision Modular System**	Material	**Concrete, Steel**
System	**Room Module System (VU. High Rise) (PPVC)**	Details	**+1500 Modules,546 homes, 4-5.7 x 10m**

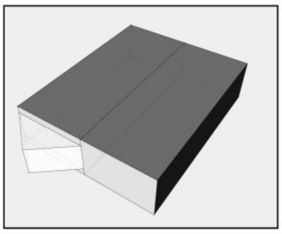
Visual 2d & 3D


GARDEN A-1

Project Code	**P-56**	Country	**China** Year **2021**
Architect	**Broad Sustainable Building Co.**	Material	**Steel**
System	**Room Module System (Volumetric Unit)**	Details	**Ten floors in 28 Hours, 4.8 x 12m**

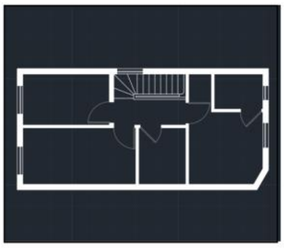
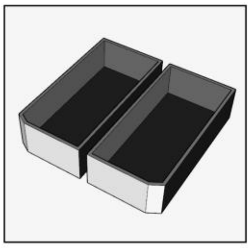
Visual 2d & 3D


BEECHWOOD WEST HOUSING

Project Code	**P-49**	Country	**England** Year **2022**
Architect	**Pollard Thomas Edwards**	Material	**Timber**
System	**Room Module System (Volumetric Unit)**	Details	**+1000 Modules, 251 Customizable low-rise houses, 5.7 x 11.8m**

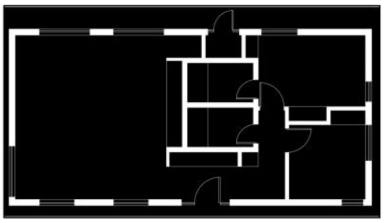
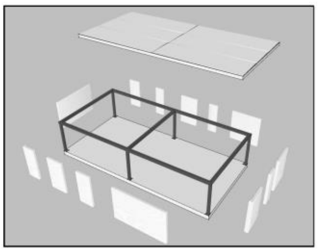
Visual 2d & 3D


MIGHTY HOUSE (3D PRINTED)

Project Code	**P-55**	Country	**USA** Year **2022**
Architect	**EYRC & Mighty Buildings**	Material	**Recycled composite stone**
System	**Panel Construction System**	Details	**3D Printed Panels, houses from 109 - 296 m2**

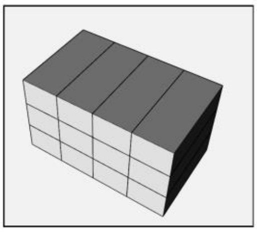
Visual 2d & 3D


WONG CHUK HANG STUDENT RESIDENCE

Project Code	**P-37**	Country	**Hong Kong** Year **2023**
Architect	**AD+RG Architect & HTA**	Material	**Concrete, Steel**
System	**Room Module System (VU. High Rise) (MIC)**	Details	**1500 Module, 1224 student rooms, 2.05 x 4.8m**

Visual 2d & 3D


Modular and prefabricated architecture has been a subject of interest for architects and designers for over a century. These construction methods have been known for their ability to save time and money while maintaining a high-quality level. However, their popularity has fluctuated over the years due to various factors, such as lack of standardization and negative perceptions. Recently, there has been a renewed interest in modular and prefabricated architecture, as new advancements have allowed for more flexibility and customization while reaping the benefits of cost savings and efficiency. The projects in Tables 4.1.1 and 4.1.2 showcase various ways companies and architects have implemented modular and prefabricated architecture in housing design. The projects span from the 19th century to the present day, highlighting this architectural approach's evolution over time.

To gain a deeper understanding of modular and prefabricated architecture, the following thesis section will examine various projects from across the globe. Emphasizing the architect's original concept, the idea behind it, and the practical implementation and assessment of the project. This exploration aims to unearth valuable perspectives on the advantages and obstacles associated with this methodology.

Starting with projects from the West and North American continent and gradually moving towards Asia in the East. This will provide a comprehensive view of how modular and prefabricated architecture has been implemented in different parts of the world. Examining projects from different regions will identify the unique approaches and innovations that have emerged in each context.

4.2 North American Modularity

Modular and prefabricated construction has significantly impacted North America's dynamic landscape, spanning almost a century, from the bustling metropolises of New York to the serene landscapes of Vancouver. Tables 4.1.1 and 4.1.2 highlight projects showcasing the region's commitment to cutting-edge design and sustainable living. From innovative residential developments in the 1920s to modern structures, modular architecture has redefined the built environment across the continent. While it is beyond the scope of this research to delve into the entire history of prefabrication in North America from the 19th century to the present day, exploring a selection of iconic architects, projects, and periods is feasible. Start by examining one of Canada's most iconic and unique modular projects, Habitat 67, and move on to modern contemporary pioneers in the United States.

4.2.1 Habitat 67

The World Expo 1967 in Montreal, Canada, saw the creation of a remarkable structure designed by Moshe Safdie, known as Habitat 67 (Figure 4.2.1). The building is a megastructure that employs prefabricated reinforced concrete modules stacked on top of each other. Habitat 67 is considered an iconic example of prefabrication and modularity in housing and is widely regarded as one of the most famous projects from the 1960s era of innovation. Discussing prefabrication and modularity in housing is almost impossible without mentioning it in the literature. In 2009, the Quebec government listed Habitat 67 as a World Heritage site to preserve its past ideas of prefabrication for future architects and prevent further apartment modifications (Morah, 2019).

Figure 4.2.1 Habitat 67 historic view (*Habitat ’67*, n.d.).

In 1961, Moshe Safdie, a Canadian architect and a graduate student from the McGill University architecture program, at age 23, had the opportunity to turn his thesis project, which was titled "A Three-Dimensional Modular Building System", into an actual building called Habitat 67 for the Montreal Expo 1967 (Figure 4.2.2) (Morah, 2019). Safdie immediately started working on the project and requested funding of 45 million dollars for its construction. However, he was only granted 15 million dollars, which almost caused him to abandon the project (B1M, 2023). Despite the shortage of funds, Safdie completed the project by shrinking the design from the original 30-floor and 1200-family community building to only 158 apartment houses, and it went on to be the central pavilion of the Expo and later became a landmark in Canadian architecture (Morah, 2019) (Smith, 2011).

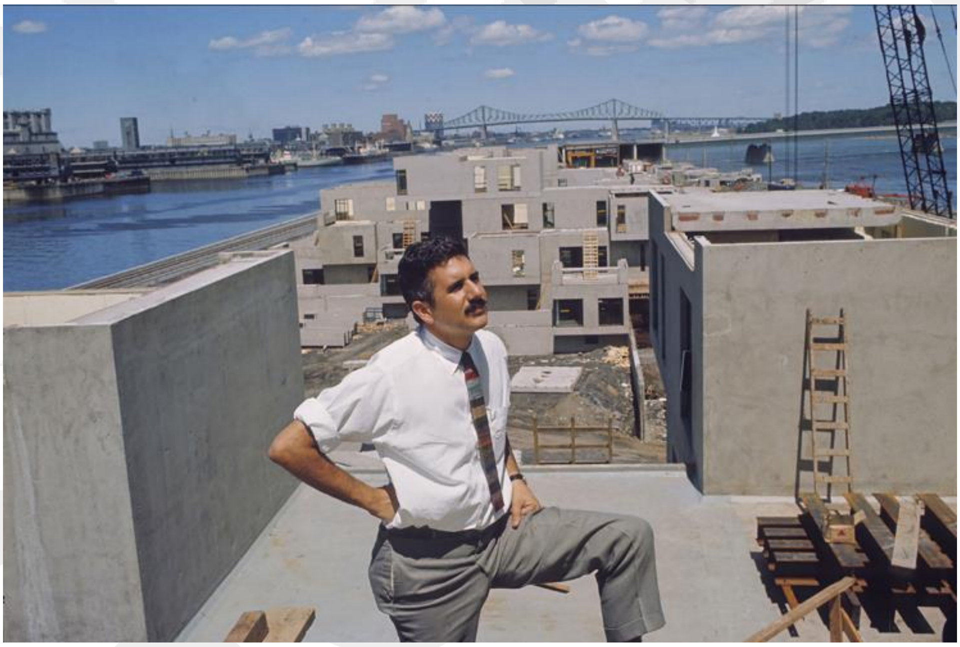


Figure 4.2.2 Young Moshe Safdie, in his 20s, during the construction of Habitat 67 (Morah, 2019).

Safdie's vision for the project was to revolutionize urban living by creating a community building where each apartment offers privacy through a private entrance and an open space rather than just a balcony. Moreover, this housing option had to be affordable for city dwellers. To achieve the desired level of privacy and foster a sense of community, the modules were arranged diagonally, creating voids. Wide, long paths functioned as streets and gathering areas for residents to socialize and children to play, mimicking the suburban lifestyle. Despite being less than half the originally planned size, the building, by design, achieved the urban feel that Safdie had envisioned (Morah, 2019).

Safdie's thesis proposes an innovative approach to constructing urban apartment buildings using prefabrication and modular units. This system, which Safdie envisioned and implemented in the project's design and construction plan, proved ideal for the project's timeline and goals. The building, which comprises 12 floors and 158 apartments, was erected using 354 reinforced concrete modular units that were fully furnished and stacked to create the structure. The apartments in the building come in eight different types, ranging from one to four-bedroom units. All modular units were manufactured uniformly, measuring 5.33 meters in width, 11.33 meters in length, and 3.2 meters in height, and then stacked like a Lego as shown in (Figure 4.2.3) & (Figure 4.2.4). Due to their heavy weight, lifting the module units on site was a challenging task requiring massive cranes (Figure 4.2.5).

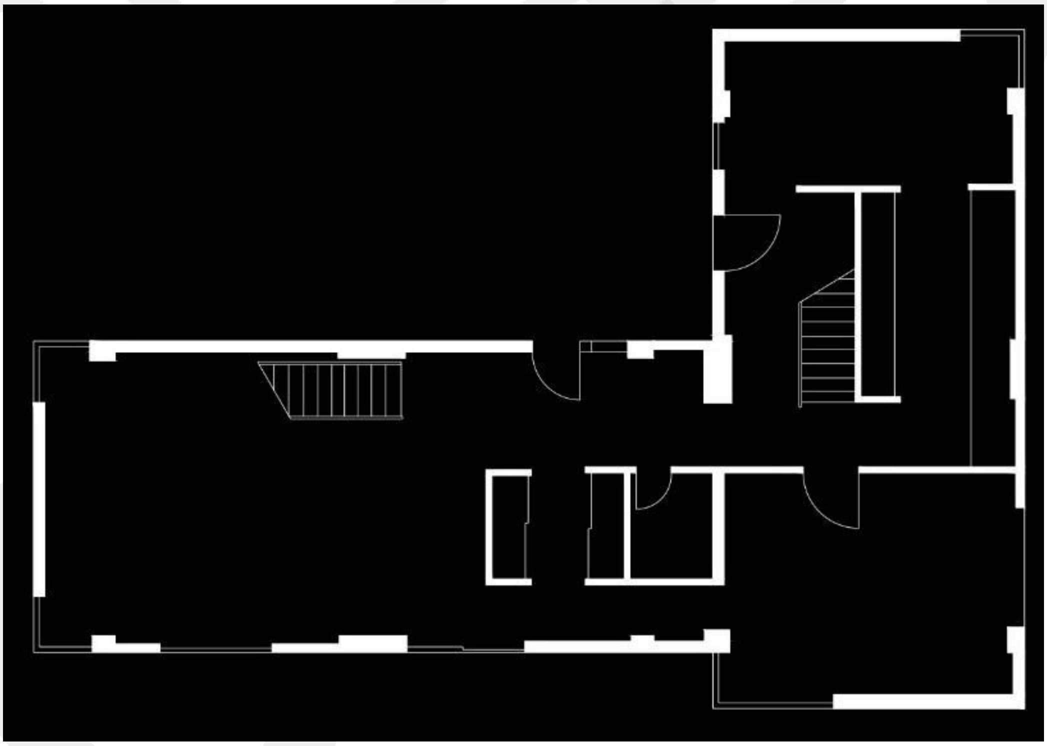


Figure 4.2.3 Habitat 67, floor plan made of two modules redrawn by the author (P-2, Tables 4.1.1 & 4.1.2)

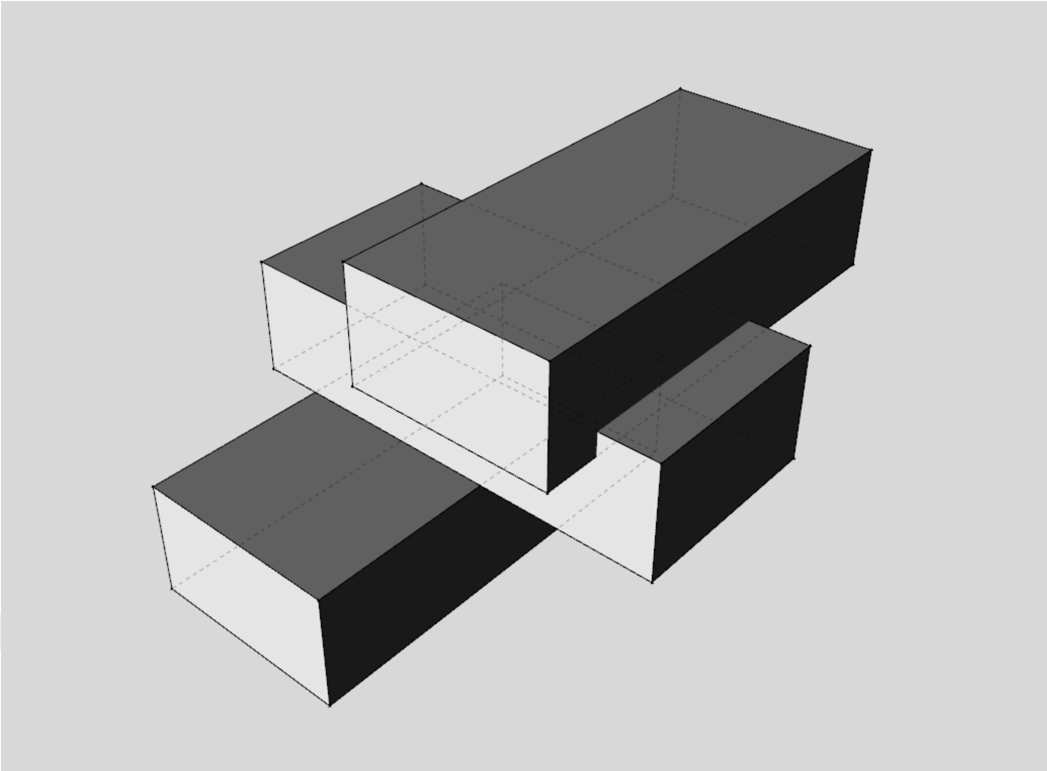


Figure 4.2.4 Habitat 67, module units stacking, made by the author (P-2, Tables 4.1.1 & 4.1.2)

Figure 4.2.5 Lifting and stacking Habitat 67 modules by cranes (*Habitat '67,* n.d.)

Opinions on the success of the Habitat 67 project have been widely debated since its inception, with differing viewpoints from supporters and critics alike. Even the project's creator, Moshe Safdie, has expressed varying opinions on its success. While this research does not aim to definitively classify the project as a success or failure, identifying its strengths and weaknesses can offer valuable insights into the broader concepts of prefabrication and modular construction. According to (Smith, 2011), following the completion of the project, Safdie deemed prefabrication impossible at the time and regarded his experiment as a failure. The reasoning behind his decision was rooted in the fact that the project had incurred higher costs without any savings, due to the excessive weight of the modules requiring massive cranes (Figure 4.2.5) and a significant labour force (Figure 4.2.6). It was determined that the material choice was the root cause of these difficulties, as noted by Paul Rudolph. The construction team left one-third of the interior modules unfinished in order to complete the project for Expo 1967 due to a labour shortage. Despite the mixed reception of the Habitat '67 project, its creator, Moshe Safdie, maintains a strong attachment to his brainchild. In a recent interview (B1M, 2023), Safdie expressed his continued enthusiasm for the project and firmly believes that it was ahead of its time not only in the 1960s but also in the present century. His unwavering conviction in the idea and execution of Habitat '67 serves as a testament to the innovative and timeless nature of the project.

Figure 4.2.6 Workers during the construction of Habitat 67 (B1M, 2023)

Despite its immense popularity since its construction, with waiting lists for residency spanning up to five years in the 1970s, Habitat 67 ultimately fell short of its intended purpose. While this project did earn Moshe Safdie widespread recognition as an architect, it failed to revolutionize urban living as he had hoped. Besides failing to revolutionize urban living, Habitat 67 could not achieve affordability either. In 1967, many wondered if the apartment prices would be reasonable. As J. Morris wrote, "Safdie created a luxurious (Rolls-Royce) design of houses; no matter what adjustments made, it would remain as expensive as a (Rolls-Royce)". Morris also believed that Safdie was naive to think that his design would solve urban issues worldwide (Morah, 2019). Currently, apartments in Habitat 67 are valued at over a million dollars, with a three-bedroom apartment on the market for 1.4 million dollars (Figure 4.2.7) according to (Slone, 2023). This price means Habitat 67 has become a building catering to a wealthy Canadian demographic.

Figure 4.2.7 A picture of the 1.4 million dollar apartment (Slone, 2023)

The unique design of Habitat 67, with modules stacked diagonally like a hillside instead of vertically like a tower, also creates some issues (Figure 4.2.8). While this design gives each apartment a private space to access sunlight directly, it also causes multiple void points in the structure, allowing cold wind to circulate through the concrete structure in colder seasons. Concrete, cold wind, and the absence of greenery make for an unpleasant and uncomfortable combination (Figure 4.2.9). Additionally, the long and wide paths make it difficult and tiring for those with less physical ability to walk comfortably (Morah, 2019).

