DEVELOPMENT OF STANDARDS FOR MODULAR CONSTRUCTION: LEARNING FROM THE FREIGHT CONTAINER

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ABSTRACT

DEVELOPMENT OF STANDARDS FOR MODULAR CONSTRUCTION: LEARNING FROM THE FREIGHT CONTAINER

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It is widely acknowledged that the construction industry has a productivity problem. Although the construction industry has a huge economic impact as one of the most important industry sectors in many countries, it is amongst the lowest R&D intensity sectors. There is an extensive gap regarding new technologies in the context of construction projects, and the value of digital processes, automation and industrialized construction are still essentially unexplored.

Modular construction is proposed as a solution to this problem. However, there is usually a case-based approach in current research without any attempt at standardization. No definitive work could be found for the architects to build their projects on. In addition, there are certain drawbacks that slow down the adoption and implementation of modular construction.

This research investigates the potential of standardization for modular buildings with an attempt to formulate the framework of a standardized design language. To that end, the standard ISO freight container was examined as an exemplary material, and a number of interviews were conducted with industry professionals to understand their perception of standardization in modular buildings. A qualitative analysis was made on the transcripts of these interviews, and the results were reported including categories, common themes, advantages-disadvantages, major barriers, drivers and potential consequences.

Keywords: Productivity in Construction, Modern Methods of Construction, Modular Construction, Standardization, Freight Container.

ÖZ

MODÜLER İNŞAAT İÇİN STANDARTLAR GELİŞTİRİLMESİ: YÜK KONTEYNERİNDEN ÖĞRENMEK

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İnşaat sektöründe verimliliğin düşük olduğu, yaygın olarak kabul edilmektedir. Birçok ülkede en önemli sanayi sektörlerinden biri olarak büyük bir ekonomik etkiye sahip olmasına rağmen, inşaat sektörü Ar-Ge çalışmalarının en düşük olduğu sektörler arasında yer almaktadır. Yeni teknolojilerin inşaat projelerinde kullanımı hala çok düşüktür ve dijital süreçler, otomasyon ve endüstriyelleşmiş inşaat ile ilgili olarak yapılması gereken çok şey bulunmaktadır.

Modüler inşaat bu soruna bir çözüm olarak önerilmektedir. Bununla birlikte, mevcut araştırmalarda genellikle herhangi bir standardizasyon arayışında olmayan vaka temelli bir yaklaşım vardır. Mimarların projelerini üzerine inşa edecekleri tanımlayıcı bir düzenleme bulunmamaktadır. Ek olarak, modüler yapı tekniğinin benimsenmesini ve uygulanmasını yavaşlatan bazı dezavantajlar vardır.

Bu araştırma, modüler binalar için standardizasyon potansiyelini araştırmakta ve standartlaştırılmış bir tasarım dilinin çerçevesini formüle etme girişiminde bulunmaktadır. Bu amaçla, örnek malzeme olarak standart ISO yük konteyneri incelenmiş ve modüler binalarla ilgili standardizasyon algılarını anlamak için endüstri profesyonelleriyle bir dizi mülakat yapılmıştır. Bu mülakatların transkriptleri üzerinde nitel bir analiz yapılmış ve kategoriler, ortak temalar, avantajlar-dezavantajlar, başlıca engeller, itici güçler ve potansiyel sonuçlar dâhil olmak üzere sonuçlar rapor edilmiştir.

Anahtar Kelimeler: İnşaatta Verimlilik, Modern İnşaat Yöntemleri, Modüler İnşaat, Standartlaşma, Yük Konteyneri.

To my mother Tûbâ Günay and my father Prof. Dr. Baykan Günay…

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LIST OF ABBREVIATIONS

ABBREVIATIONS	
BIC	Bureau International des Containers
BIM	Building Information Modeling
CSC	International Convention for Safe Containers
DfMA	Design for Manufacturing and Assembly
HC	High-Cube ISO Containers
IBS	Industrialized Building System
ISBU	Intermodal Steel Building Unit
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
MiC	Modular Integrated Construction
MMC	Modern Methods of Construction
NLP	Natural Language Processing
OCT	Offsite Construction Technique
OSC	Offsite Construction
OSM	Offsite Manufacturing
PFVMC	Prefabricated Volumetric Modular Construction
PMC	Permanent Modular Construction
PPVC	Prefabricated Prefinished Volumetric Construction
TEU	Twenty-foot Equivalent Unit

CHAPTER 1

INTRODUCTION

1.1 Background and Motivations

In many countries, the construction industry has a huge economic impact as one of the most important industry sectors. However, the construction industry is amongst the lowest R&D intense sectors with less than 1% of net sales, with a decline in the labor productivity as well (Oesterreich & Teuteberg, 2016). The construction industry, which is responsible for 40% of global CO_2 emissions, has shown very slow growth especially in the last two decades, with an annual average of only 1% (Sheikhkhoshkar et al., 2024). This is mostly attributed to the complexity of construction projects, uncertainty and short-term thinking in the industry, fragmented supply chain, and the culture of the industry (Oesterreich & Teuteberg, 2016). Analyses show that there is an extensive gap regarding new technologies in the context of construction projects, and the value of digital processes, automation and industrialized construction are still essentially unexplored, whereas automated construction methods could improve efficiency and accuracy during production processes (Schönbeck et al., 2020). The level of manual input in the construction industry is still high compared to manufacturing industries (Premakumara & Siriwardana, 2024).

To boost productivity in the construction industry, design and engineering processes need to be rethought and a greater emphasis should be placed on constructability during design processes (MGI, 2017). The Institution of Civil Engineers (ICE), UK, has identified 12 common causes for low construction productivity, given below (G. Wright, 2022).