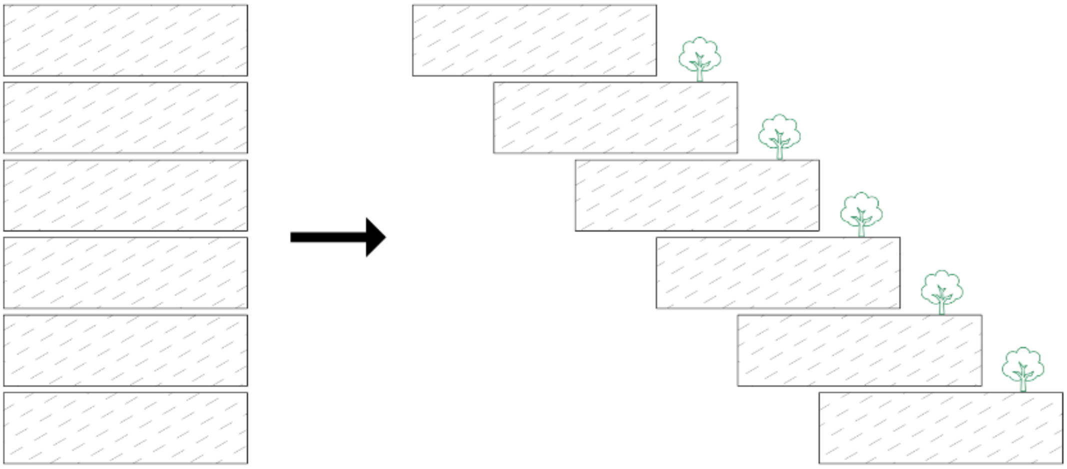


Figure 4.2.8 Modules stacked diagonally instead of vertically, redrawn by the author using (B1M, 2023)

Figure 4.2.9 Winter View of Habitat 67 (Morah, 2019)

Although Habitat 67 may not have entirely achieved Safdie's goal of resolving urban living issues, it does not imply that the project concept is flawed. Despite the issues, many building residents have reported enjoying their time there. Privacy has been a critical focus for many residents, and the design has strived to bridge the gap between an apartment in the city and a suburban house. The concrete modules with thick walls have proved to be an excellent soundproofing solution, and the space between modules and walls has given residents a great sense of privacy. Additionally, the idea of an open roof for each apartment instead of balconies has allowed residents to feel and enjoy the outdoors in their homes (Figure 4.2.10). According to (Morah, 2019), many comments on the project have praised Habitat 67 for demonstrating that high-density buildings can be constructed in the city while still ensuring a reasonable level of privacy. Despite the building's challenges, Habitat 67 remains a groundbreaking experiment in urban housing that has paved the way for future modular residential designs.

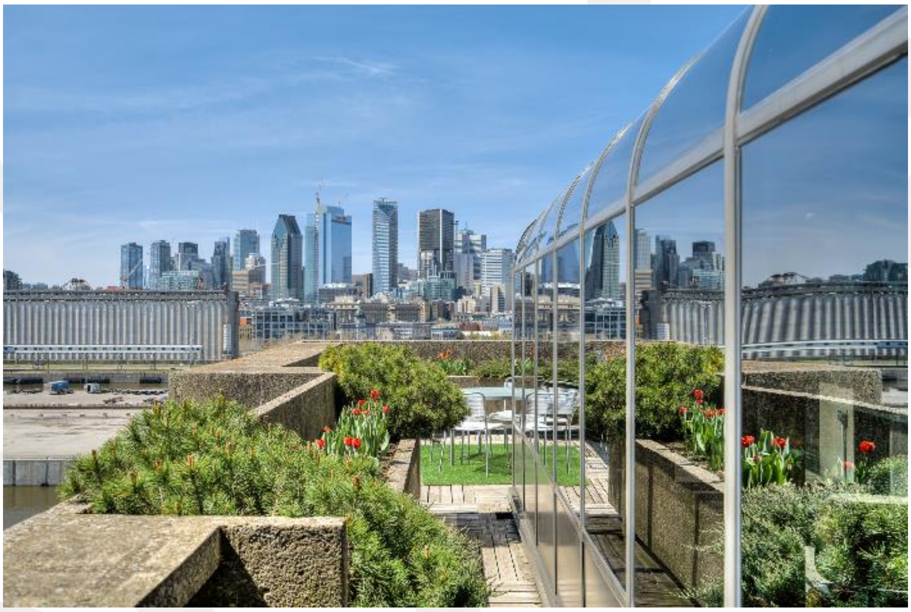


Figure 4.2.10 View from the private roof of a Habitat 67 apartment (Slone, 2023)

Habitat 67 is a building that has been standing for over 57 years; however, the exciting floor behind its construction has yet to be finished. The construction project, unfortunately, experienced a deviation from the original plans designed by Safdie. The primary reason behind this deviation was the inadequate funding. In addition, the limited availability of CAD programs and 3D printing technology during the 1960s meant that Safdie and his team had to rely on handmade 2D plans, sketches, and models for the project. However, Safdie mentioned in an interview that LEGOs were instrumental in helping him during the design phase of Habitat 67. The modular nature of LEGOs and their ability to be easily clicked together in any direction proved ideal for the project. Despite not being entirely constructed, Safdie's vision for Habitat 67 has been finally brought to life digitally. Neoscape, an agency specializing in architectural visualization and visual storytelling, collaborated with Safdie Architects to create a digital version of the original whole project (B1M, 2023). The team worked with Safdie to build the digital version of Habitat 67 with its full masterplan scale - a 30-floor community building that can accommodate 1200 families (Figure 4.2.11). They used Unreal Engine, a game development engine by Epic Games, to create the digital version, now available online through their website under the name Hillside Sample (Games, n.d.).

Figure 4.2.11 Habitat 67, full master plan, ArchViz scene by (Games, n.d.)

Despite concerns about its effectiveness, Habitat 67 is an iconic project widely considered one of the most significant architectural undertakings of the 20th century. Some articles today refer to the project as a failed dream, but it represented a significant prefabrication experiment involving creating hundreds of complex concrete modules. The modules' design, manufacturing, assembly, transportation, and on-site construction posed significant challenges, which are still relevant today. The project's success or failure is still a subject of debate. However, it is clear that Safdie aimed to maximize the potential of prefabricated modules in a way that distinguishes it from many current modular projects. Often, these projects lack significant deviations from traditional construction methods in the finishing step. Using concrete as a construction material for megastructure projects is not favored due to its high carbon footprint. If the project were designed now with an alternative material that reduces costs and carbon emissions, it could elicit a different response and greater acceptance.

4.2.2 The Packaged house

In 1947, Walter Gropius and Konrad Wachsmann collaborated to design a mass-produced prefabricated house called the Packaged House for the American market. Gropius arrived in America in 1937, and Wachsmann followed him four years later in 1941 (Smith, 2011). This effort was made to cater to the needs of wartime housing during World War II. However, the project did not reach the production phase and remained a mere aspiration of the designers. Nevertheless, it is a significant example of the desire for prefabrication during the 1900s. The movement was motivated to provide quickly erected houses for migrant weapons factory workers during the war. After the war, the factories used during the war were to be transformed to produce more prefabricated houses for returning veterans and their families. In 1942, the National Housing Agency set a target to produce 42,000 houses, and General Panel Corporation was formed later that year to work on the Packaged House (Imperiale, 2012). Both Gropius and Wachsmann had prior experience in working with prefabrication houses. Gropius had designed the Hirsch copper house in Germany, and Wachsmann had worked with Christoph and Unmack in Germany in the late 1920s (Herbert, 2021). The Packaged House design comprises a rectangular plan based on panel system construction (Figure 4.2.12) and (Figure 4.2.13), primarily with a single floor. Panels were manufactured in factories and joined on-site using Wachsmann's four-way metal joining system.

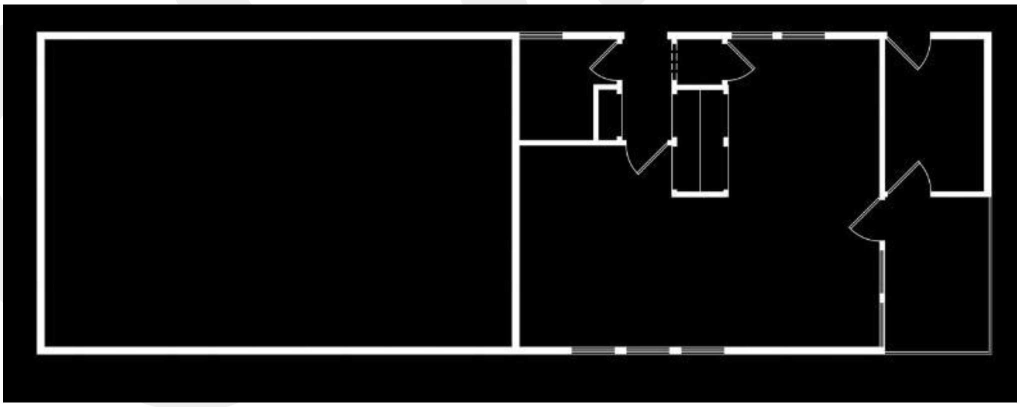


Figure 4.2.12 Type A, Packaged house floor plan, redrawn by the author (P-42, Tables 4.1.1 & 4.1.2)

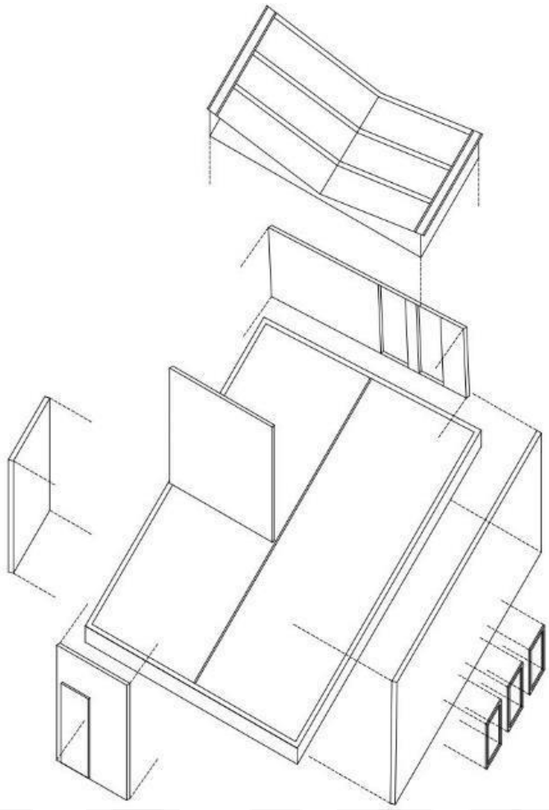


Figure 4.2.13 Exploded Isometric 3D View of the Packaged house panels redrawn by the author (P-42, Tables 4.1.1 & 4.1.2)

The project's originality was attributed to the contributions made by Walter Gropius and Konrad Wachsmann. Gropius played a crucial role in the project's conceptualization and development with his theoretical expertise, esteemed reputation, and extensive network. On the other hand, Wachsmann's expertise and dedication to technical development, and attention to detail were instrumental in the project's execution. Wachsmann's modular universal building system, developed during his time in the internment camp in France, was a remarkable achievement that caught Gropius's attention. Gropius shared Wachsmann's passion for standardized parts systems, a principle he had espoused since his days at Bauhaus. Gropius was responsible for patenting the system, while Wachsmann worked tirelessly to improve the metal joining system, driven by his creativity and belief in the system's potential (Figure 4.2.14). The wooden standard panels were used for all building parts, including walls, partitions, floors, and roofs, and were identical (Figure 4.2.15). The metal joining system panels, which allowed for various arrangements depending on the architect or consumer's desires, were creatively designed to connect in two, three, or four ways (Herbert, 2021) (Imperiale, 2012).

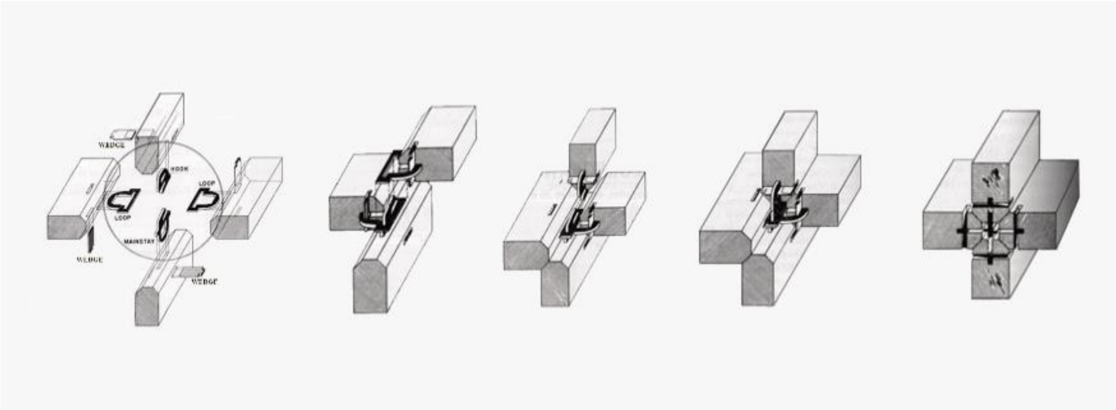


Figure 4.2.14 “The general panel system locks together like a Chinese puzzle.” From (Architectural Forum, February, 1947) (Imperiale, 2012)

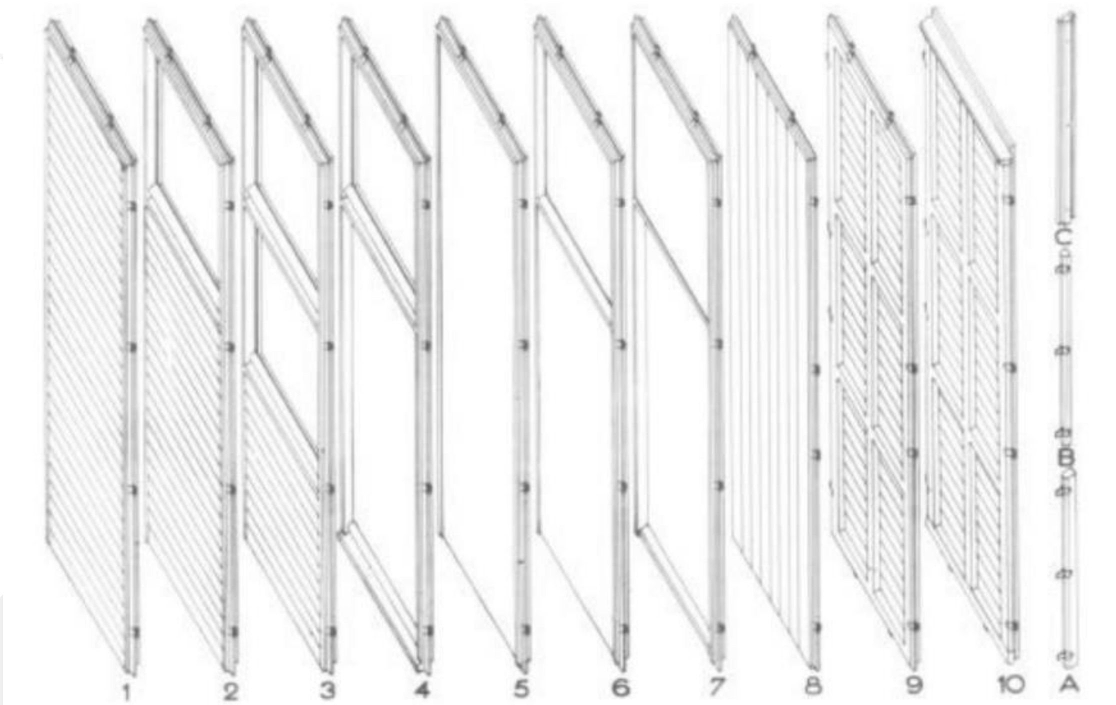


Figure 4.2.15 Konrad Wachsmann’s standard panels, 1941 (Herbert, 2021)

Despite the extensive efforts of Gropius and Wachsmann, the Packaged House project, envisioned as a revolutionary example of prefabrication houses, was never brought to fruition even after five years of development. Nevertheless, the project is a significant illustration of the evolution of prefabrication houses during the earlier decades, showcasing Gropius's extensive experience and Wachsmann's groundbreaking metal connecting system invention. The project's cancellation was not due to shortcomings in the Package house itself but resulted from unfortunate timing. The factory production line was ready for operation in 1947, but the program was terminated, and the government withdrew funding.

4.2.3 Boxabl

One noteworthy exemplar from North America, specifically the United States, is Boxabl - a prominent producer of modular homes. While numerous companies worldwide and in the US manufacture either prefabricated or modular houses, Boxabl stands out as a current and continuous producer of modular homes, as evidenced in Tables 4.1.1 and 4.1.2. Their module, known as "Casita" (Figure 4.2.16), is a modern, new modular housing system that produces boxy-shaped houses using new technology and innovative materials. Founded in 2017 in Las Vegas, Nevada, USA, Boxabl is a relatively new company valued at 3 billion dollars after only a few years. While there is a need for more literature on modular houses, their importance is noteworthy in the current modular housing and technology scope. This section aims to define and introduce Boxabl modular homes and briefly overview their features.

Figure 4.2.16 Boxabl module "Casita" (Boxabl – Accessory Dwelling Unit, n.d.)

During its design phase, Boxabl envisioned a revolutionary concept in modular housing. Currently offering a single standardized design known as Casita, each module is a square and measures approximately 5.9 meters with an area of 35m^2. The Casita is a compact single-bedroom apartment featuring a full-sized kitchen, a living area, and a dedicated bedroom space (Figure 4.2.17). While customization options are not yet available, the modules can be stacked vertically or connected horizontally to create larger living spaces (Figure 4.2.18). Constructed from a combination of steel, concrete, and EPS foam, Boxabl's homes are designed to withstand various weather conditions, including water, fire, wind, and mold, thanks to advanced insulation technology. The modules arrive almost fully completed from the factory, including furniture, appliances, fixtures, plumbing, electrical, heating, air-conditioning, and built-in LED lighting. The highly energy-efficient homes are ready for installation upon delivery and can be transported for a fee based on distance, folded to 6m by 2.6m dimensions for transport convenience (Figure 4.2.19) & (Figure 4.2.20). Installation is a straightforward process, with the Casita quickly unfolding and bolting onto any foundation type using Boxabl's signature connector plates, requiring only a day for completion. The responsibility of installation lies with the customer, who must contact a Boxabl-certified and state-licensed installer in your area.

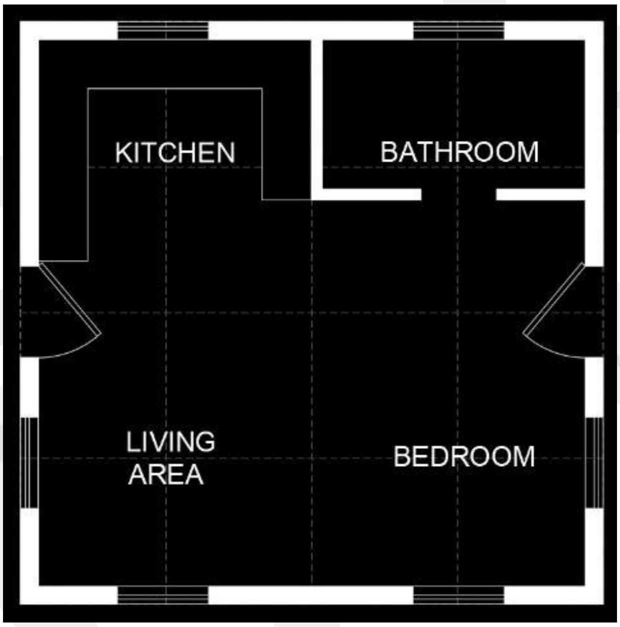


Figure 4.2.17 Boxabl module floor plan, redrawn by the author (P-53, Tables 4.1.1 & 4.1.2)

Figure 4.2.18 Boxabl modules connected together for more space (Boxabl – Accessory Dwelling Unit, n.d.)

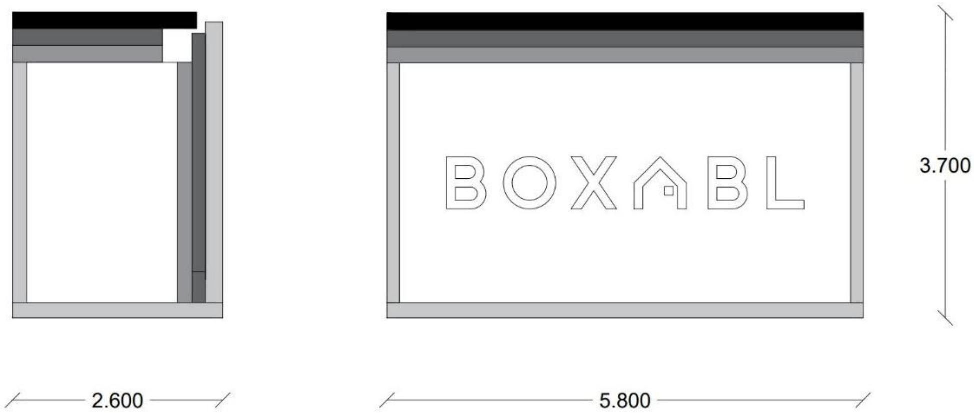


Figure 4.2.19 Boxabl module folded for transportation, redrawn by the author (INC., 2023)

Boxabl presents several notable advantages, making it an attractive option in the modular housing market. Firstly, the homes are highly energy-efficient due to quality walls and insulation, contributing to environmental sustainability. The construction process generates lower waste, aligning with modern eco-conscious practices. Boxabl's modules are fully approved across the United States, and their popularity has soared, driven by high demand and notable customers like Elon Musk, who purchased one for use as a guest house. The ease of shipping and installation adds to the appeal, especially with the expandable vertical or horizontal growth options—moreover, the ability to modify the façade after installation provides a degree of customization. However, there are challenges associated with Boxabl. The production level struggles to meet the increasing demand, resulting in long customer waiting periods. Poor communication with the company can lead to problems like site preparation issues before delivery, often attributed to government regulations and requirements. Furthermore, the limited options available may not fully cater to a diverse customer base, potentially hindering broader market satisfaction. Despite these drawbacks, Boxabl remains a promising player in the modular housing industry.

Figure 4.2.20 Boxabl module during transportation (Boxabl – Accessory Dwelling Unit, n.d.)

Boxabl is a relatively new modular home producer with a promising foldable concept and quality modules. The foldable house offers several advantages, such as portability, low cost, ease and speed of assembly, lightweight construction, reusability, and recyclability. Boxabl aims to produce high-quality, low-cost, and fast-produced housing modules through continuous research and testing of new designs, materials, finishes, and customizable options. The company is expanding the factory to achieve a production line with a one-module-per-minute capacity. Among the available modules, the Casita module meets all quality, comfort, and sustainability requirements, but its success will depend on customers' interest in owning such a house. To achieve this, Boxabl needs to offer more customization options to appeal to a broader range of customers and improve its production line to meet the high demand and gain trust. Boxabl is one of the latest examples of modular homes, representing the long history of prefabricated and modular projects spanning over a hundred years, as shown in Tables 4.1.1 and 4.1.2. However, many issues and obstacles still exist that diminish trust and demand for this type of housing. Innovative companies like Boxabl may be capable of overcoming these challenges shortly.

4.2.5 Exploring additional projects

Several other visionary companies and architects have made significant contributions to the dynamic architectural landscape of North America by incorporating modular design and pushing the boundaries of innovation and sustainability. One of the most notable projects is the Dymaxion House (P-43, Tables 4.1.1 & 4.1.2), designed by architect Buckminster Fuller in 1927 (Figure 4.2.21). This prefabricated concept was ahead of its time and envisioned a mass-produced, sustainable single-family house that would be the living machine of the future (Merin, 2019). The hexagonal plan layout was suspended from the ground by a central pole and cables made entirely of aluminum, chosen for its strength, low weight, and minimal maintenance requirements. However, the design was never built as Fuller had envisioned. In 1948, an investor in the project combined all of Fuller's ideas and prototypes to create the Wichita House with some modifications (Merin, 2019). The layout is circular instead of hexagonal and is lifted only a few centimeters above the ground (Figure 4.2.22). Although Fuller's concept was never adopted on a mass scale, it was innovative. The futuristic aeroplane-shaped house with lightweight materials could be erected in a single day (Smith, 2011). Even today, the prototype is restored in the Henry Ford Museum for observers to imagine a future dwelling.

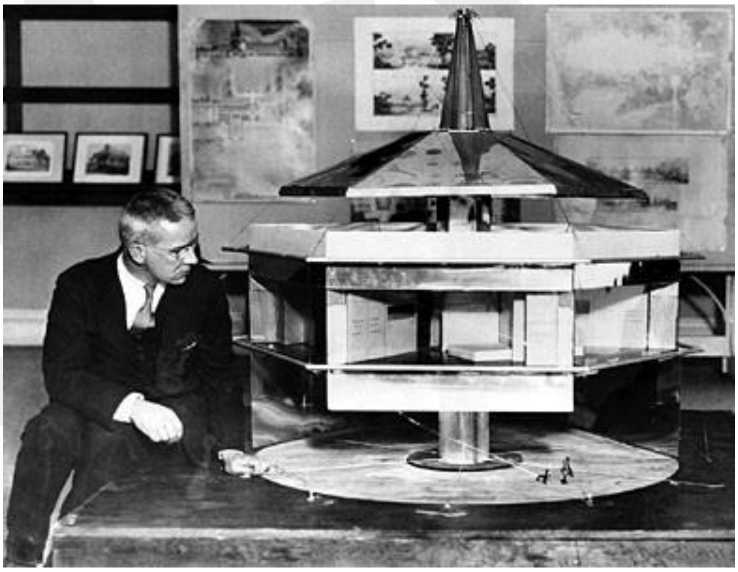


Figure 4.2.21 Buckminster Fuller next to the Dymaxion House (Merin, 2019)

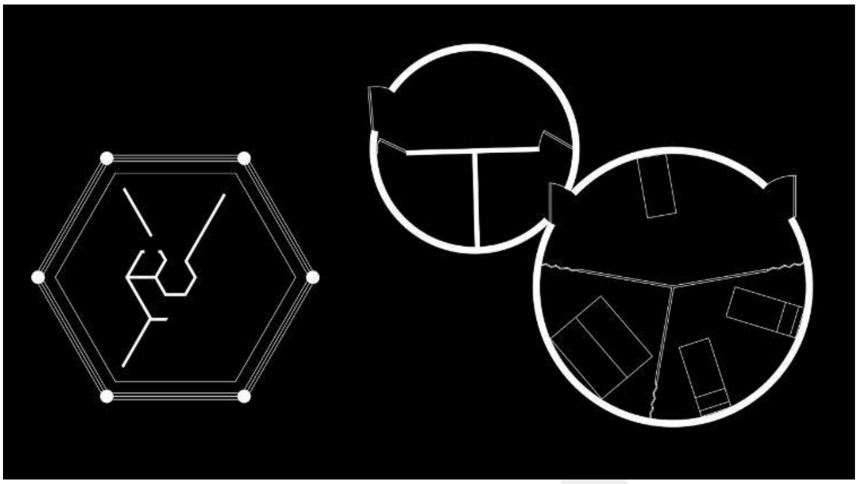


Figure 4.2.22 Dymaxion House & Wichita House floor plans, redrawn by the author (P-43, Tables 4.1.1 & 4.1.2)

In contrast to Fuller's vision, The B2 Tower (Figure 4.2.23) stands as an example of modern modular and prefabricated projects. Designed and constructed by SHoP architects in the United States, it was the tallest modular residential building globally in 2016, completed using volumetric modular units (*B2 | SHoP*, n.d.). The modules were manufactured almost entirely inside factories (Figure 4.2.24) and were then stacked to form 32 floors, creating a range of apartment layouts varying from studio to three bedrooms. The modular technology employed in the B2 Tower proved to be highly efficient, decreasing noise and traffic impacts on dense urban sites while increasing construction efficiency. As a result, the project was completed 18 months ahead of schedule compared to traditional construction methods. However, the module size was limited by transportation and crane requirements, as stated by David Farnsworth (Farnsworth, 2014). Although it is worth noting that the units were designed so that their modular construction may go unnoticed by residents (Farnsworth, 2014), this observation holds for most current modular project types, be they low or high-rise, underscores the significant difference between Fuller's Dymaxion house and contemporary architectural firms. Previously, innovation was expressed in the construction methods and the project's design rather than simply replicating a pre-existing project using a different methodology. The question of which approach is superior and beneficial is complex but worth exploring.

Figure 4.2.23 B2 Tower during construction, lifting a module by crane (B2 | SHoP, n.d.)

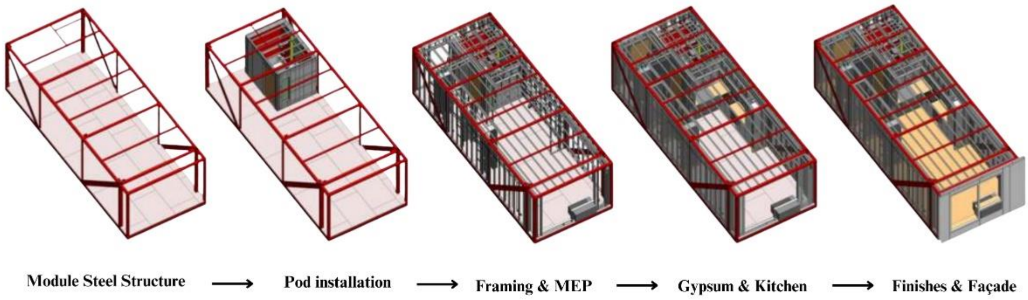


Figure 4.2.24 Process of modules prefabrication for B2 Tower by (Forest City Ratner Companies, 2012)

Innovative modular concepts and designs are not absent today. While residential building projects tend to use modular construction to reduce cost and build faster only, there are still innovative single-family houses modular and prefabricated projects in and out of North America, as shown in (Tables 4.1.1 & 4.1.2). Rocio Romero Prefab, for example, is a beacon of contemporary prefab homes, seamlessly blending sleek aesthetics with eco-friendly principles (P-5, Tables 4.1.1 & 4.1.2). Resolution: 4 Architecture, renowned for its inventive solutions, has carved a niche in the market by delivering modular designs that prioritize functionality without compromising style (P-3, Tables 4.1.1 & 4.1.2). Michelle Kaufmann, a trailblazer in the green building movement, has championed sustainable modular homes, fusing modern elegance with a commitment to environmental responsibility. Anderson Anderson Architecture's prefabrication approach extends beyond residential spaces, exploring innovative solutions for diverse architectural challenges (P-1, Tables 4.1.1 & 4.1.2). Marmol Radziner Prefab, synonymous with craftsmanship and precision, has consistently redefined luxury in modular living, proving that elegance and efficiency need not be mutually exclusive. Together, these architectural pioneers in North America exemplify a shared idea of modularity (Smith, 2011).

4.3 European Modularity

The modular and prefabricated concept has a long-standing presence in the European housing sector, with each country having unique projects with prefabrication. Despite the differences in approach, the various European countries' experiences with modular housing have affected their respective housing markets. While this study does not seek to cover the entire history of modularity in Europe, it is essential to explore the central regions of Europe and introduce modular projects through selected case studies to assess the stage of modularization and prefabrication of the building (Tables 4.1.1 & 4.1.2), starting with the United Kingdom. The UK's housing market is under significant pressure, suffering from a yearly shortage of a hundred thousand homes (Bayliss & Rory, 2020). While modular projects such as hotels and student dormitories are well-established, the residential housing market is still developing under modular methods (Bayliss & Rory, 2020). This research lists 22 projects in the UK, starting with Murray Grove in 1999, the first major residential project to use modular construction in the country (Lawson et al., 2014), and Raines Court Housing in 2003, the first modular housing scheme funded by the Housing Corporation as a pilot project for prefabricated and off-site construction housing projects (Melvin, 2005). Tables 4.1.1 and 4.1.2 also highlight Apex House, the tallest modular building in Europe in 2017 (Bayliss & Rory, 2020). Finally, the research concludes UK projects with the Beechwood West Housing project, which offers customizable modular and prefabricated homes, arguably the best modular system yet. In modularity and prefabrication, Germany is considered the origin of European modularity and even the world, with architects such as Le Corbusier, Konrad Wachsmann, and the Bauhaus school of Walter Gropius. Scandinavian countries have also approached modularity in architecture uniquely. Although modular construction benefits the housing market and the environment, its use in Scandinavian countries primarily solves the harsh climate that makes construction difficult most of the year. Prefabricated techniques enable project delivery inside factories during the cold winter and provide a safe area for workers away from extremely low temperatures. The European modular projects demonstrate a beautiful coexistence between the old and the new, focusing on sustainability and adaptive reuse.

4.3.1 Murray Grove & Raines Court UK

The Murray Grove project (P-6, Tables 4.1.1 & 4.1.2), located in London, England, is a significant milestone in the history of modular architecture in the UK, as it represents the first significant modular residential development built in 1999 (Figure 4.3.2) (Lawson et al., 2014). The project was designed by Cartwright Pickard, who collaborated with Yorkon manufacturers to construct a five-floor apartment building consisting of approximately 90 modules (Figure 4.3.3) (Bayliss & Rory, 2020). These steel volumetric units have partially open sides, enabling the creation of various apartments ranging from one to three bedrooms. The rectangular modules measure 8 meters in length, 3.2 meters in width, and have a standard height of 3.2 meters. Each module was fully completed inside factories before being assembled on-site in ten days. Two modules were combined to create a single-bedroom apartment (Figure 4.3.4). The entire project was completed within six months. The 30 affordable rental homes built using this approach proved efficient and widely popular, with the building quality still evident over 20 years later. The innovative design and manufacturing process allowed for quick and efficient construction while maintaining high quality (Bayliss & Rory, 2020). The success of this project has paved the way for the use of modular construction techniques in the UK and beyond.

Figure 4.3.2 Murray Grove building in Hackney, London (Pickard, 1999)

Figure 4.3.3 Murray Grove modules installation by crane (Lawson et al., 2014)

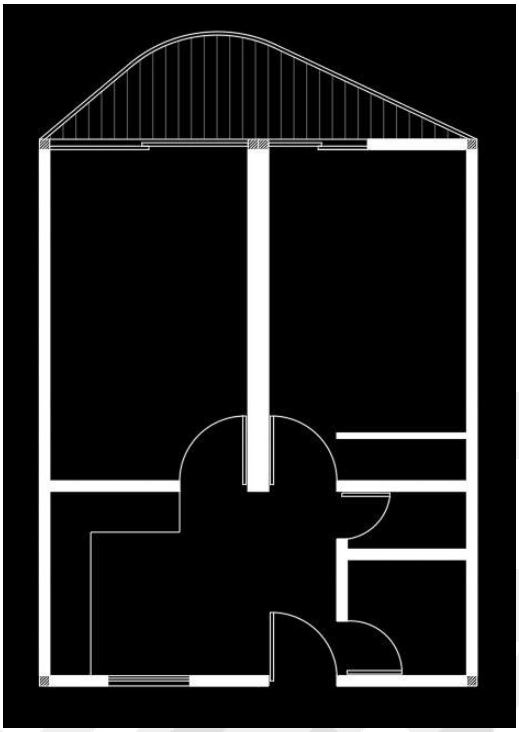


Figure 4.3.4 Murray Grove one-bedroom floor plan, redrawn by the author (P-6, Tables 4.1.1 & 4.1.2)

Peabody Trust maintained its partnership with Yorkon in developing the Raines Court social housing project following their successful collaboration on the Murray Grove project (P-7, Tables 4.1.1 & 4.1.2). Completed in 2003 in London, England, Raines Court (Figure 4.3.5) was the first subsidized prototype housing scheme funded by the Housing Foundation, as referenced in (Melvin, 2005).