1. The lack of an integrated approach during design development

2. Transfer of design responsibility during handover stages
3. Lack of sufficiently flexible specifications
4. Inefficient procurement procedures
5. Inefficient project leadership
6. Lack of integrated project structures that support collaborative working
7. Inadequate resource and skills planning
8. Poor logistics and supply-chain arrangements
9. Failure to place a strong focus on safety and welfare
10. Lack of reliable productivity data
11. Lack of commercial incentivization
12. Poor project and contract management

1.1.1 New Industrial Paradigms

Porter and Heppelmann (2014) examined the influence of information technology on industries in three major waves: the first was the automation of activities in the value chains, the second was the rise of internet and now the third is the integration of information technology and the product itself. The authors argue that the first IT wave affected the construction industry through concepts like computer aided design and manufacturing resource planning, but the third wave had a significant impact on the construction industry from design to operation stages. In fact, information technology has a vast use in the construction industry from computer aided design to building management systems using smart, connected products.

The term Industry 4.0 was coined by Germany in 2011, to refer to the 4th Industrial Revolution (Manavalan & Jayakrishna, 2019). Industry 4.0 can be summarized as the organization of production processes based on technology and devices autonomously communicating with each other along the value chain, and the most important aspect of Industry 4.0 is networking (Klinc & Turk, 2019). Industry 4.0 is a strategic approach using the latest technological innovations converging information and communication systems, and it has the potential to increase operation effectiveness and promote new business models (Manavalan & Jayakrishna, 2019). Industry 4.0 is the integration of information and communication technologies with industrial technology (Ben-Daya et al., 2019), and it represents a smart manufacturing networking concept where machines and products interact with each other without human control (Ivanov et al., 2019).

Table 1.1 The Four Industrial Revolutions (Klinc & Turk, 2019)

Industry 1.0	Mechanization Energy production from water sources and steam power allowed transition from agrarian and rural societies into 18th century industrial societies.
Industry 2.0	Electrification Use of electricity, as a main power source, enabled electrically powered mass production of goods.
Industry 3.0	Automation With the introduction of computerization into existing serial production in the 1970s, design could be digitally supported, and machines could be numerically controlled. Also called digital revolution, this allowed IT-based manufacturing automation.
Industry 4.0	Networking The key element of Industry 4.0 is a technology-based organization of production processes using devices that autonomously communicate with each other along the value chain. The most important aspect of Industry 4.0 is that the human interface between the information systems and the material world is being removed.

Although Industry 5.0 is yet at a stage of abstract ideas generalized from practices, it may be defined as a new visionary concept in search of a more sustainable, human-centric, and resilient industry (Madsen & Berg, 2021). Industry 5.0 is about collaboration of machines and humans, placing human in the center of creativity and leaving manual and repetitive work to machines where the agility of the organization is crucial (Mihardjo et al., 2019). Thus, social issues inherent in Industry 4.0 are addressed in Industry 5.0. Whereas Industry 4.0 places machines before humans, Industry 5.0 seeks a more sustainable practice, integrating human values with technology (Sindhwani et al., 2022) where the human and machine reconcile and work in perfect symbiosis with one another (Longo et al., 2020).

Sindhwani et al. (2022) argue that the idea of Society 5.0 originating in Japan may be considered as the starting point of Industry 5.0. The authors explain the complete idea of Industry 5.0 as achieving a bio-oriented and sustainable society, preserving the values of humanity and the environment.

Demir et al. (2019) present two visions for Industry 5.0, first of which is "human-robot co-working". Robots and humans work together in this vision, and humans focus on tasks requiring creativity whereas robots do the rest. The second vision for Industry 5.0 presented by the authors is bioeconomy, where a balance between ecology, industry, and economy is intended through smart use of biological resources for industrial purposes. Thus, the Fifth Industrial Revolution brings back human workers to the factory, pairing humans and machines combining human brainpower and creativity with the workflows of intelligent systems (Nahavandi, 2019).

1.1.2 Construction 4.0

Soon after Industry 4.0, the term "Construction 4.0" was used in 2016 for the first time, based on construction firms' awareness of the digitization of the construction industry embracing four key concepts as digital data, automation, connectivity, and digital access (Forcael et al., 2020). Although definition of this new term has been evolving since then, Forcael et al. (2020) summarized Construction 4.0 as "*a transformative framework where 3 transformations take place: industrial production and construction, cyber-physical systems, and digital technologies*". The concept failed to attract much attention in the construction industry (Oesterreich &

Teuteberg, 2016). There is a consensus in the literature that construction is inefficient, low in productivity and reluctant to use new technologies compared to manufacturing industries.

Conventional construction is dependent on implicit knowledge of individuals, but building processes can be more evidence-based and less dependent on implicit knowledge through the use of artificial intelligence technologies (Schönbeck et al., 2020). Automated construction processes require predefined products and customized production methods, where prefabrication and robot techniques prevail (Schönbeck et al., 2020). Thus, Construction 4.0 does not mean just traditional construction with technological upgrades, but it is a new perspective of innovation and increased productivity, standing on two pillars as digitization of the construction industry and industrialization of construction processes (Forcael et al., 2020). A solid background is required for Construction 4.0 including advanced technological development, skilled labor and an innovative legal framework that can deal with issues related to use of such technology (Forcael et al., 2020).

In fact, Industry 4.0 requires the construction industry to reshape itself along the whole construction value chain including the planning, construction, operation, and maintenance stages, in which artificial intelligence will act as the backbone (Pan & Zhang, 2021). The human interface between the machines and the material world is being changed now with sensors and controllers providing a human-free interface between the real and the digital worlds (Klinc & Turk, 2019).