Figure 4.3.5 Raines Court project UK 2003 (Bayliss & Rory, 2020)

The project was designed as an experimental venture for off-site prefabrication and construction, with Allford Hall Monaghan Morris architect, Wates construction, and Yorkon manufacturer collaborating to build a six-floor apartment building consisting of 127 self-supported modules forming 60 private and shared homes (Bayliss & Rory, 2020). The steel volumetric room units were manufactured in factories and delivered to the site equipped with bathrooms, kitchens, doors, windows, internal decorations, external cladding, and roofing. The modules' length varied from 9.6 to 11.6 meters, while the width was set to 3.8 meters for transportation without the need for special outriders on high roads (Figure 4.3.6) (Lawson et al., 2014) (Melvin, 2005).

Figure 4.3.6 The process of building the Raines Court project includes stages of factory production, transportation, and site installation (Melvin, 2005)

Two modules were required to create a two-bedroom apartment, with one module for the living/dining/kitchen and the second module for the bedrooms (Figure 4.3.7) (Lawson et al., 2014). Overall, the construction process took 23 months, five months less than the traditional method, but the site installation for the 127 modules took only four weeks. The modules' installation on-site gave the impression of an instant building, as they were delivered and stacked almost every 30 minutes (Melvin, 2005). Upon completion, all homes were sold in three weeks, proving the success of Raines Court's goals.

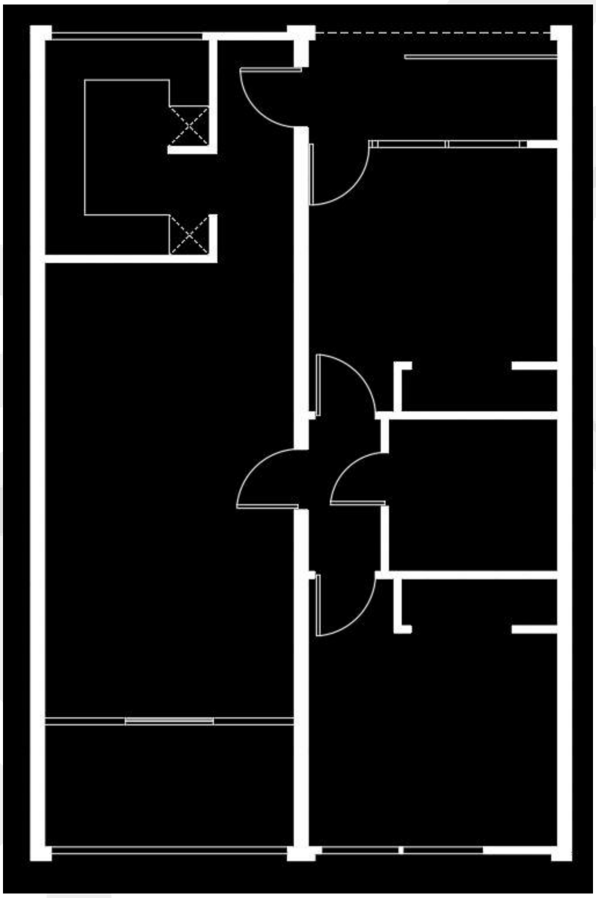


Figure 4.3.7 Raines Court two-bedroom floor plan, redrawn by the author (P-7, Tables 4.1.1 & 4.1.2)

4.3.2 Beechwood West customizable homes

The concept of prefabrication that offers high-quality modular homes with numerous customization options is genuinely ideal. Beechwood West (P-49, Tables 4.1.1 & 4.1.2) has successfully achieved this by creating an online platform with over a million combinations, delivering standard, fast, sustainable, and customizable homes.

Beechwood West has implemented a prefabrication concept that provides high-quality modular homes with extensive customization options through an online platform. The project involved the collaboration of Swan Housing Association, NU Living manufacturer, and Pollard Thomas Edwards architect to develop a personalized neighborhood of 251 homes in London. The primary objective was to offer cost-effective construction through offsite factory production and allow residents to customize their homes to their preferences through room layout, external finishes, and internal specifications. The modular system utilized an online configurator, enabling residents to choose from five house types, specify bedroom numbers, arrange floor plans, and select external finishes, roofs, and windows; this resulted in over a million unique design options for each family house (Figure 4.3.8). However, having an extensive array of options made drawings a significant challenge for the team to manage and ensure quality. The construction of the 251 houses occurred between 2016 and 2022, with the primary material being Cross-Laminated Timber (CLT) (Bayliss & Rory, 2020). The project relied on adopting a digital process for designing modular houses, which has the potential to revolutionize prefabrication on a large scale. Although the project concluded in 2022, its full potential and suitability for diverse locations require further inspection, testing, and ongoing development.

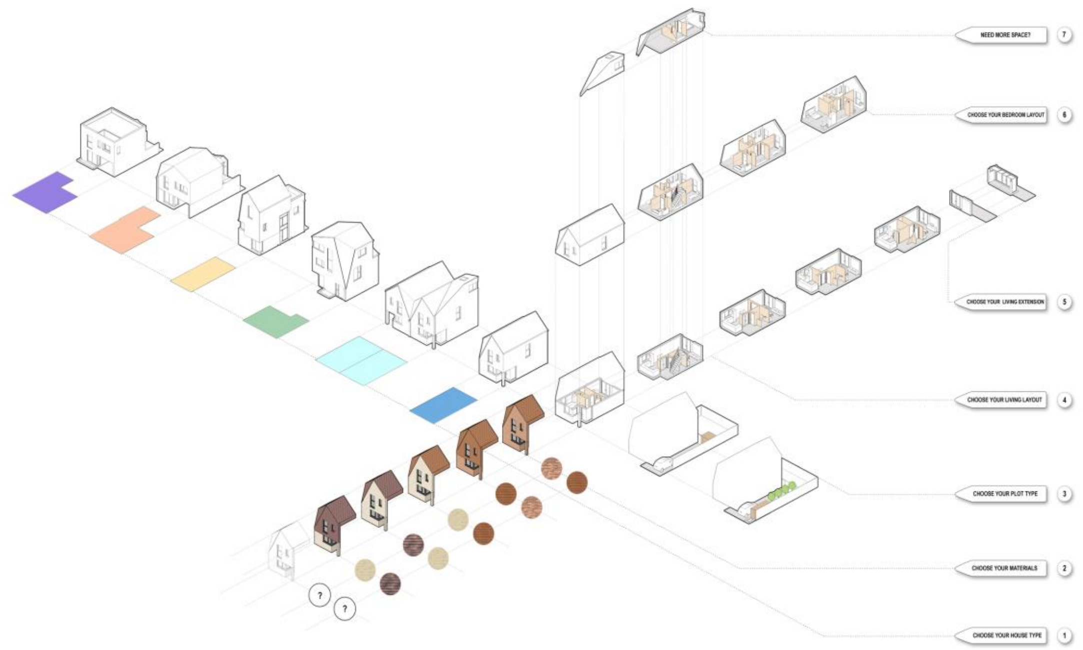


Figure 4.3.7 Custom Build Strategy for Beechwood West houses (Edwards, n.d.)

4.3.3 Additional European Projects

Tables 4.1.1 and 4.1.2 present over 35 modular projects from 11 European countries within the purview of this research. Each project, architect, and company were selected with due care and diligence based on several factors, including but not limited to significance, design, technique, and available information. It is important to note that even more modular projects are beyond those listed. As previously mentioned, it is crucial to thoroughly delve into several of these projects to understand modularity across continents. Chapter 2 of the thesis lists some historical projects from Europe. In addition, this chapter mentions two projects - Murray Grove and Raines Court. This section will briefly overview three other projects: a modular high-rise building, a small innovative modular dwelling, and a modular family house.

Ten Degrees (P-52, Tables 4.1.1 & 4.1.2), located at 100a George Street in London, England, represents a remarkable achievement in modular construction. The building stands at an impressive height of 135 meters, making it the tallest modular building in the world (Design, n.d.) (Tide, n.d.), and boasts two residential towers with 38 and 44 floors, respectively. The project comprises 546 homes, including studios and one-, two-, and three-bedroom apartments, thus offering residents a wide range of options. In keeping with its commitment to accessibility, 109 of these homes are available at affordable prices (Bayliss & Rory, 2020). The success of Ten Degrees is a testament to the impressive collaboration between HTA Design architect, Tide Construction, and Vision Modular Systems manufacturer, who have worked together on seven modular projects, including the previous tallest modular building in Europe, Apex House (P-46, Tables 4.1.1 & 4.1.2), each one improving and refining upon the last. The construction process of Ten Degrees was highly efficient, with foundation and concrete cores, volumetric unit manufacture, modules installation, and internal and external finishes all intertwined to complete the project in just 31 months (Figure 4.3.9). This is a remarkable 42% faster than traditional construction methods. The twin concrete cores were completed in 2018, and from there, the process of stacking the 1500 modules began, with 50 modules installed weekly (Bayliss & Rory, 2020). Overall, the Ten Degrees project represents a significant milestone in modular construction, demonstrating the feasibility and advantages of this innovative building method. The collaboration between HTA Design, Tide Construction, and Vision Modular Systems has resulted in an outstanding achievement that sets new standards in sustainable and affordable housing.

Figure 4.3.9 The construction process of Ten Degrees, craning, installation of modules, and façade works (Bayliss & Rory, 2020)

The MIMA House (P-31, Tables 4.1.1 & 4.1.2) is a modular housing project conceptualized by MIMA Architects in 2011 (Figure 4.3.10). It boasts a striking minimalist design with clean lines, generous windows, and a strong emphasis on simplicity. MIMA's architects invested years of research to create a flexible and adaptable living space, resulting in a highly versatile and cost-effective area of about 36 square meters (Figure 4.3.11). Inspired by traditional Japanese houses, the MIMA House incorporates prefabricated elements such as Shoji screens, Fusuma panels, and Tatami mats. The house comprises a square post and beam wooden frame measuring 1.5 by 3 meters, with plywood panels installed on a 1.5-meter grid, allowing for flexible changes to the layout based on individual needs (Figure 4.3.12). The innovative design and material choices of the MIMA House enable it to seamlessly blend into any landscape and cater to the evolving demands of modern living. MIMA House is a remarkable and unique modular housing project that exudes a sense of beauty and sophistication. However, it may not be a practical option for everyone due to its limited size and unique design features that may not suit everyone's lifestyle. Overall, the MIMA House is a stunning architectural masterpiece showcasing prefabrication's creativity, possibility, and simplicity.

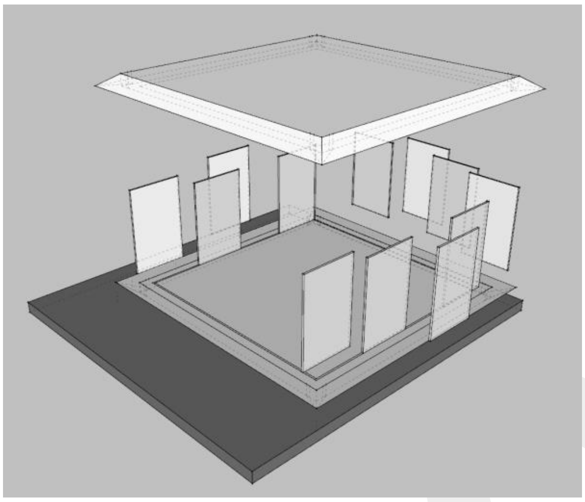


Figure 4.3.10 MIMA house model made by the author (P-31, Table 4.1.1 & 4.1.2)

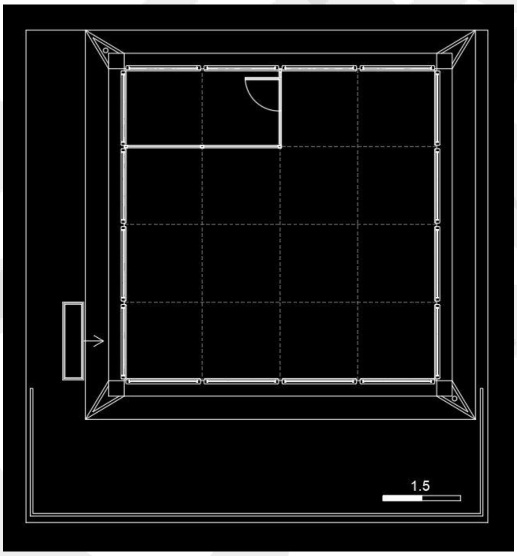


Figure 4.3.11 MIMA house floor plan, redrawn by the author (P-31, Table 4.1.1 & 4.1.2)

Figure 4.3.12 Installing plywood panels on the grid (ArchDaily, 2011)

The ONV House (P-12, Tables 4.1.1 & 4.1.2), designed by the ONV architect based in Copenhagen, is a contemporary and streamlined prefab housing solution offering high flexibility and quality. With six distinct options, this minimalist dwelling is ideal for those seeking a simple yet stylish living space (Figure 4.3.13). The prefabricated construction technique enables quick and efficient on-site assembly, reducing construction time and costs (Figure 4.3.14). Moreover, the design can be effortlessly expanded by adding modules, with the smallest option being 60m^2 and the largest being 160m^2, comprising four modules (Figure 4.3.15). Constructed using timber frames and glass components, the volumetric room modules take up to 12 weeks to complete and are highly efficient for the Scandinavian market. The house has been featured in numerous publications as a cost-effective building solution due to its extensive windows that optimize natural light and scenery and well-planned interior spaces that contribute to its eco-friendly design. Overall, the ONV House is a chic and sustainable prefab housing solution that offers excellent value to those looking for a modern and versatile living space.

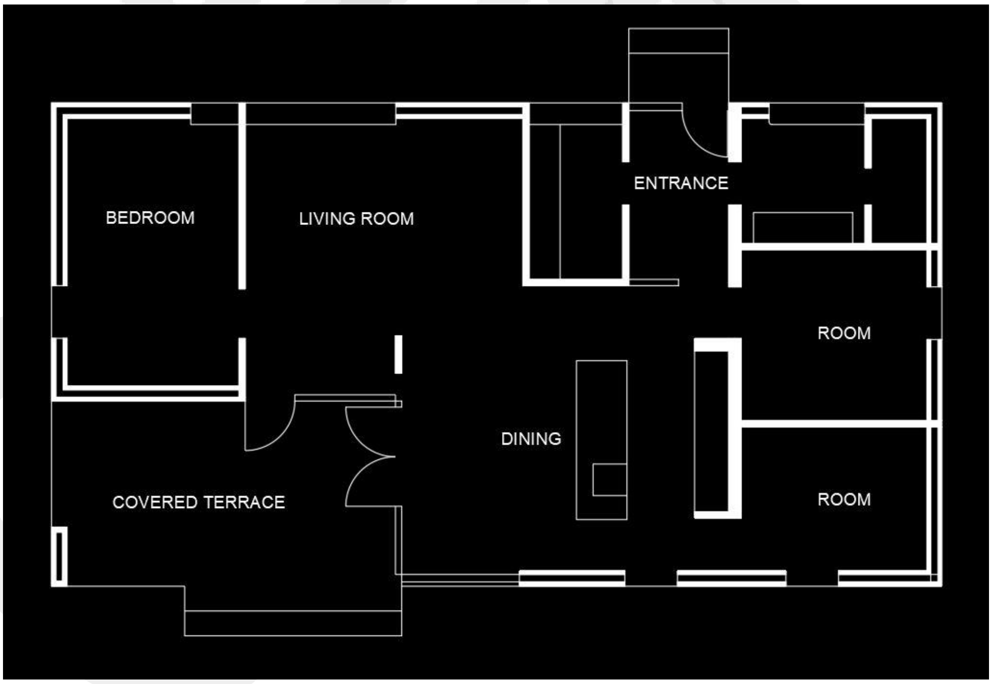


Figure 4.3.13 ONV house plan, C type, 103m2, redrawn by the author (P-12, Tables 4.1.1 & 4.1.2)

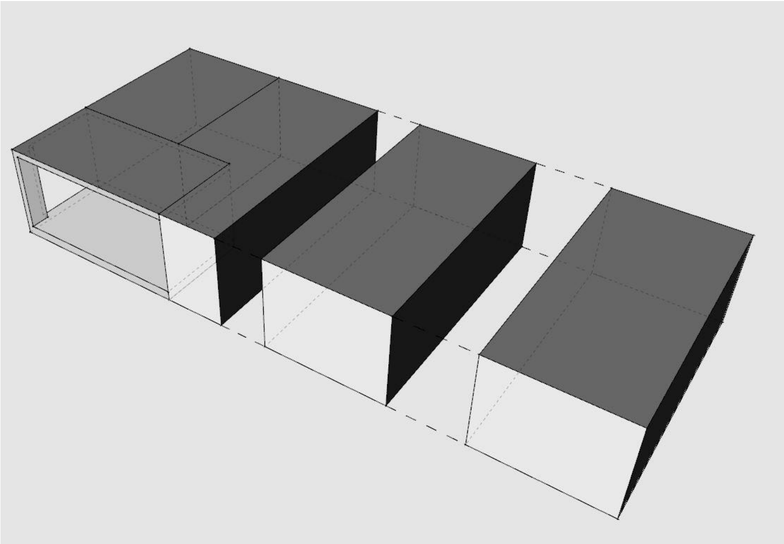


Figure 4.3.14 ONV house, 3D models for C type made by the author (P-12, Tables 4.1.1 & 4.1.2)

Figure 4.3.15 Transportation and installation of ONV house modules (Staib et al., 2008)

The history and current state of architectural modularity in Europe is characterized by numerous innovative architects and projects, both successful and failed, ultimately contributing to advancing the prefabrication and modularity process. Other notable projects essential to highlight include the Loftcube transportable room module unit (P-13, Tables 4.1.1 & 4.1.2), designed by a German company. This innovation features square modules composed of steel and timber that can be assembled in only six days. The CUB House by Futureform is another excellent example (P-22, Tables 4.1.1 & 4.1.2), offering an expandable modular system housing option based on the family's needs and future growth, evolving from a basic two-module house to a multi-floor building.

The Tiny House Noa (P-40, Tables 4.1.1 & 4.1.2), a prefab kit home designed by Jaanus Orgusaar in Estonia, features a hexagonal floor layout, with walls and roof made up of identical rhombuses, allowing for easy expansion by simply adding another module. Finally, the New Islington Houses project in Manchester (P-47, Tables 4.1.1 & 4.1.2), England, by Urban Splash and Shedkm, is a successful example of prefabrication. The residential area comprises 43 townhouses, with volumetric modules made of cross-laminated timber CLT. These can be customized based on the family's needs and delivered as fully water-tight and pre-finished homes in just a few weeks.

Overall, the projects mentioned above in this chapter demonstrate the immense potential of modularity in architecture in Europe and offer valuable lessons for future improvements in prefabrication and modularity.

4.4 East Asian Modularity

In architecture and construction, prefabrication and modularity significantly impact the East Asian region, including Japan, China, Singapore, Hong Kong, and Australia, which has been at the forefront of adopting and advancing these innovative practices. The roots of prefabrication in the region can be traced back to the post-war era when rapid urbanization and reconstruction efforts necessitated efficient and cost-effective building solutions.

Japan led the way in modular architecture with the Nakagin Capsule Tower, an iconic example that inspired modularity across Japan, Asia, and the world. In China, multi-story and high-rise buildings are the focus of modular applications. Since 2007, companies have implemented advanced modular construction techniques that have made headlines worldwide, with projects like The Mini Sky City and the Ten-floor Holon Building.

Hong Kong introduced prefabrication and modularity to the construction sector in the mid-1980s. However, until 2020, modular building had yet to be completed. Nevertheless, the HKSAR Government is promoting the MiC system and encouraging innovation in construction. As a result, two pilot projects have been constructed, one shown in (P-37, Tables 4.1.1 & 4.1.2). Meanwhile, Singapore is a mature modular market in the region, using prefabricated components since the 1980s. At least fifteen modular projects have been completed using PPVC, and the number of residential and other projects adopting PPVC in Singapore is increasing annually. Asia's dynamic and ever-changing cities offer an ideal platform for revolutionary modular initiatives. Across Tokyo's futuristic skyline to Singapore's urban landscape, this segment highlights a range of projects that exemplify Asia's dedication to progress and optimized city living. These initiatives demonstrate how modular construction fulfills the requirements of swift urbanization while promoting a symbiotic relationship with the environment.

4.4.1 Japan & Nakagin Capsule Tower

Japan is renowned worldwide for its pioneering approach to architectural modularity in the housing industry. Across the centuries, the Japanese house has been an exemplary model of fundamental modular organization, standardization, and unitization in timber construction. Several centuries ago, a basic module measuring unit, known as "Shaku," was used (Staib et al., 2008). Even today, Tatami mats are still used as a traditional measuring unit. As a nation prioritizing rationalization and standardization, Japan has seen rapid development, with Toyota, the renowned car manufacturer, now expanding its manufacturing capabilities to include prefabricated homes. These homes are designed to meet high durability and energy efficiency standards, using automotive sector principles to ensure quality, efficiency, and sustainability in residential architecture. One of the leading providers of modern prefabricated housing solutions is Sekisui House, a prominent Japanese housebuilder. The company is dedicated to meeting the evolving needs of homeowners while emphasizing both functionality and aesthetic appeal. With numerous projects completed both within Japan and internationally, Sekisui House has significantly contributed to the global housing industry.

The Nakagin Capsule Tower (P-36, Tables 4.1.1 & 4.1.2), designed by Kisho Kurokawa, serves as an emblematic representation of postwar modernity in Japan, embodying the avant-garde spirit and forward-thinking design principles of the Metabolism movement. Situated in the heart of Tokyo, this architectural masterpiece is a rare gem that epitomizes the precision and sophistication of the Metabolism period. Completed in 1972, the Nakagin Capsule Tower is a testament to the movement's visionary approach, envisaging a dynamic and adaptable urban future by stacking 144 capsules like building blocks (Figure 4.4.1).

Figure 4.4.1 Nakagin Capsule Tower 1972 by Kisho Kurokawa (Lin, 2011)

Kisho Kurokawa was a founder and prominent figure of the Metabolist Movement, a group of architectural designers with a futuristic vision who came together in the 1960s. The movement was motivated by the poor condition of the country caused by two catastrophic disasters, the Great Kanto Earthquake in 1923 and World War II in 1945 (Her, 2020). These tragedies propelled the establishment of the Metabolist Movement and served as the foundation for the country's pathway. The primary impetus for this movement was the critical need for more effective means to shelter people. Metabolic Architecture ideas, in general, had the ambition of organic megastructure projects divided into different sections, a permanent core foundation, and a replaceable outer part to adapt to the country's development (Lin, 2011) (Her, 2020).

Metabolists envisioned the sea and sky as the habitats of the future. An exemplar of this vision is the Marine City by Kiyonori Kikutake in 1959, a proposal for a megastructure floating in the sea, containing a Linear Ocean City with a cylindrical concrete tower and several standardized housing units clipped into the tower (Figure 4.4.2). Despite the Metabolist members' various ideas, concepts, and proposals, Kurokawa's Nakagin Capsule Tower is the only project that embodies the movement's goals (Lin, 2011).

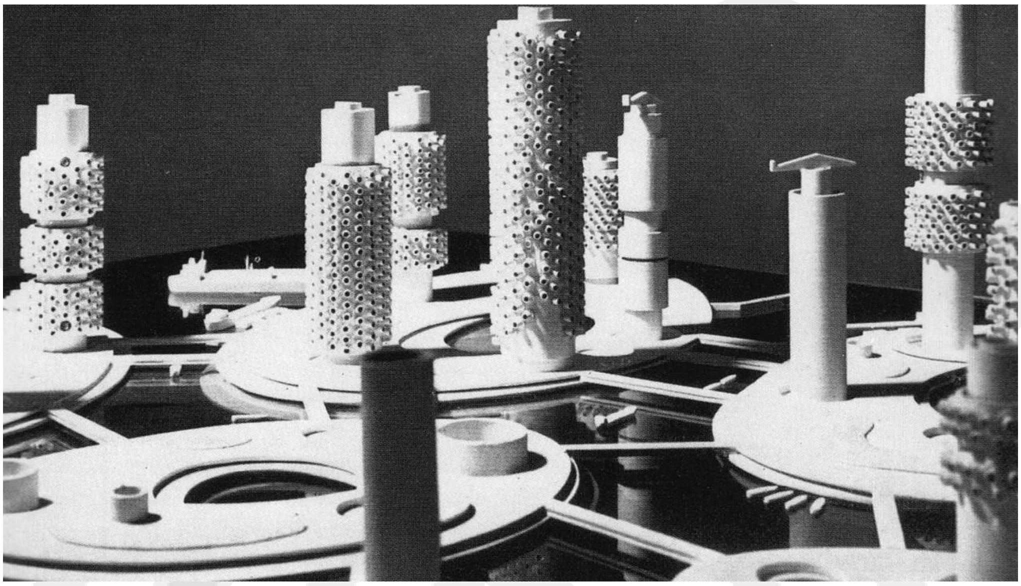


Figure 4.4.2 Model of the Marine City (Marine City: Tokyo's Futuristic Megastructure by Kiyonori Kikutake | ArchEyes, n.d.)

In 1970, at the World Exposition in Osaka, Kisho Kurokawa presented his Takara Beautilion design, consisting of a frame made of 3D steel pipes with prefabricated cube capsules connected to it (Figure 4.4.3). The Beautilion was popular at the 1970 World Exposition in Osaka and impressed visitors with its innovative design (Lin, 2011). Kurokawa's ideas for prefabrication were reminiscent of the futuristic concepts of Buckminster Fuller from the 1960s, who also tried to take full advantage of prefabrication methods. However, Kurokawa's design was more organic and practical. The success of the Takara Beautilion caught the attention of businessman Torizo Watanabe, who partnered with Kurokawa to design a dedicated capsule building (Lin, 2011). Two years later, in 1972, the Nakagin Capsule Tower was completed and became the first capsule construction in the world (Staib et al., 2008).

Figure 4.4.3 Takara Beautilion at the 1970 World Exposition (RIBA, n.d.)

The building had three main components: a permanent concrete core structure, moveable elements (capsules), and service utilities (Figure 4.4.4). Two reinforced concrete towers formed the main structure, with 144 capsules bolted on using only four high-tension bolts (Staib et al., 2008) (Lin, 2011). This allowed the capsules to be easily installed, detachable, and replaceable. Kurokawa's design of a permanent structure and moveable units that could be removed and attached individually gave the tower a dynamic appearance of constant evolution (Staib et al., 2008). The capsules were manufactured in factories in other cities, with only the two towers built on-site—the capsules' size is approximately 4.5 tatami mats, the size of a traditional Japanese tearoom. Tatami mats have been used in Japanese houses for centuries and are a standard module unit for measuring. The capsules were made of steel and measured around 2.3m by 3.8m, with a height of 2.15m (Figure 4.4.4). The interior components and furniture were designed for the capsules and fully fitted with everything necessary. The construction period of the Nakagin Capsule Tower took 15 months in total to build the concrete towers and install the capsules (Figure 4.4.5) (Staib et al., 2008).

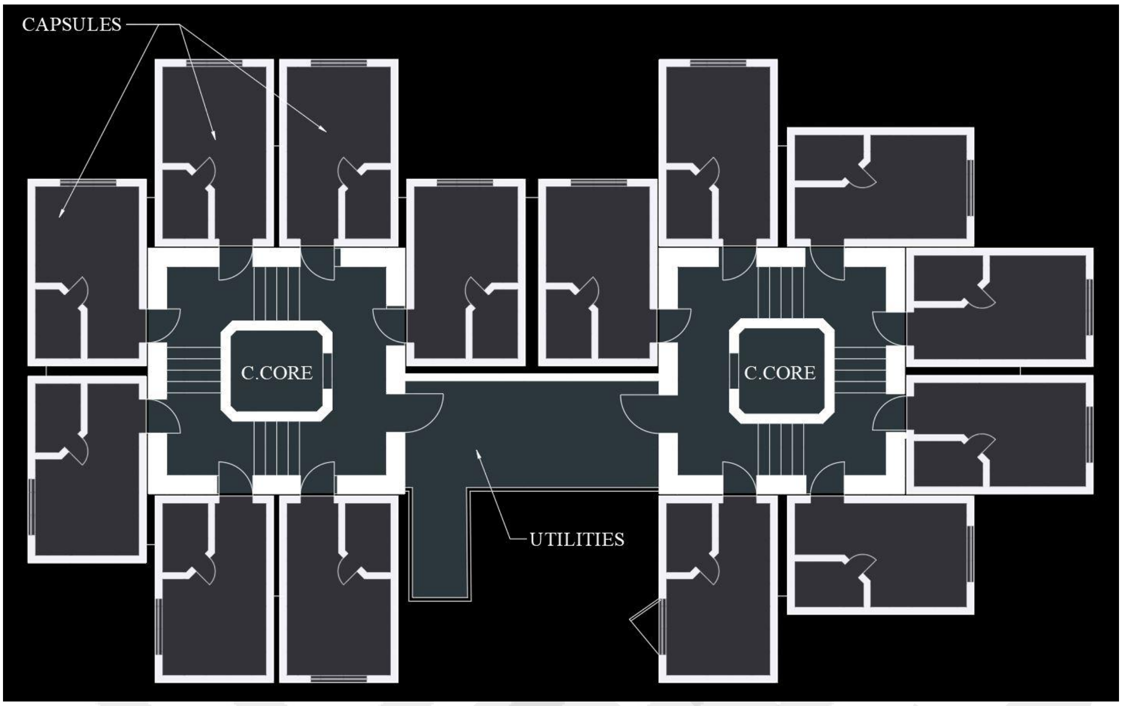


Figure 4.4.4 Nakagin Capsule Tower typical floor plan, redrawn by the author (P-36, Tables 4.1.1 & 4.1.2)

Kurokawa aimed to create a housing solution for travelers, stating that "The Capsules are housing for homo moves: people on the move." The tower became an iconic example of prefabrication and modularity and of Kurokawa's innovative approach to architecture with flexible and adaptable living spaces. Nicolai Ouroussoff, an architectural critic at The New York Times, expressed the importance of the building after his visit. He stated that the Capsule Tower is a beautiful architectural piece representing a cultural ideal. Furthermore, the building serves as a powerful reminder of what could have been if different values were prioritized (Lin, 2011).

Figure 4.4.5 Nakagin Capsule Tower construction process (Lin, 2011)

The Nakagin Capsule Tower is an iconic modular project that architects and the public worldwide have admired for its unique design. However, the very principles that guided its creation have also led to its eventual demise. Kurokawa, the architect behind the project, predicted a lifespan of 60 years for the concrete cores and 25 to 30 years for the capsules (Lin, 2011). However, the building has become old and worn out over time due to a lack of regular maintenance and capsule replacements (Her, 2020). The rapid changes in Tokyo's urban landscape have also threatened the Nakagin Capsule Tower and other notable Metabolism buildings such as Sony Tower and Sofitel Tokyo. The high land cost in Japanese cities has made demolition a more economically viable option. Safety concerns have also been raised, including health issues due to the use of asbestos and stability issues in the event of earthquakes (Lin, 2011) (Her, 2020).

The decision to demolish such an iconic and historic building has faced significant opposition from architects and designers worldwide. In 2007, Kurokawa proposed a renovation plan involving new utilities and larger, unfurnished capsules with only a prefabricated bathroom. This plan was seen as a more cost-efficient option than complete demolition. Kurokawa, until the last year of his life, kept fighting to save the building, and he launched a campaign to save the building, which was supported by many architects and designers in Japan and internationally. More than 10,000 architects from 100 countries participated in a vote; 95% supported preserving and protecting the building, and 75% supported Kurokawa's renovation proposal. DoCoMoMo, the international non-profit organization for architecture archiving, listed the Tower as a world heritage in an attempt to protect it (Lin, 2011). This massive support indicates the importance and historical status of this building as an architectural artefact worldwide.

Although discussions over the protection of the Tower have been ongoing for more than a decade, the building fell short of meeting the requirement for protection under Japanese law. Despite these efforts, the building was ultimately demolished in 2022, approximately 50 years after its construction (Figure 4.4.6). However, to preserve the memory of the building and its Metabolist ideals, 23 capsules were saved and scattered around the world (*Where Are the 23 Modules Saved from the Demolished Nakagin Capsule Tower Now? | ArchDaily*, n.d.).

Figure 4.4.6 Demolition process of the Nakagin Capsule Tower (*Demolition of Iconic Nakagin Capsule Tower Begins in Tokyo*, n.d.)

4.4.2 Further East Asian modularity

In modular construction, China and Singapore exemplify innovation and rapid urban development, seamlessly integrating modular projects into their evolving cityscapes. With its vast urban expanses and ambitious infrastructure projects, China has embraced modular construction as a critical strategy to meet the demands of rapid urbanization. China's modern prefabrication approach is through rapid construction with unusual speed, such as one remarkable architectural feat of constructing a 57-floor skyscraper, the Mini Sky City (P-57, Tables 4.1.1 & 4.1.2), in just 19 days (Figure 4.4.7). The construction process utilized a prefabrication technique, where various building sections were prefabricated off-site and assembled on-site using cranes. This technique enabled the construction team to complete the project in record time while reducing labour costs and minimizing environmental impact. Despite the speed of construction, the building's safety and durability were not compromised, as it was designed to withstand earthquakes and typhoons. Additionally, the Mini Sky City's energy-efficient features make it a model for sustainable architecture, and it has become a symbol of China's push toward modernization and innovation. Another example is a modular apartment block by Broad Group, Garden A-1 (P-56, Tables 4.1.1 & 4.1.2), which emphasizes its remarkable speed. Completed in just 28 hours, the building showcases the efficiency of the modular construction method (Figure 4.4.8). The project, led by the Broad Group, highlights the potential for rapid and sustainable urban development.

Figure 4.4.7 The 57 floor Mini Sky City erected in 19 days (The Mini Sky City, n.d.)

Figure 4.4.8 Ten floor stainless-steel modular building in 28 hours (*Ten-Storey Stainless-Steel Apartment Block Built in 28 Hours*, n.d.)

Singapore is a city renowned for its meticulous urban planning and sustainable practices. One of the innovative solutions they have adopted to address space constraints is modular construction, specifically through the use of the PPVC system. The Singapore government has been actively promoting the adoption of offsite construction systems, with the Government Land Sales GLS program mandating that 65% of the superstructure's floor area be built with offsite volumetric construction. The Clement Canopy project (P-51, Tables 4.1.1 & 4.1.2) is a notable example of international modular construction built in 2019 (Figure 4.4.9). There are 505 residential units in two 40-floor apartment blocks. The units come in 2, 3, or 4-bedroom options (Figure 4.4.10). The project utilized precast prefinished volumetric (PPVC) construction, with each module weighing between 18 and 30 tons; the heavy modules require specialized cranes to install the 1866 modules used for the entire project (Figure 4.4.11). These modules were designed to adhere to local traffic guidelines for easy transport. The PPVC modules are precast six-sided reinforced concrete units, contributing to the project's efficiency. The installation phase took approximately 12 months, with an average floor cycle time of six to nine days, while the whole construction phase took about 28 months. This approach showcased improved productivity, site safety, and overall work quality compared to traditional construction methods, allowing the project to be completed well ahead of the scheduled timeline. Clement Canopy represents Singapore's vision for modularity and is recognized as one of the leading Asian countries in adopting prefabrication and modularity in architectural projects.