1.1.3 Modular Construction

Modular construction can be summarized as producing standardized components of a structure in an offsite factory and then assembling them onsite (McKinsey & Company, 2019). There is no consensus in the literature about the taxonomy and nomenclature of modular construction methods, and the terms of offsite construction, prefabrication, and modular construction are sometimes used interchangeably. However, modular construction can be assessed as a type of Offsite Construction under the umbrella term Modern Methods of Construction, as shown in the figure below.

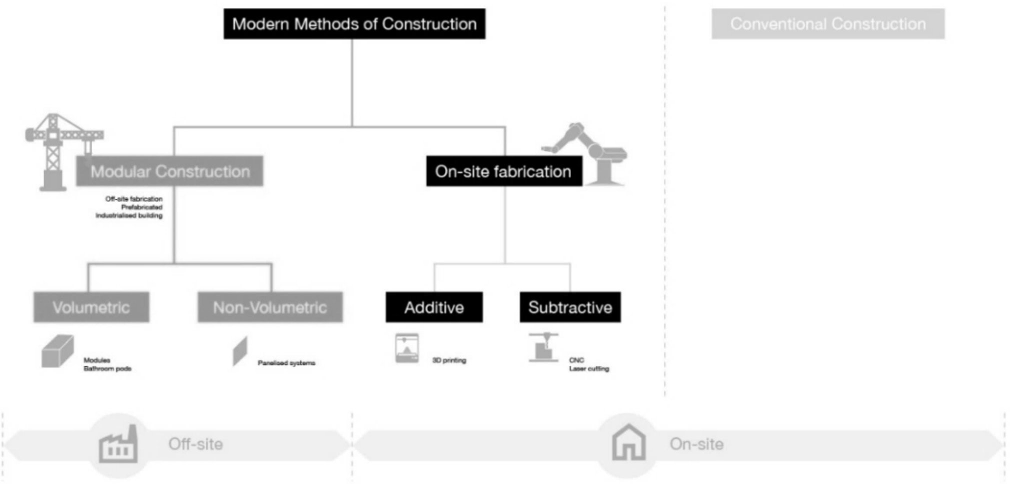


Figure 1.1. Modern Methods of Construction (Wintour, 2023)

Modular construction is not a new concept, but recently it's back on the agenda as conventional construction seems to be failing to solve the current problems of the construction industry (McKinsey & Company, 2019). Modular construction provides significant advantages in terms of circularity, and it is capable of reducing construction time and minimizing construction waste (J. Li et al., 2023). A $130 billion market is estimated for modular construction in Europe and the United States by 2030, and data gathered from construction companies show that companies are already investing in prefabrication facilities (McKinsey & Company, 2019).

Low productivity in the construction industry is a general concern shared by both the academic community and industry professionals. It is also widely acknowledged that industrialization and automation of the construction sector would be the solution to this problem, in a manner like the automotive and aerospace industries. In the automotive industry, more than 80% of the tooling and equipment in a body shop are shared by all models produced in the assembly line, instead of being specific to an individual model (Al-Zaher & ElMaraghy, 2014). Success of the automotive industry lies in the principle of flexibility where the industry gains huge economies of scale in manufacturing using flexible set of body-structure geometries, reference points and common components (Al-Zaher & ElMaraghy, 2014). Thus, the trend toward customization of vehicles has led automotive manufacturers to gravitate towards modularization of vehicle design, so that they can respond to market needs and keep the manufacturing costs under control at the same time (Al-Zaher & ElMaraghy, 2014).

Thus, considering the new industrial paradigms mentioned above, modular construction needs to be further explored as a tool to remedy the problem. This study aims to investigate a framework of standardization for modular buildings with a focus on industrial production. For this, the standard ISO freight container has been selected as an exemplary material. There are two reasons for selecting this unit. First, it is used as a building block from time to time. Second, it has a standardization story that could inspire the modular construction industry.

1.1.4 Existing Research on Modular Construction

A query was made in ProQuest with the following keywords in NOFT (Anywhere except full text) mode:

> "modular construction" OR "prefabricated construction" OR "off-site construction" OR "industrialized construction" OR "industrialised construction"
> OR ("prefabricated prefinished volumetric construction" OR PPVC)
> OR ("design for manufacture and assembly" OR DfMA)

After sorting out irrelevant documents, 78 dissertations were found in this query. 43 of these dissertations are doctoral studies and 35 are master's studies. These 78 dissertations were categorized into 11 groups as given in the figure below. Most of the dissertations were related to some kind of online tool development, design system development, product development or improvement, and structural performance assessment.

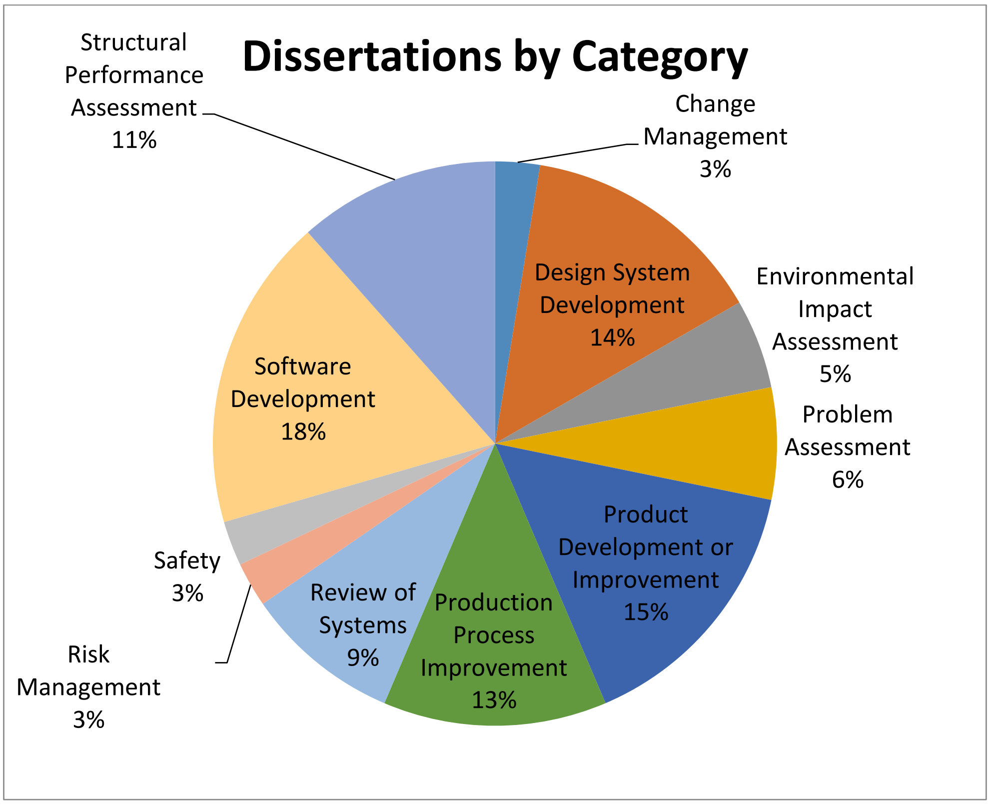


Figure 1.2. Number of Dissertations by Category

The dissertations were also categorized by decade as given in the figure below. It is observed that the popularity of the topic increases especially after 2000. As of today, 29 dissertations have been produced in the present decade, but a projection for the entire decade was made to show the upward trend.

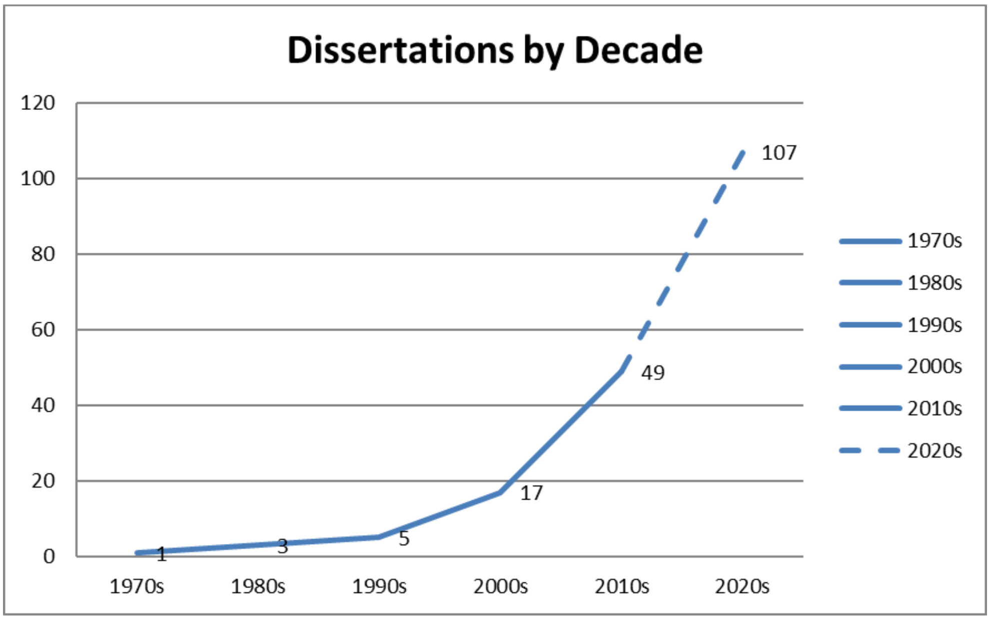


Figure 1.3. Number of Dissertations by Decade

Other than dissertations, academic papers were reviewed as well. The same keywords of (“modular construction” OR “prefabricated construction” OR “off-site construction” OR “industrialized construction” OR “industrialised construction” OR (“prefabricated prefinished volumetric construction” OR PPVC) OR (“design for manufacture and assembly” OR DfMA)) were queried in Scopus in TITLE+ABSTRACT+KEYWORDS fields, and the results were processed in VOSviewer.

7,385 documents were found when the search was limited to Engineering field and English language. In VOSviewer, these papers were analyzed by author keywords according to co-occurrence. The minimum number of occurrences of a keyword was set to 10, which allowed 147 keywords to meet the threshold. As a result, the Network of Keywords, given below, was obtained.