Figure 4.4.9 The Clement Canopy project (Bayliss & Rory, 2020)

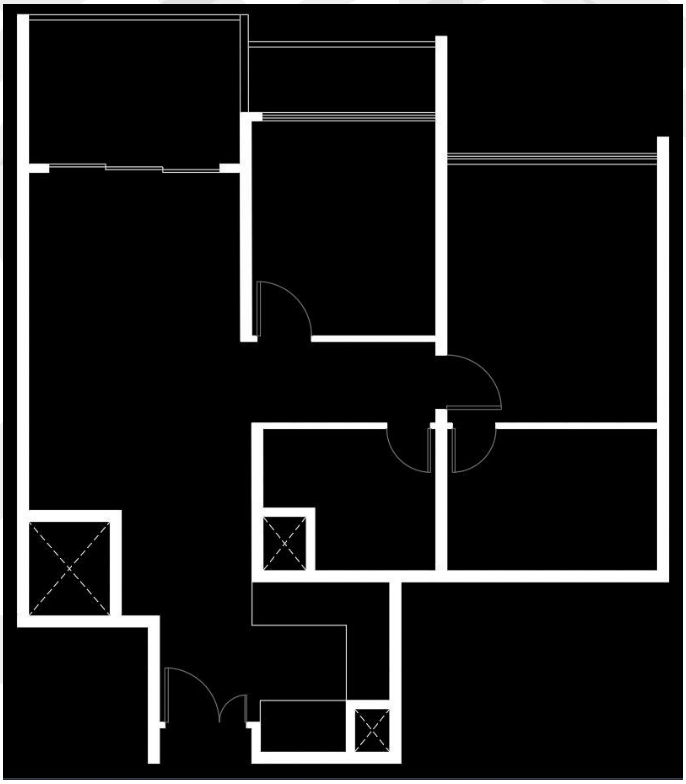


Figure 4.4.10 The Clement Canopy floor plan of the 2-bedroom example, redrawn by the author (P-51, Tables 4.1.1 & 4.1.2)

Figure 4.4.11 Tower Crane lifting a PPVC module ((BCA), n.d.)

The journey into the world of modular projects across the globe has exposed a vast array of architectural styles and design philosophies captured in our illustrative map. With a meticulous selection of approximately 57 projects from North America, Europe, and Asia, our compendium comprehensively explores the nuanced intricacies of prefabrication and modular methodologies. Presented chronologically from the 19th century to the present day, the table provides a detailed overview of project details, from names and architects to countries, years, and system types, along with detailed plan drawings and immersive 3D models. Critical projects from each region, such as Habitat 67 in North America, Murray Grove in Europe, and Nakagin Capsule Tower in East Asia, offer pivotal insights into the evolution of prefabrication and modularity with its successful and unsuccessful ideas. (Smith, 2011) posits that the potential reasons for the failure of prefabrication can be attributed to proprietary systems, which can lead to design limitations for operation and maintenance, thereby reducing the structure's lifecycle. Furthermore, the reliance on a single source for components can also increase the operational costs of the structure. These limitations highlight the need for greater flexibility in the design of prefabricated structures to ensure their longevity and cost-effectiveness. Architectural works such as Buckminster Fuller's Dymaxion House, Walter Gropius' Packed House, Moshe Safdie's Habitat 67, and Kisho Kurokawa's Nakagin Capsule Tower showcase unique and innovative designs. While some of these projects never came to fruition, and others were only produced as singular projects, they were successful in their own right. However, they were not successful as a mass-produced prefabrication concept. Over the past century, countless efforts and techniques have been employed to construct projects using prefabricated methods. These endeavors aimed to offer an alternative to traditional construction practices, but unfortunately, most of these ideas and projects failed to come to fruition. The few successfully built remain isolated examples, lacking the mass production and widespread impact necessary to revolutionize the constructivist industry.

As we transition towards the final chapter, this exploration is a foundation for bridging theoretical understanding with tangible examples of modular construction worldwide. The architectural marvels unveiled in this chapter act as a catalyst for a discussion on the global impact of modular construction, encouraging readers to delve deeper into the chapters for a holistic understanding of this transformative architectural paradigm.

Chapter 5

Discussion, Conclusions and Future Prospects

5.1 Discussion

The thorough examination of architectural modularity throughout the past century conducted in this research resulted in tracing the evolution of the concept of modularity in housing construction. A comprehensive timeline was created to summarize the most significant events in the history of prefabrication and highlight critical projects that illustrate the utilization of these techniques. (Figure 5.1.1) is presented below and displays the main historical events from the book (Smith, 2011) on the left side and the principal prefabrication projects listed in this thesis research on the right.

The term "module" has evolved interestingly over time, as the research shows (Figure 5.1.2). Initially, it was used as a tool for measuring ancient architecture. Later, it was adopted to describe various materials, components, and, eventually, panels. As time passed, the definition expanded to encompass whole volumetric units. In the near future, the term may be applied to describe systems that produce elements, such as 3D construction systems that can be transported to different locations to fabricate construction elements using locally sourced materials.

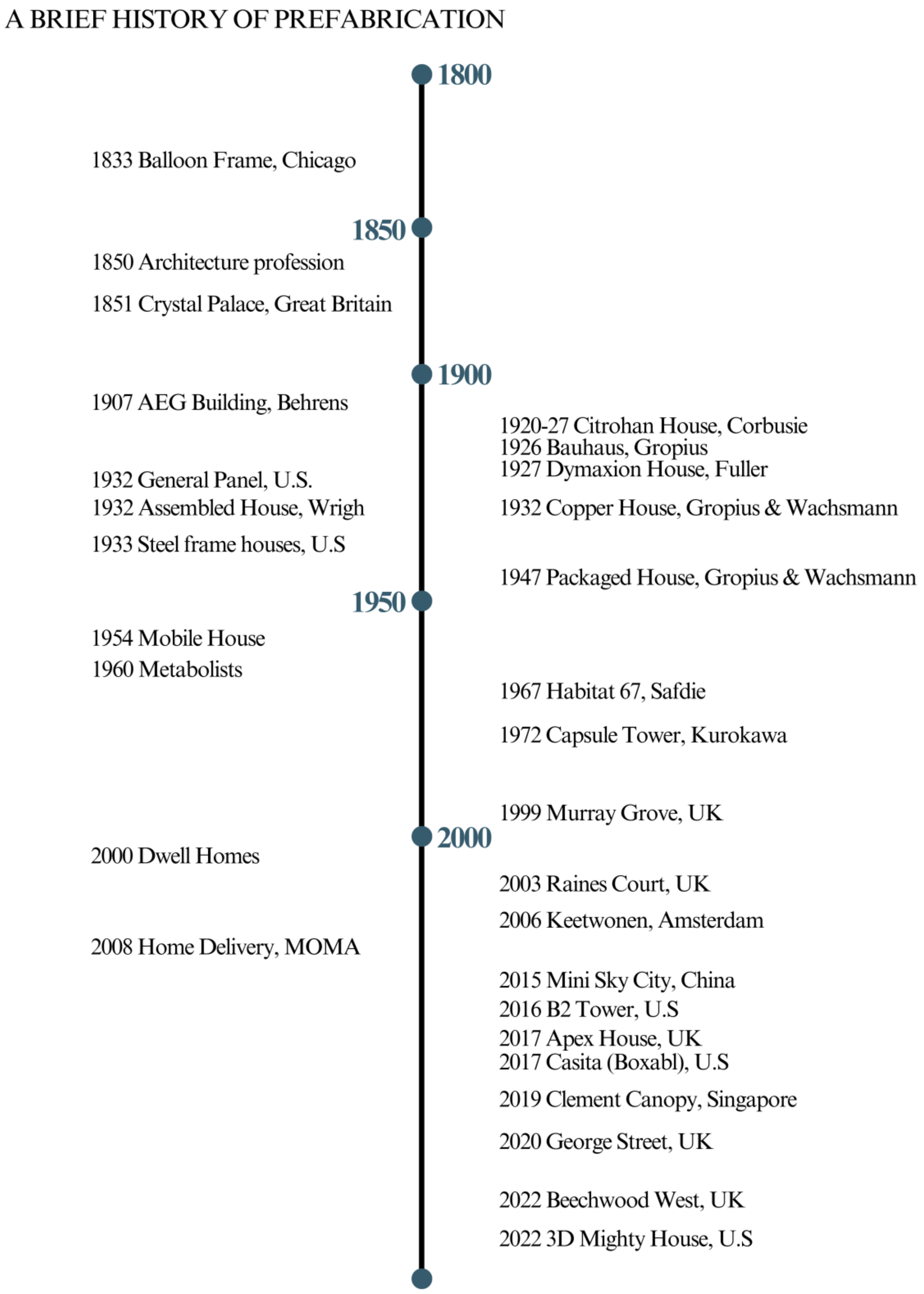


Figure 5.1.1 Timeline of prefabrication and modularity history made by the author

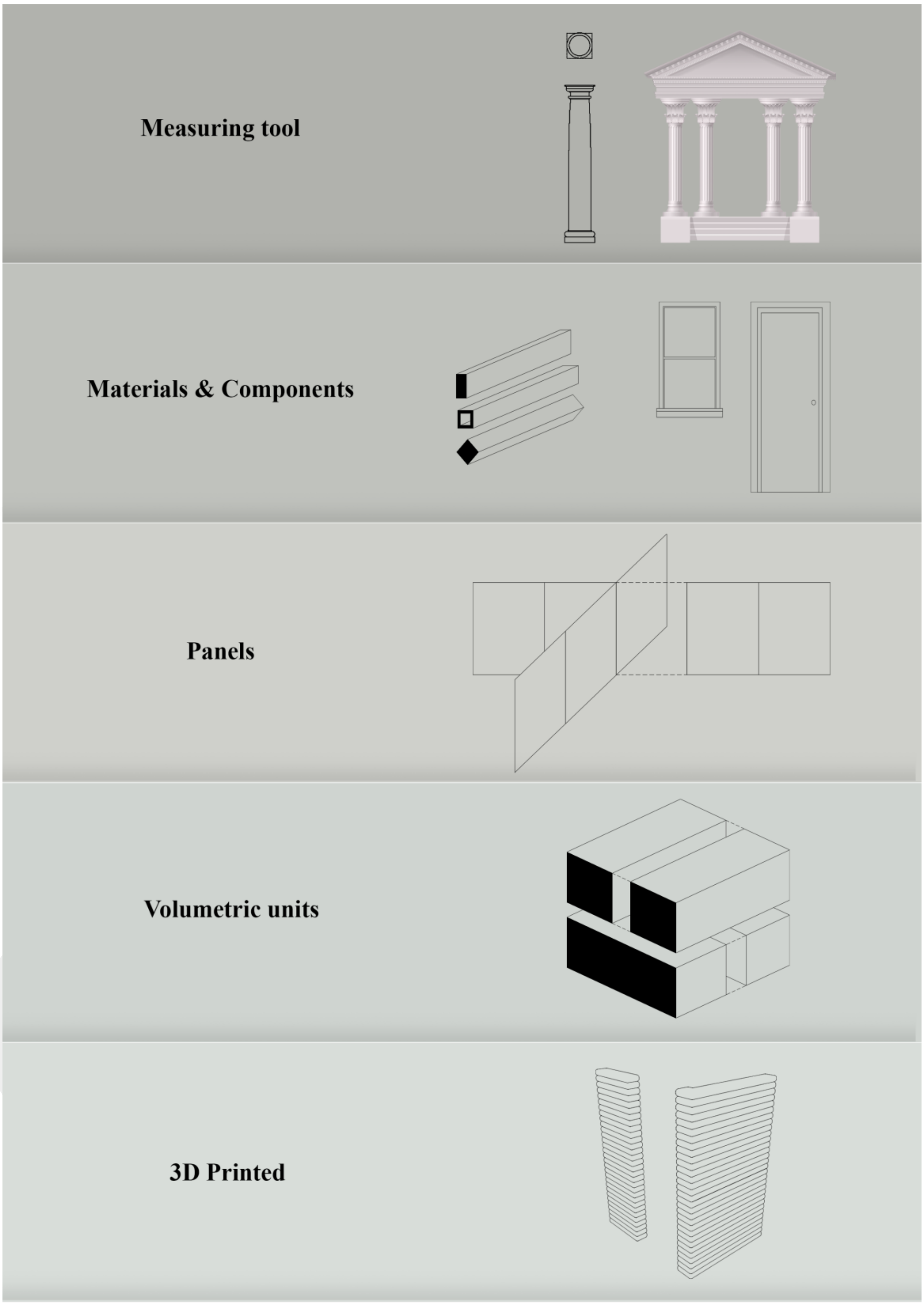


Figure 5.1.2 The development of the term module made by the author

The projects listed in Tables 4.1.1 and 4.1.2, utilized in this research, comprise a compilation of historical and modern innovation ideas and small and large modular projects. These projects chronologically demonstrate the evolution of modularity and prefabrication throughout the last century, commencing with an innovative prefabricated panel construction system in the early 1900s, followed by the design of volumetric units for projects and continuous technical advancements in these methods from the late 1900s until 2000. Volumetric room module unit projects are currently being developed with high quality and almost 100% prefabrication. Moreover, 3D printing technology and computerized systems are revolutionizing the design and building of prefabricated modular projects in the 21st century.

After analyzing the data in Tables 4.1.1 & 4.1.2, precisely the type of system and material of the projects, it becomes evident that the Room Module System (RMS) is the most widely used system for housing modular projects. It is used in 78.9% of the 57 projects. Panel Construction System (PCS) follows with only 19.3% of the projects. The last 1.8% represents only one project, where a mixed system of all frame, panel, and room module systems was used (Figure 5.1.3). These data demonstrate how the RMS is the ideal system for modular projects that take full advantage of the benefits of modularity in housing design. In fact, by examining the table further, it is apparent that more high residential projects have been constructed using the RMS in recent times. Companies chose the RMS to erect projects faster and easier in complicated sites while maintaining building quality simultaneously. In terms of building materials, steel reigns supreme, accounting for nearly half of all projects constructed with steel modules. Timber comes in second at 21.5%, followed closely by concrete at 20.5%. The remaining 8.3% of projects utilize aluminum, copper, and recycled stone materials (Figure 5.1.3). The popularity of steel can be attributed to its excellent strength-to-weight ratio, which makes it easy to transport, assemble, and build.

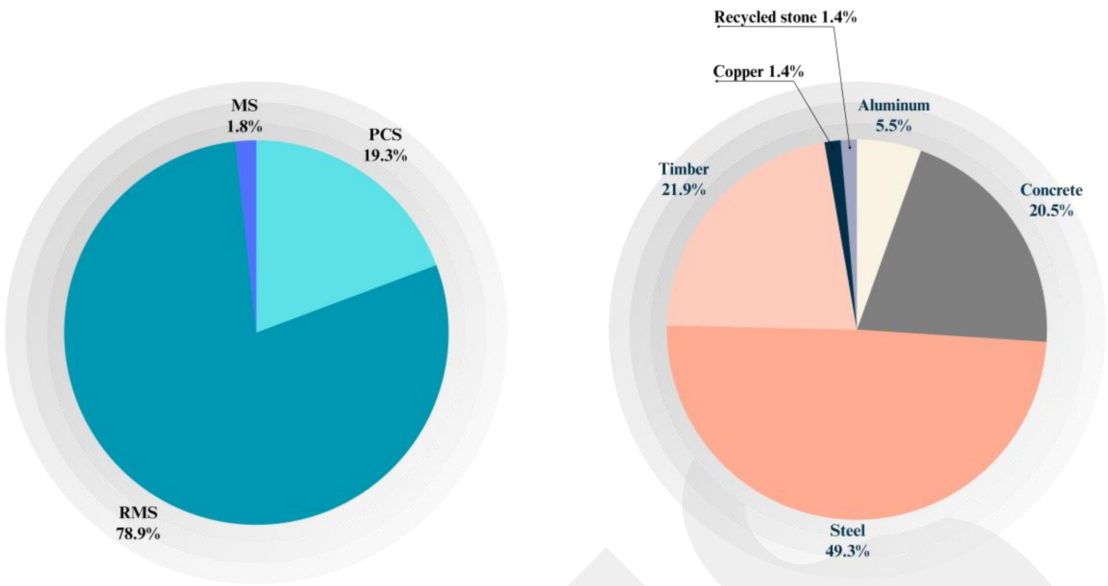


Figure 5.1.3 Pie charts depicting project types based on prefabricated systems (left) and project materials (right) created by the author

The information presented in Table 4.1.1 sheds light on the size of module units used in RMS (room module system) projects. The table details the width and length of modules analyzed in various projects. According to the data, the modules' minimum and maximum widths are 2.05 and 8 meters, respectively, while the average width is 4 meters. Likewise, the modules' minimum and maximum lengths are 2.66 and 22 meters, respectively, with an average length of 9.5 meters (Figure 5.1.4). It is important to note that the average dimensions of modules in the table comply with the module's dimensions limited by transportation requirements mentioned in Chapter 3 of the thesis.

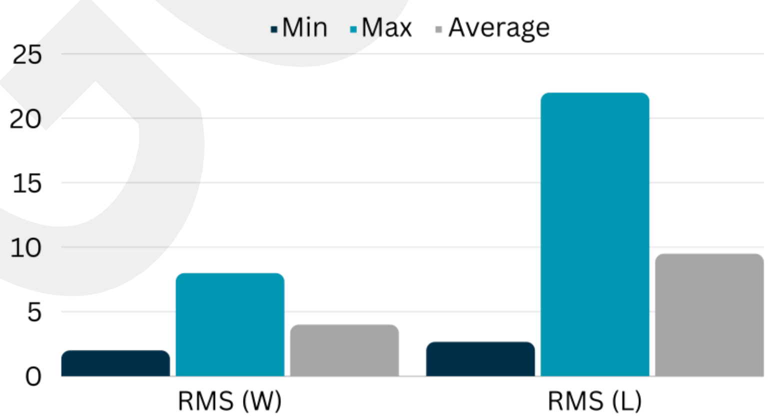


Figure 5.1.4 Modules Dimension chart, Min, Max, and Average, created by the author

Regarding the PCS and MS system projects, it is notable that the average floor area for these residential units is quantified at approximately 150 square meters. However, it is imperative to acknowledge the considerable variation in floor area, with the minimalist MIMA House being the smallest unit with a floor area of 36 square meters and the largest being a three-story single-family house, which boasts a capacious 311 square meter floor area (Figure 5.1.5). Such significant differences in floor area among the PCS and MS projects indicate the diverse range of architectural designs and approaches employed in residential prefabricated panel construction.