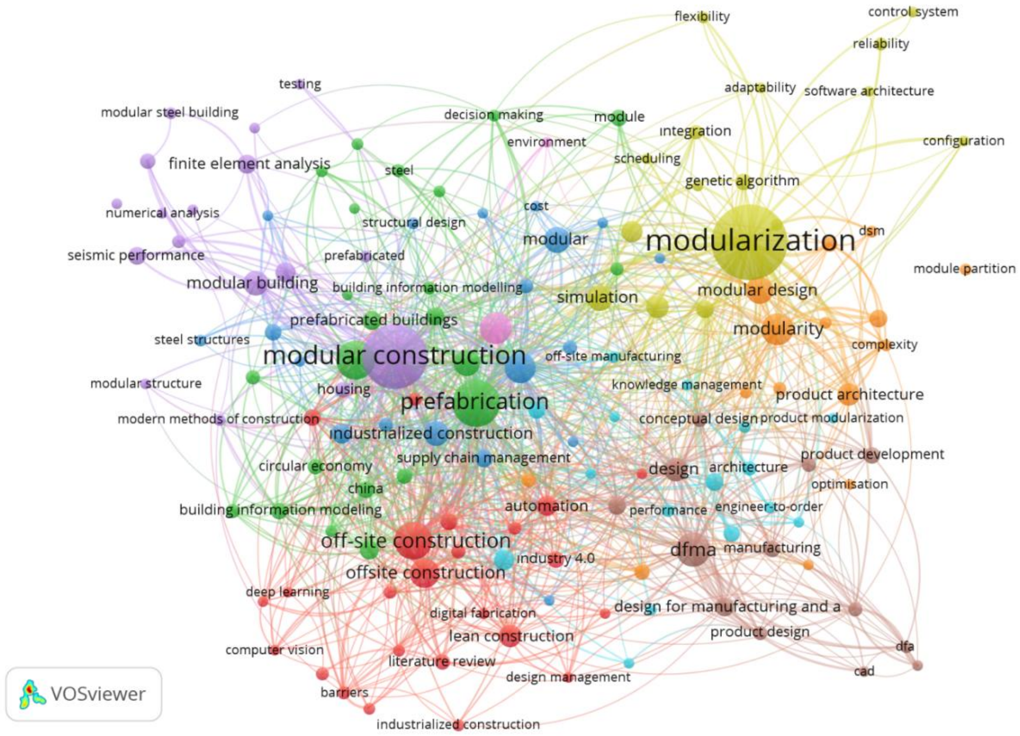


Figure 1.4. Keyword Map produced in VOSviewer

A significant finding is that although majority of dissertations are produced in the United States (44), UK (12) and Canada (11), China leads the way when a citation analysis is made on the academic papers.

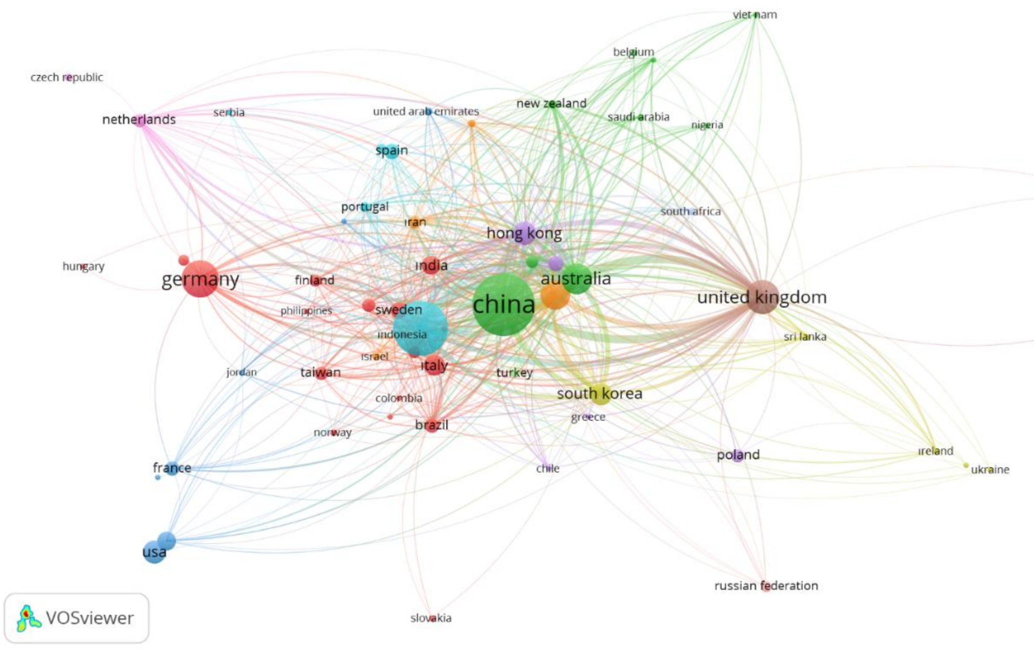


Figure 1.5. Citation Map produced in VOSviewer

Research related to standardization in modular buildings is scarce in the literature. The table in the next page shows the results of a querry with the keywords ("standardization" AND ("modular construction" OR "modular buildings" OR "prefabrication")). Of the 11 papers found in this query, 7 were published in the last 3 years. This shows that the topic is gaining attraction. 4 of these papers were written by authors from China. In terms of the research topic, 3 papers were related to spatial dimensions, 2 papers were related to standardization of building types, 3 were about precast component and pod design, 2 were about joint design, and 1 was about standardization of processes.