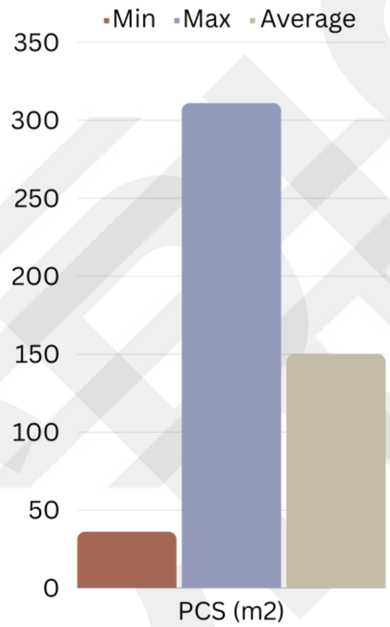


Figure 5.1.5 PCS projects floor area chart, Min, Max, and Average, created by the author

Modular architecture is an innovative approach to constructing homes, but it faces a significant challenge in limited customization options for low-rise housing projects. This, in turn, can lead to decreased resident interest in adopting modular homes. To address this limitation and encourage greater acceptance of modular design in housing, Pollard Thomas Edwards architects have come up with an ingenious solution. They have developed an online configurator that allows residents to personalize their homes with various choices, including room layout, external finishes, and internal specifications (P-49, Tables 4.1.1 & 4.1.2). This concept holds immense promise for revolutionizing the modular housing industry. However, it requires further inspection, testing, and ongoing development to realize its potential and suitability for diverse locations fully.

Another challenge of modular architecture is the transportation requirements, which can restrict the flexibility of module design and size and the distance between the factory and the site. When the distance is significant, it can negatively impact the project's economic and environmental efficiency. As a result, companies have developed innovative design solutions, such as foldable modules, to overcome this limitation. Airship transportation is a potential solution to the current transportation issues. It is a futuristic and sustainable mode of transportation that offers a greener and more efficient alternative to traditional means. With airship transportation (Figure 5.1.6), it is possible to address the challenges currently facing modular transportation, giving more freedom to its design.

Figure 5.1.6 Flying Whales' airships (Welcome to the Big Blimp Boom | MIT Technology Review, n.d.)

In conclusion, this thesis traces the evolution of modular design and prefabrication throughout the last century, beginning with its origins and gaining popularity in the mid-19th century before declining towards the end. In current times, there is renewed attention towards modularity all over the world. By following this timeline, we can predict the future of modular design, which is closely linked to and influenced by technological advancements. This raises intriguing questions about the role of 3D-printed systems in modular design - can they be considered modules, and how can integrating 3D printing technology expand the horizons of modular construction? These inquiries open opportunities for future exploration and innovation at the dynamic intersection of modular design and emerging technologies.

5.2 Conclusions

To sum up, this dissertation has thoroughly examined the concepts of prefabrication and modularity, specifically emphasizing modular housing architecture. The central question was, "What is the importance of modularity in the development of architectural housing, and how has this notion developed throughout history?" As a result of a comprehensive investigation that delved into ratios, the history of modularity, the Industrial Revolution, and modern modular architecture, numerous noteworthy discoveries have been made.

Chapter 2 of this research has yielded invaluable insights into the presence of ratios in all facets of life, illuminating the significance of the Fibonacci Series in modularity. Furthermore, it delves into the definition and application of modules in ancient history as expounded upon by Vitruvius and Leon Battista Alberti, before delving into the Industrial Revolution era to expound on the pivotal role played by architects and movements at the dawn of the 19th century.

Chapter 3 delves into the implications of this research, specifically examining the importance of modularity in architectural design. The chapter explores the fundamental concepts of prefabrication and modularity, providing a comprehensive overview of various available module types and materials. Additionally, the chapter outlines the percentage of prefabrication offered by factories, highlights the significance of lean production systems over traditional construction methods, and evaluates the seismic and sustainable performance of modular buildings.

The synthesis of project data in Chapter 4 has proved to be a precious resource in enhancing our understanding of how architects and companies worldwide are adopting modular construction. It provides an extensive and comprehensive collection of case studies across three continents. The projects were meticulously selected and analyzed based on multiple factors, such as the dates, locations, historical significance, types of prefabrication, and technologies utilized. This exhaustive approach has resulted in important information that is a vital reference for anyone interested in modular construction.

The exploration of modular construction unveils a multifaceted landscape that offers both innovative solutions and challenges. The Prefab molds/module system, outlined as a straightforward and user-friendly approach in the quest for housing solutions, stands out for its adaptability using locally available materials. Despite the advantageous ability of modular projects to be disassembled, reused, or relocated, the separation of the house from the land poses a hurdle in attracting substantial investment from large-scale investors or financial institutions.

Furthermore, the quest for speed in construction, as emphasized by Joe Tanney (Smith, 2011), raises a pertinent question about whether modular and prefabricated projects are faster and genuinely better. This critical consideration highlights the need for a balanced approach that prioritizes efficiency and quality in the construction process.

In summary, this thesis highlights the significance of modular housing and adds significant insights to the academic conversation. A thorough examination of past and present prefabrication shows that this construction method is the way of the future. However, there is still much room for improvement and advancement before it can fully replace traditional construction. The construction industry can benefit from the insights gained through research on modular construction. This can aid in advancing the field by promoting universal practices that can be customized to meet specific regional needs and demands. This research provides a solid foundation for ongoing investigation and progress in modular housing and encourages scholars and professionals to continue exploring and implementing its potential.

5.3 Societal Impact and Contribution to Global Sustainability

The housing crisis is a significant problem that needs to be addressed urgently. The prefabrication and modular construction methods can play an essential role in solving this crisis. These methods help achieve sustainability goals by reducing waste, minimizing the environmental impact, and increasing cost efficiency. The prefabrication process allows for faster construction, which can be crucial in high-demand areas. Moreover, the modular approach can provide flexible design options and allow for customization that meets the community's specific needs. By adopting these methods, we can build affordable, safe, and sustainable homes that cater to the needs of the present without compromising the ability of future generations to meet their own needs, as defined by Brundtland in 1987.

5.4 Future Prospects

In the context of this research, expanding the scope of project samples becomes imperative to glean a comprehensive understanding of the global landscape of modular architecture. Given the burgeoning trend of modular construction worldwide, a broader and more diverse selection of projects from different parts of the world would contribute significantly to the depth and breadth of the research. This expansion would enrich the dataset and facilitate a nuanced analysis of regional variations, cultural influences, and contextual factors shaping modular architectural practices.

Moreover, a more in-depth exploration of modular systems is essential to comprehend their advantages and disadvantages fully. Delving into the intricacies of various modular systems can shed light on their specific functionalities, efficiencies, and adaptability to diverse contexts. Understanding the nuances of these systems would enable researchers, architects, and stakeholders to make informed decisions regarding their applicability and potential impact on the built environment.

Furthermore, the research could extend its focus to explore how modular architecture addresses critical issues such as housing crises, urban congestion, and environmental sustainability. A thorough investigation into the potential of modular solutions to mitigate these challenges could unearth valuable insights into the real-world implications of modular construction. This exploration might encompass not only the physical aspects of modular buildings but also the social, economic, and environmental dimensions, providing a holistic perspective on the transformative power of modular architecture.

In essence, the future trajectory of this research should involve a global expansion of project samples and a more detailed examination of modular systems, coupled with an exploration of how modular architecture can effectively contribute to addressing pressing issues in contemporary urban environments. Such a comprehensive approach would undoubtedly contribute to the growing body of knowledge in the field of modular architecture, informing and guiding its continued evolution on a global scale.

BIBLIOGRAPHY

(BCA), B. and C. A. (n.d.). *Case Study - The Clement Canopy*. Retrieved January 8, 2024, from https://www1.bca.gov.sg/buildsg/productivity/design-for-manufacturing-and-assembly-dfma/prefabricated-prefinished-volumetric-construction-ppvc/prefabricated-prefinished-volumetric-construction-case-study-the-clement-canopy

Aiken, J. A. (1980). *Leon Battista Alberti ' s System of Human Proportions Author (s): Jane Andrews Aiken Source : Journal of the Warburg and Courtauld Institutes , 1980 , Vol . 43 (1980), pp . 68- Stable URL : http://www.jstor.com/stable/751189 REFERENCES Linked referenc*. *43*, 68–96.

Ap, L. (2017). *Modular for Architects*.

ArchDaily. (2011). *MIMA House*. https://www.archdaily.com/192043/mima-house-mima-architects

Arellano, M. (2018). *On the Dislocation of the Body in Architecture: Le Corbusier's Modulor | ArchDaily*. https://www.archdaily.com/902597/on-the-dislocation-of-the-body-in-architecture-le-corbusiers-modulor

B1M, T. (2023). *How a 23-Year-Old Solved Urban Sprawl - YouTube*. https://www.youtube.com/watch?v=Qwbp9T-WS-I&list=LL&index=23

B2 | SHoP. (n.d.). Retrieved December 31, 2023, from https://www.shoparc.com/projects/b2/

Basulto, D. (2011). *Le Corbusier meets Albert Einstein | ArchDaily*. https://www.archdaily.com/167240/le-corbusier-meets-albert-einstein

Bayliss, S., & Rory, B. (2020). *the modular housing handbook* (Vol. 01). RIBA Publishing.

BOMBA, D. E. (2006). *MODULARITY IN THE HISTORICAL PERIOD AND EXAMINING THE MODULARITY ON THE "ŞEHZADE MEHMET MOSQUE."*

Boxabl – Accessory Dwelling Unit. (n.d.). Retrieved December 29, 2023, from https://www.boxabl.com/

Cohen, J. (2014). *Le Corbusier ' s Modulor and the Debate on Proportion in*. *2*(1), 1–14.

Corbusier, L. (2021). *The Modulor* (P. de Francia & A. Bostock (Eds.); A reimpres). birkhauser.

Demolition of iconic Nakagin Capsule Tower begins in Tokyo. (n.d.). Retrieved January

8, 2024, from https://www.dezeen.com/2022/04/12/nakagin-capsule-tower-demolition-begins-tokyo/

Deng, E., Zong, L., Ding, Y., Zhang, Z., Zhang, J., & Shi, F. (2020). *Seismic performance of mid-to-high rise modular steel construction - A critical review. January*.

Design, H. (n.d.). *Ten Degrees, 100a George Street*. Retrieved January 6, 2024, from https://www.hta.co.uk/project/101-george-street

Edwards, P. T. (n.d.). *Beechwood Village → Pollard Thomas Edwards*. Retrieved January 4, 2024, from https://www.pollardthomasedwards.co.uk/projects/index/beechwood-village/

Farnsworth, D. (2014). Modular tall building design at Atlantic Yards B2. *CTBUH 2014 Shanghai Conference*, 492–499.

Forest City Ratner Companies. (2012). *Building 2 at Atlantic Yards*. http://esd.ny.gov/subsidiaries_projects/AYP/AtlanticYards/AdditionalResources/11292012_B2_PublicPresentation.pdf

Frampton, K. (1992). *Modern Architecture A Critical History (World of Art) 3 Sub Edition.pdf* (3rd editio, pp. 123–129). Thames & Hudson.

Games, E. (n.d.). *Hillside Sample in UE Feature Samples - UE Marketplace*. Retrieved December 17, 2023, from https://unrealengine.com/marketplace/en-US/product/hillside-sample-project

Gemma Falconer Da Silva. (n.d.). *Building the Future with 3D Printing and Real-Time Visualization*. Retrieved January 14, 2024, from https://www.archdaily.com/968146/building-the-future-with-3d-printing-and-real-time-visualization

Gropius, W. (1965). *The New Architecture and the Bauhaus*. The MIT Press.

Gropius, W., & Wachsmann, K. (2021). Gropius, Hirsch, and the Saga of the Copper House. *MIT Press Open Architecture and Urban Studies*.

Habitat '67. (n.d.). Retrieved November 30, 2023, from https://www.safdiearchitects.com/projects/habitat-67

Her, K. (2020). *Nakagin Capsule Tower: In Pieces*. *1960*(May 1960), 672–675.

Herbert, G. (2021). The Packaged House: A Wartime Proposal. *The Dream of the Factory-Made House*. https://doi.org/10.7551/mitpress/2494.003.0018

Imperiale, A. (2012). American Wartime Dream: The Packaged House System of Konrad Wachsmann and Walter Gropius. *ACSA Fall Conference*, 39–43.

INC., B. (2023). *Front Door Studio Casita PMRV*. 1–8.

Kotas, T., Analysis, E., Buildings, S., Society, A., Engineers, A., Analysis, E., & Buildings, S. (2001). A STUDY ON THE DISTINCTION BETWEEN MODULARITY AND PREFABRICATION BUILDING METHODS. *Language, Society and Power. An Introduction*, *3*(Chapter 4), 56–74. https://doi.org/10.1007/978-1-4939-6911-1

Lawson, M., Ogden, R., & Goodier, C. (2014). *Design in Modular Construction*.

Lin, Z. (2011). Nakagin capsule tower: Revisiting the future of the recent past. *Journal of Architectural Education*, *65*(1), 13–32. https://doi.org/10.1111/j.1531-314X.2011.01158.x

Luther, A. M. B. (2009). *TOWARDS PREFABRICATED SUSTAINABLE HOUSING – AN INTRODUCTION*. *July 1957*, 1–18.

M, M. M. M., Lam, N. T. K., Godbole, S., & Rajeev, P. (2019). Safety of Modular Buildings in Seismic conditions. *Australian Earthquake Engineering Society, Newcastle, NSW*.

Maison Citröhan. (n.d.). Retrieved December 1, 2023, from https://en.wikiarquitectura.com/building/maison-citroehan/

Marine City: Tokyo's Futuristic Megastructure by Kiyonori Kikutake | ArchEyes. (n.d.). Retrieved January 7, 2024, from https://archeyes.com/marine-city-megastructure-kiyonori-kikutake/

Melvin, J. (2005). Raines court. *Architectural Design*, *75*(4), 126–130. https://doi.org/10.1002/ad.116

Merin, G. (2019). *Architecture Classics: The Dymaxion House / Buckminster Fuller | ArchDaily*. https://www.archdaily.com/401528/ad-classics-the-dymaxion-house-buckminster-fuller

Miller, T. D. (1998). Defining Modules , Modularity and Modularization Evolution of the Concept in a Historical Perspective. *Proceedings of the 13th IPS Research Seminar*, 1–19.

Morah, N. (2019). *Humanising Megascale: Habitat 67*. *January*.

Paula Pintos. (n.d.). *TECLA Technology and Clay 3D Printed House / Mario Cucinella Architects*. Retrieved January 14, 2024, from https://www.archdaily.com/960714/tecla-technology-and-clay-3d-printed-house-mario-cucinella-architects

Persaud, D., & O'Leary, J. P. (2015). Fibonacci Series, Golden Proportions, and the

Human Biology. *JP. Fibonacci Series*, *2*(5), 1–6. www.austinpublishinggroup.com

Pickard, C. (1999). *Murray Grove*. https://www.cartwrightpickard.com/housing/murray-grove/

RIBA. (n.d.). *Takara Pavilion, Expo'70, Osaka*. Retrieved January 7, 2024, from https://www.ribapix.com/takara-pavilion-expo70-osaka_riba24129#

Russell, A. L. (2012). *Modularity : An Interdisciplinary History of an Ordering Concept*. *47*(3).

Slone, I. (2023, October 23). *Inside a funky Habitat 67 apartment on the market for $1.4 million - Macleans.ca*. https://macleans.ca/economy/realestateeconomy/live-in-habitat-67/

Smith, R. E. (2011). Prefab Architecture: A Guide to Modular Design and Construction. In *John Wiley & Sons, Inc.* http://books.google.com/books?hl=en&lr=&id=pOCliGMKpzUC&oi=fnd&pg=PT20&dq=PREFAB+ARCHITECTURE:+a+guide+to+modular+design+and+construction&ots=j0n5GteYZ6&sig=wUYE0qhNDvy5tN_r6P9WQe79p4U

Staib, G., Dörrhöfer, A., Rosenthal, M., Knippers, J., & Helbig, T. (2008). COMPONENTS AND SYSTEMS MODULAR CONSTRUCTION DESIGN STRUCTURE NEW TECHNOLOGIES. In *Edition DETAIL – Institut für internationale Architektur-Dokumentation GmbH & Co. KG München* (Vol. 1, Issue 1).

Ten-storey stainless-steel apartment block built in 28 hours. (n.d.). Retrieved January 8, 2024, from https://www.dezeen.com/2021/06/22/broad-group-modular-apartment-block-28-hours/

The Mini Sky City. (n.d.). Retrieved January 8, 2024, from https://archinspires.com/2023/09/06/the-mini-sky-city-how-architects-built-a-57-story-skyscraper-in-just-19-days/

Tide. (n.d.). *Ten Degrees*. Retrieved January 6, 2024, from https://tideconstruction.co.uk/projects/ten-degrees/

Vitruvius. (2009). *ON ARCHITECTURE* (R. (Translator) Tavernor & R. S. (Introduction) (Eds.)). Penguin Classics.