Table 1.2 Articles on standardization in the field of modular construction

Authors	Title	Year	Journal/ Country	Type of Standards
Luo, X.; Zheng, X.; Liao, C.; Xiao, Y.; Deng, C.; Liu, S.; Chen, Q.	Research on the Modular Design Method and Application of Prefabricated Residential Buildings	2024	Buildings / China	Volumetric Modules
Biltoria, A. K. & Roy, U. K.	Affordable housing using industrialized construction: a market-based standardization of housing units in India	2023	Architectural Eng. and Design Manage. / India	Spatial
Qin, J.; Tan, P.; Cai, G.; Li, Y.; Zhang, N.; Liu, Z.	Cross-sectional and bidirectional connection design methods for volumetric steel modules	2023	Structures / China	Joints
Geiger, M.; Hock, D.; Nübel, K.	Development of a Novel Production Model for Labour Productivity: Modular Construction Toolkit Design	2023	Buildings / Germany	Process
Li, N.; Feng, Y.; Liu, J.; Ye, X.; Xie, X.	Research on the Modular Design and Application of Prefabricated Components Based on KBE	2023	Buildings / China	Precast Components
Lacey, A. W.; Chen, W.; Hao, H.	Experimental methods for inter-module joints in modular building structures – A state-of-the-art review	2022	Building Engineering / Australia	Joints
Su, M.; Yang, B.; Wang, X.	Research on Integrated Design of Modular Steel Structure Container Buildings Based on BIM	2022	Advances in Civil Engineering / China	Modulus System
Økland, A.; Johansen, A.; Olsson, N. O. E.	Shortening lead-time from project initiation to delivery: A study of quick school and prison capacity provision	2017	IJMPB / Norway	Design of Public Buildings
O'Connor, J. T.; O'Brien, W. J.; Choi, J. O.	Standardization Strategy for Modular Industrial Plants	2015	Constr. Eng. Manage. / USA	Design of Industrial Plants
Kudsk, A.; O'Brien Grønvold, M.; Hvam, L.; Thuesen, C.	Stepwise Modularization in the Construction Industry Using a Bottom-Up Approach	2013	Open Construction and Building Technology / Denmark	Pods (Balconies & Shafts)
Jaillon, L., Poon, C.S.	The evolution of prefabricated residential building systems in Hong Kong: A review of the public and the private sector	2009	Automation in Construction / Hong Kong	Precast Components

1.2 Research Question, Aim and Objectives

In accordance with the problem defined above, the "Research Question" of this study has been formulated as follows:

> *"What would be the framework of standardization in modular* buildings *to increase productivity?"*

- *Is it possible to achieve worldwide standardization in modular buildings?*
- *What could we learn from the evolution of and standardization in other industries?*
- *What would be the main criteria for the development of a framework of standards in modular buildings?*

Accordingly, the "Aim" is "*to explore the possibility and requirements of standardization in modular buildings*", and the "Objectives" are defined as follows:

- *Investigate the current status of modular construction and prefabrication in the industry*
- *Investigate the historical development of the ISO container used in the shipping industry as an example of standardization*
- *Explore the criteria of standardization in ISO containers*
- *Investigate the potential of standardization in modular construction through industry surveys*
- *Develop a framework of standardization in modular buildings based on the findings from the industry surveys*

1.3 Research Methodology

The structure of this study is given in the flowchart below. After defining the problem as the lack of productivity in the construction industry, modular construction is proposed as a solution to this problem. An extensive literature review was made on the subject. To compare the findings from the literature review to the actual situation in the industry, a number of interviews were conducted with industry professionals. For this, a semi-structured interview was designed. In conclusion, qualitative analyses were made on the results of these interviews.

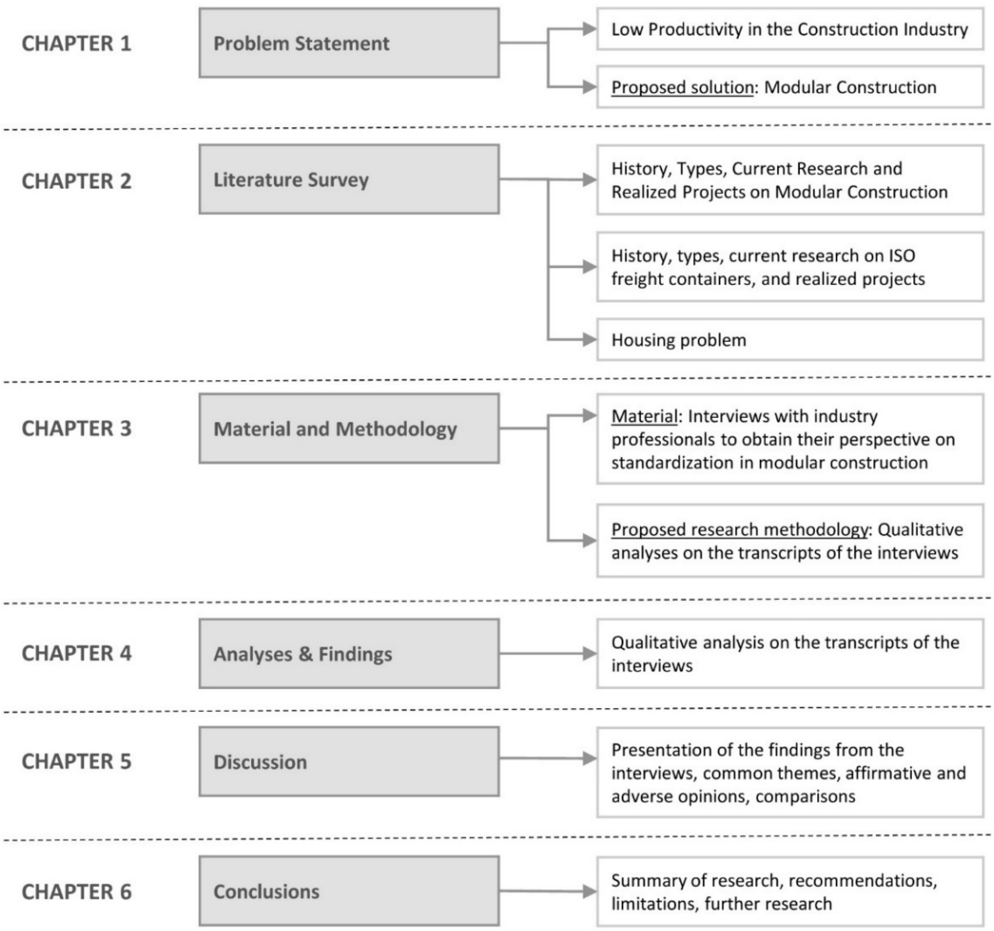


Figure 1.6. Research Flowchart

1.4 Scope and Limitations of Research

This study is based on the opinions of a limited number of industry professionals. The interviewing process was stopped at the point that was satisfactory for the purposes of this dissertation. In the future, this research could be extended to cover more interviewees from more countries. A comparative study could be made to make a more precise determination of different conditions and different approaches in different countries or regions.