Welcome to the big blimp boom | MIT Technology Review. (n.d.). Retrieved February 6, 2024, from https://www.technologyreview.com/2023/06/28/1074332/lighter-than-air-vehicles-lta/

Where Are the 23 Modules Saved from the Demolished Nakagin Capsule Tower Now? | ArchDaily. (n.d.). Retrieved January 8, 2024, from https://www.archdaily.com/1006528/where-are-the-23-modules-saved-from-the-demolished-nakagin-capsule-tower-now

APPENDIX

App.1 Image and data credits of projects in Tables 4.1.1 & 4.1.2

P-43 *Gallery of Architecture Classics: The Dymaxion House / Buckminster Fuller - 1*. (n.d.). Retrieved December 1, 2023, from https://www.archdaily.com/401528/ad-classics-the-dymaxion-house-buckminster-fuller/51dee10ee8e44e6873000005-ad-classics-the-dymaxion-house-buckminster-fuller-image

Smith, R. E. (2011). Prefab Architecture: A Guide to Modular Design and Construction. In *John Wiley & Sons, Inc.*

Gallery | E2: Dymaxion House - Buckminster Fuller. (n.d.). Retrieved February 8, 2024, from https://e2dymaxionhouse.wordpress.com/gallery-8/

P-32 *Maison Citröhan - Data, Photos & Plans - WikiArquitectura*. (n.d.). Retrieved December 1, 2023, from https://en.wikiarquitectura.com/building/maison-citroehan/

Smith, R. E. (2011). Prefab Architecture: A Guide to Modular Design and Construction. In *John Wiley & Sons, Inc.*

P-30 Gropius, W., & Wachsmann, K. (2021). Gropius, Hirsch, and the Saga of the Copper House. *MIT Press Open Architecture and Urban Studies*.

Gropius, W. (1965). *The New Architecture and the Bauhaus*. The MIT Press.

P-42 *Construcción de una Packaged House, Walter Gropius y Konrad Wachsmann... | Download Scientific Diagram*. (n.d.). Retrieved December 1, 2023, from https://www.researchgate.net/figure/Figura-3-Construccion-de-una-Packaged-House-Walter-Gropius-y-Konrad-Wachsmann-1941_fig3_321764824

Herbert, G. (2021). The Packaged House: A Wartime Proposal. *The Dream of the Factory-Made House*. https://doi.org/10.7551/mitpress/2494.003.0018

P-2 *Habitat '67*. (n.d.). Retrieved December 1, 2023, from https://www.safdiearchitects.com/projects/habitat-67

Morah, N. (2019). *Humanising Megascale: Habitat 67*. *January*.

P-36 *KISHO KUROKAWA*. (n.d.). Retrieved December 1, 2023, from https://www.kisho.co.jp/page/209.html

Lin, Z. (2011). Nakagin capsule tower: Revisiting the future of the recent past. *Journal of Architectural Education*, *65*(1), 13–32. https://doi.org/10.1111/j.1531-314X.2011.01158.x

Her, K. (2020). *Nakagin Capsule Tower: In Pieces*. *1960*(May 1960), 672–675.

Staib, G., Dörrhöfer, A., Rosenthal, M., Knippers, J., & Helbig, T. (2008). COMPONENTS AND SYSTEMS MODULAR CONSTRUCTION DESIGN STRUCTURE NEW TECHNOLOGIES.

P-35 Staib, G., Dörrhöfer, A., Rosenthal, M., Knippers, J., & Helbig, T. (2008). COMPONENTS AND SYSTEMS MODULAR CONSTRUCTION DESIGN STRUCTURE NEW TECHNOLOGIES.

P-10 *bürohaus rathenow – architekten prof klaus sill*. (n.d.). Retrieved December 1, 2023, from https://architektenprofsill.de/portfolio/rathenow

Staib, G., Dörrhöfer, A., Rosenthal, M., Knippers, J., & Helbig, T. (2008). COMPONENTS AND SYSTEMS MODULAR CONSTRUCTION DESIGN STRUCTURE NEW TECHNOLOGIES.

P-8 *archiweb.cz - Bearth-Candinas House*. (n.d.). Retrieved February 8, 2024, from https://www.archiweb.cz/en/b/dum-bearth-candinas

Staib, G., Dörrhöfer, A., Rosenthal, M., Knippers, J., & Helbig, T. (2008). COMPONENTS AND SYSTEMS MODULAR CONSTRUCTION DESIGN STRUCTURE NEW TECHNOLOGIES.

P-11 *Hotel Post - mkp*. (n.d.). Retrieved December 1, 2023, from https://www.mkp-ing.com/projekt/hotel-post

Staib, G., Dörrhöfer, A., Rosenthal, M., Knippers, J., & Helbig, T. (2008). COMPONENTS AND SYSTEMS MODULAR CONSTRUCTION DESIGN STRUCTURE NEW TECHNOLOGIES.

P-6 *Murray Grove • Housing • What do we do • Cartwright Pickard*. (n.d.). Retrieved December 1, 2023, from https://www.cartwrightpickard.com/housing/murray-grove/

P-1 *Cameleon House - anderson anderson*. (n.d.). Retrieved December 1, 2023, from https://andersonanderson.com/cameleon-house/

Staib, G., Dörrhöfer, A., Rosenthal, M., Knippers, J., & Helbig, T. (2008). COMPONENTS AND SYSTEMS MODULAR CONSTRUCTION DESIGN STRUCTURE NEW TECHNOLOGIES.

P-5 *Gallery of An Interview with Rocio Romero, Pre-Fab Pioneer - 4*. (n.d.). Retrieved December 1, 2023, from https://www.archdaily.com/356032/pre-fab-s-reigning-queen-rocio-romero/51509f84b3fc4b85280000cf-pre-fab-s-reigning-queen-rocio-romero-photo

Smith, R. E. (2011). Prefab Architecture: A Guide to Modular Design and Construction. In *John Wiley & Sons, Inc.*

P-7 *Raines Court – Residential Projects – Allford Hall Monaghan Morris | AHMM*. (n.d.). Retrieved December 1, 2023, from https://www.ahmm.co.uk/projects/residential/raines-court/

Lawson, M., Ogden, R., & Goodier, C. (2014). *Design in Modular Construction*.

P-18 Lawson, M., Ogden, R., & Goodier, C. (2014). *Design in Modular Construction*.

P-9 *Einfamilienhaus S. Gohm Hiessberger Architekten*. (n.d.). Retrieved December 1, 2023, from https://www.austria-architects.com/en/gohm-hiessberger-architekten-feldkirch/project/einfamilienhaus-s-2

Staib, G., Dörrhöfer, A., Rosenthal, M., Knippers, J., & Helbig, T. (2008). COMPONENTS AND SYSTEMS MODULAR CONSTRUCTION DESIGN STRUCTURE NEW TECHNOLOGIES.

P-14 *micro compact home | About the company*. (n.d.). Retrieved December 1, 2023, from http://www.microcompacthome.at/company/

Lawson, M., Ogden, R., & Goodier, C. (2014). *Design in Modular Construction*.

P-16 *shedkm • moho*. (n.d.). Retrieved December 1, 2023, from https://www.shedkm.co.uk/work/moho/

Lawson, M., Ogden, R., & Goodier, C. (2014). *Design in Modular Construction*.

P-44 *Loblolly House | Prefabricated Architecture Integrated with Nature*. (n.d.). Retrieved December 1, 2023, from https://kierantimberlake.com/page/loblolly-house

Smith, R. E. (2011). Prefab Architecture: A Guide to Modular Design and Construction. In *John Wiley & Sons, Inc.*

P-15 Lawson, M., Ogden, R., & Goodier, C. (2014). *Design in Modular Construction*.

P-24 Lawson, M., Ogden, R., & Goodier, C. (2014). *Design in Modular Construction*.

P-28 *Painter House & Peter House - Rollalong: UK Modular Offsite Construction*. (n.d.). Retrieved December 1, 2023, from https://rollalong.co.uk/project/peter-painter-house/

Lawson, M., Ogden, R., & Goodier, C. (2014). *Design in Modular Construction*.

P-34 *Keetwonen Amsterdam*. (n.d.). Retrieved December 1, 2023, from https://www.jmw-architecten.nl/portfolio/keetwonen-amsterdam/?lang=en

Smith, R. E. (2011). Prefab Architecture: A Guide to Modular Design and Construction. In *John Wiley & Sons, Inc.*

P-25 Lawson, M., Ogden, R., & Goodier, C. (2014). *Design in Modular Construction*.

P-3 *RES4 | Resolution: 4 Architecture | Prefab*. (n.d.). Retrieved December 1, 2023, from https://www.re4a.com/prefab#/house-on-sunset-ridge/

Smith, R. E. (2011). Prefab Architecture: A Guide to Modular Design and Construction. In *John Wiley & Sons, Inc.*

P-45 *Cellophane House | Prefabricated Architecture & Design for Disassembly*. (n.d.). Retrieved December 1, 2023, from https://kierantimberlake.com/page/cellophane-house

Smith, R. E. (2011). Prefab Architecture: A Guide to Modular Design and Construction. In *John Wiley & Sons, Inc.*

P-13 *Living - Imagine a place...* (n.d.). Retrieved December 1, 2023, from https://loftcube.net/living

Staib, G., Dörrhöfer, A., Rosenthal, M., Knippers, J., & Helbig, T. (2008). COMPONENTS AND SYSTEMS MODULAR CONSTRUCTION DESIGN STRUCTURE NEW TECHNOLOGIES.

P-19 Lawson, M., Ogden, R., & Goodier, C. (2014). *Design in Modular Construction*.

P-22 Lawson, M., Ogden, R., & Goodier, C. (2014). *Design in Modular Construction*.

P-26 Lawson, M., Ogden, R., & Goodier, C. (2014). *Design in Modular Construction*.

P-33 *Wolverhampton < BMCE - Barrett Mahony Consulting Engineers*. (n.d.). Retrieved December 1, 2023, from https://bmce.ie/portfolio/wolverhampton/

Smith, R. E. (2011). Prefab Architecture: A Guide to Modular Design and Construction. In *John Wiley & Sons, Inc.*

P-40 *Tiny Houses | Jaanus Orgusaar*. (n.d.). Retrieved December 1, 2023, from https://www.jaanusorgusaar.com/tiny-element-houses/

Iverson, B. L., & Dervan, P. B. (2010). *TINY HOUSE NOA*. 7823–7830.

P-27 Lawson, M., Ogden, R., & Goodier, C. (2014). *Design in Modular Construction*.

P-12 *Prefab Homes: Danish ONV Houses - Prefab Homes*. (n.d.). Retrieved December 1, 2023, from https://www.busyboo.com/2010/10/14/prefab-homes-onv/

Staib, G., Dörrhöfer, A., Rosenthal, M., Knippers, J., & Helbig, T. (2008). COMPONENTS AND SYSTEMS MODULAR CONSTRUCTION DESIGN STRUCTURE NEW TECHNOLOGIES.

P-17 Lawson, M., Ogden, R., & Goodier, C. (2014). *Design in Modular Construction*.

P-20 Lawson, M., Ogden, R., & Goodier, C. (2014). *Design in Modular Construction*.

P-31 *MIMA*. (n.d.). Retrieved December 1, 2023, from https://www.mimahousing.com/projects/mima-house

ArchDaily. (2011). *MIMA House*. https://www.archdaily.com/192043/mima-house-mima-architects

P-41 *Covas*. (n.d.). Retrieved December 1, 2023, from https://www.salgadoeliñares.com/index.php/proxectos/casas/covas

Seven Modular Housing in Covas / Salgado e Liñares Architects | ArchDaily. (n.d.). Retrieved February 8, 2024, from https://www.archdaily.com/255002/seven-modular-housing-in-covas-salgado-e-linares-architects

P-29 *HTA Design - Olympic Way*. (n.d.). Retrieved December 1, 2023, from https://www.hta.co.uk/project/olympic-way

Lawson, M., Ogden, R., & Goodier, C. (2014). *Design in Modular Construction*.

P-23 Lawson, M., Ogden, R., & Goodier, C. (2014). *Design in Modular Construction*.

P-21 Lawson, M., Ogden, R., & Goodier, C. (2014). *Design in Modular Construction*.

P-57 *The Mini Sky City*. (n.d.). Retrieved January 8, 2024, from https://archinspires.com/2023/09/06/the-mini-sky-city-how-architects-built-a-57-story-skyscraper-in-just-19-days/

J57 Mini Sky City - Sections. (n.d.). Retrieved February 8, 2024, from https://sections.arcelormittal.com/Project_gallery/J57_Mini_Sky_City/EN

P-47 Bayliss, S., & Rory, B. (2020). *the modular housing handbook* (Vol. 01). RIBA Publishing.

shedkm • new islington. (n.d.). Retrieved February 8, 2024, from https://www.shedkm.co.uk/work/new-islington/

P-54 Bayliss, S., & Rory, B. (2020). *the modular housing handbook* (Vol. 01). RIBA Publishing.

Farnsworth, D. (2014). Modular tall building design at Atlantic Yards B2. *CTBUH 2014 Shanghai Conference*, 492–499.

B2 | SHoP. (n.d.). Retrieved December 31, 2023, from https://www.shoparc.com/projects/b2/

P-58 *La Trobe Tower - Hickory*. (n.d.). Retrieved February 8, 2024, from https://www.hickory.com.au/project/la-trobe-tower/

La Trobe Tower - Rothelowman Rothelowman. (n.d.). Retrieved February 8, 2024, from https://rothelowman.com.au/project/la-trobe-tower/

La Trobe Tower: Prefabrication Allows Completion In 16 Months. (n.d.). Retrieved February 8, 2024, from https://www.the-possible.com/la-trobe-tower-hickory-modular-construction-system/

P-46 Bayliss, S., & Rory, B. (2020). *the modular housing handbook* (Vol. 01). RIBA Publishing.

HTA Design - Apex House. (n.d.). Retrieved February 8, 2024, from https://www.hta.co.uk/project/apex-house

Apex House, Wembley (Student Accommodation) – Vision Modular Systems. (n.d.). Retrieved February 8, 2024, from https://www.visionmodular.com/portfolio-item/apex-house-wembley-student-accommodation/

Scape Wembley | Student Living | Tide. (n.d.). Retrieved February 8, 2024, from https://tideconstruction.co.uk/projects/apex-house-wembley/

P-39 Xu, Z., Zayed, T., & Niu, Y. (2020). Comparative analysis of modular construction practices in mainland China, Hong Kong and Singapore. *Journal of Cleaner Production*, *245*, 118861. https://doi.org/10.1016/j.jclepro.2019.118861

NTU Residential Hall (Nanyang Crescent Hall) - Construction Database. (n.d.). Retrieved February 8, 2024, from https://constructiondatabase.org/projects/singapore/ntu-residential-hall-nanyang-crescent-hall/

P-53 INC., B. (2023). *Front Door Studio Casita PMRV*. 1–8.

Boxabl – Accessory Dwelling Unit. (n.d.). Retrieved December 29, 2023, from https://www.boxabl.com/

P-50 Bayliss, S., & Rory, B. (2020). *the modular housing handbook* (Vol. 01). RIBA Publishing.

Mapleton Crescent | Metropolitan Workshop. (n.d.). Retrieved February 8, 2024, from https://metwork.co.uk/work/mapleton-crescent/

P-38 Xu, Z., Zayed, T., & Niu, Y. (2020). Comparative analysis of modular construction practices in mainland China, Hong Kong and Singapore. *Journal of Cleaner Production*, *245*, 118861. https://doi.org/10.1016/j.jclepro.2019.118861

P-51 Bayliss, S., & Rory, B. (2020). *the modular housing handbook* (Vol. 01). RIBA Publishing.

(BCA), B. and C. A. (n.d.). *Case Study - The Clement Canopy*. Retrieved January 8, 2024, from https://www1.bca.gov.sg/buildsg/productivity/design-for-manufacturing-and-assembly-dfma/prefabricated-prefinished-volumetric-construction-ppvc/prefabricated-prefinished-volumetric-construction-case-study-the-clement-canopy

P-48 Bayliss, S., & Rory, B. (2020). *the modular housing handbook* (Vol. 01). RIBA Publishing.

P-52 *HTA Design - Ten Degrees, 100a George Street*. (n.d.). Retrieved December 1, 2023, from https://www.hta.co.uk/project/101-george-street

Bayliss, S., & Rory, B. (2020). *the modular housing handbook* (Vol. 01). RIBA Publishing.

P-56 BROAD GROUP. (2021). *Holon Building*. http://en.broad.com/ProductShow-111.aspx

Holon Overview：Holon Building leads the global building upgrading（Version 231122）. (n.d.). Retrieved February 8, 2024, from http://en.broad.com/ProductShow-131.aspx

P-49 *Beechwood Village → Pollard Thomas Edwards*. (n.d.). Retrieved December 1, 2023, from https://www.pollardthomasedwards.co.uk/projects/index/beechwood-village/

Bayliss, S., & Rory, B. (2020). *the modular housing handbook* (Vol. 01). RIBA Publishing.

P-55 *Mighty Buildings - Projects & Designs*. (n.d.). Retrieved February 8, 2024, from https://www.mightybuildings.com/projects-and-designs

P-37 *NEWS*. (n.d.). Retrieved December 1, 2023, from http://www.adrg.com.hk/projects?product_id=418

Bayliss, S., & Rory, B. (2020). *the modular housing handbook* (Vol. 01). RIBA Publishing.

CIC MiC | Projects In Hong Kong | Student Residence at Wong Chuk Hang Site for the University of Hong Kong | Modules Installation. (n.d.). Retrieved February 8, 2024, from https://mic.cic.hk/en/ProjectAlbum/219

CURRICULUM VITAE

2012 – 2018	B.Sc., Architecture, Dar Al-Uloom University, Riyadh, SAUDI ARABIA
2023	Certificate, Sustainable Building Design, Online Education Platform Edx, MITx
2020 – Present	M.Sc., Architecture, Abdullah Gül University, Kayseri, TURKEY

PUBLICATIONS

J1) Eltan, B., Kavi, M., Shahin, N., & Arslan, Z. (2023). *spektrum TASARIM REHBERLERİ* (10th ed., p. 62).

PROFESSIONAL EXPERIENCE

C1) 2011-2015 SUSF Offices, Office Assistant, Riyadh, SAUDI ARABIA

C2) 2016 Perfect Home Company, Architecture Training, Riyadh, SAUDI ARABIA

C3) 2017-2018 LORD Company, Project Manager, Riyadh, SAUDI ARABIA

C4) 2019-Present Freelance Architect, TURKEY