1.5 Disposition

Chapter 1 – Introduction

In the First Chapter of this thesis, the problem statement is given together with brief information about the new industrial paradigms. Existing research on modular construction is summarized, and the research question, aim, and objectives are defined.

Chapter 2 – Literature Review

In the Second Chapter of this thesis, information about Modular Construction is given including brief history, types, design processes, and benefits and constraints. Also, examples of realized modular projects are given. In the second part of this chapter, a detailed examination of the ISO Freight Container is made including definition, history, structural properties, connection details, uses in construction, existing research, etc. This chapter ends with information about the Housing Crisis in the world and a Critical Review of Literature.

Chapter 3 – Material and Methodology

In the Third Chapter of this thesis, the material and research method used in this study are defined. The material of this study is the transcriptions of interviews conducted with industry professionals. Selected research method is qualitative analysis.

Chapter 4 – Analysis and Findings

In the Fourth Chapter of this thesis, findings of the qualitative analysis performed on the interview transcripts are given.

Chapter 5 – Discussion

In the Fifth Chapter of this thesis, a comparative analysis of the findings and results is made. Common themes and categories are identified.

Chapter 6 – Conclusion

In the Sixth Chapter of this thesis, a summary of this study is given with a course of action, contributions, limitations, and potentials of further study.

CHAPTER 2

LITERATURE REVIEW

2.1 Modular Construction

In the manufacturing industries, production is made in a factory environment with all technological equipment and tools readily available. However, in the construction industry, a new factory is established from scratch on each project site, which increases overheads, workmanship costs and waste. Modular construction is a subsection of off-site construction (or prefabrication) in which building processes are moved into a controlled factory environment (Jin et al., 2020). There are two stages of transition to offsite manufacturing, the first of which is moving construction works into an offsite facility, and the second one is using robotics and other automation technologies just like the automotive industry (McKinsey & Company, 2019).

Prefabrication is seen as the future of architecture by many (Grębowski & Kałdunek, 2017) because it improves the speed of construction, quality of architecture, efficiency of materials, and worker safety while reducing environmental impacts (Boafo et al., 2016). The shortage of skilled labor available for on-site work is one of the main drivers of prefabrication (AIA, 2019). The Chinese government promotes building prefabrication technologies to cope with the environmental problems and to speed up building construction (Satola et al., 2020). They have already mandated that 15% of new constructions should be produced with prefabrication techniques by 2020, and they are targeting 30% for 2025 (Satola et al., 2020).

Offsite construction, which can also be called industrialized building, offsite fabrication, prebuilt construction, or prefabricated building (Boafo et al., 2016), can be examined at different levels: (1) component manufacturing and subassembly, (2) non-volumetric preassembly without usable space, (3) volumetric preassembly with usable space, and (4) modular construction (Hwang et al., 2018) (Jin et al., 2020). Modular construction refers to components, elements or modules being constructed in a factory and then brought to site to be installed in position (Hwang et al., 2018; Wuni et al., 2020).

With its associated supply chain arrangements, offsite construction is considered as a solution for several problems, mainly low productivity, of the construction industry (Wuni et al., 2020). Major benefits of offsite construction are clean and improved workflow, higher productivity, reduced construction time and wastes (Hwang et al., 2018), and higher safety with reduced accidents (Tumminia et al., 2018). Prefabrication may provide up to 50% reduction in waste production and 20% reduction in energy consumption (Satola et al., 2020). In addition, waste recycling is higher in prefabricated buildings and disassembled parts of a prefabricated building are more usable because they are built in a dry construction system, which allows a complete separation of materials (Tavares et al., 2021).

Balasbaneh & Ramli (2020) report that half of the total raw materials produced in the world are used in construction, and more than half of the planet's waste is produced by the construction industry. Therefore, sustainable construction has a critical impact on the environment. The authors indicate that modular structures are more environment-friendly and generate fewer emissions of greenhouse gases. Offsite construction has economic advantages as well. Speedier construction times enable financial benefits like reduced interest charges, earlier commencement of business, and rental incomes (Goh & Goh, 2019).

In off-site construction, building components are produced in a dimensional pattern showing dimensional characteristics with a less variety of typologies making these components compatible even if produced in different factories (Pereira-De-Oliveira et al., 2022). Inflexibility for design changes and higher initial costs are major hindrances of offsite construction (Hwang et al., 2018), but on the other hand, standardization of building components simplifies the project and the construction processes, reduces consumption of raw materials and minimizes wastes (Pereira-De-Oliveira et al., 2022). The cost advantages of modular construction are not fully explored yet because there are both cost advantages and cost increases related to it (McKinsey & Company, 2019). For example, the impact of modular construction on full life-cycle costs and the cost of factory investment must be studied further.

House manufacturing may be effectively coupled with Industry 4.0 through modular container housing systems in a controlled industrial environment (Trancossi et al., 2018). However, inadequate knowledge related to offsite manufacturing may be a critical barrier (Balasbaneh & Ramli, 2020), because construction companies associate offsite manufacturing with large investments (Goh & Goh, 2019). One significant constraint that must be taken into consideration is transportation as the delivery of modules requires oversized heavy vehicles which may impact urban traffic and road structure (Hwang et al., 2018).

There is a negative perception in the public against modular construction methods because it may cause buildings to lose aesthetic values in terms of individuality, uniqueness, and personality (Hwang et al., 2018). In his book titled 'The Timeless Way of Building', Alexander (1979) points at the geometric combination of repeating physical elements in a town or a building, and how the relationship among the elements defines the patterns as well as the elements themselves. He criticizes modern architecture and urban design arguing that they have broken the languages established and shared by communities in hundreds of years, and the buildings produced in this manner are dead, as well as the language itself. Alexander apparently despises modular construction and modular components and argues that the modular panels tyrannize the geometry of a room. Similarly, Lewis Mumford, historian of the city and technology, denounces modern architecture, likening it to cardboard boxes, shoe boxes, egg cartons, and file cabinets (Klose, 2015). However, considering the advantages it provides, it may be a wiser decision to try to create the architectural quality with the given, instead of totally rejecting it, because the flexibility of arrangements offered by modular units may satisfy Alexander's search for a unique adaptation to individual needs and sites. And, designing with prefabricated components does not necessarily mean a barrier to creativity with all the options they provide (Boafo et al., 2016).

It is true that some special buildings may require special construction techniques and arrangements. However, most buildings do not fall into this category, and considering the benefits of high productivity, speed of construction, safety and comfort of the work environment, advantages of offsite construction would probably outweigh any compromise to be made in terms of aesthetic values. Customers are mostly not even aware of the difference between a modular and traditional building and will not object to it as long as functional needs are met (McKinsey & Company, 2019). Klose (2015) argues that what people want most of the time is only a home, whether it be a cell, a container, or a classical house of brick and mortar.

The historical research book, “the Dream of the Factory-Made House,” written by Gilbert Herbert (1984), tells the story of the packaged house “dreamed” by Walter Gropius and Konrad Wachsmann. Therein, Herbert (1984) argues that although the fundamental motivation behind the search for a factory-made house was solving the housing crisis, the creative and intellectual challenge inherent in the design itself was the reward for many architects, because a system of prefabrication could generate thousands of buildings compared to a single building designed by an architect.

2.1.1 Brief History of Modular Construction

Using a module as a measurement unit in architecture goes back as far as the Greeks, who used the diameter of the column as the regulatory unit from which all dimensions were derived (Pereira-De-Oliveira et al., 2022). Afterwards, the Romans based their constructional proportions on anthropometric measurements such as human leg or arm. In the Ten Books of Architecture, Vitruvius defines the ratio of base, capital, and entablature of Ionic Order columns in detail (Vitruvius Pollio, 1990).

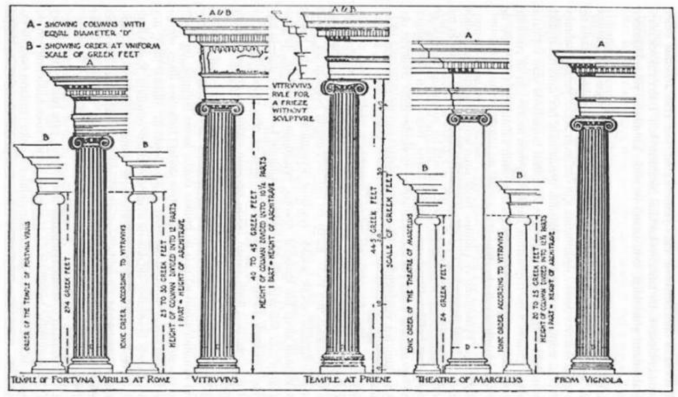


Figure 2.1. Ionic Order ratios (Vitruvius Pollio, 1990)

Earliest example of modular construction is generally accepted as the 17th century houses, constructed in England and sent to the fishing village of Cape Ann, which is in Massachusetts, USA now (Jelenic & Petrovcic, 2021). Similarly, timber frame houses were made in England and delivered to Australian settlements in the late 1700s and early 1800s. As a matter of fact, prefabrication in the nineteenth century would primarily be an instrument of new settlements, because shelter was the basic issue for the people opening the vast territories of newly discovered continents to development (Herbert, 1984).

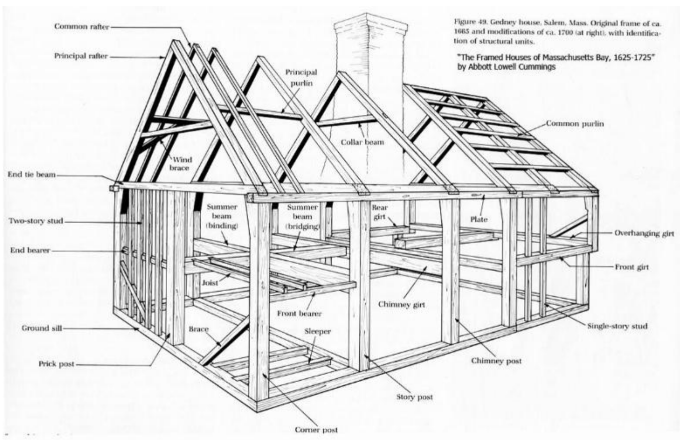


Figure 2.2. Framing variations of Framed Houses of Massachusetts Bay (Harris, 2024)

In 1830, the Manning Portable Colonial Cottage, an expert system of prefabricated timber frame and infill components, was developed for emigrants (Boafo et al., 2016). In the same years, balloon framing became very popular in the USA due to short erection times.

Figure 2.3. Balloon frame house, Omaha Reservation, Nebraska, 1877 (Huets, 2013)

The Crystal Palace, Britain's Great Exhibition of 1851, was one of the most extensive examples of prefabrication (Jelenic & Petrovcic, 2021) The building, which used light and cheap materials such as iron, wood, and glass, was designed by Sir Joseph Paxton in less than two weeks and constructed in only a few months. The palace, which consisted entirely of prefabricated components, was taken apart, piece by piece, and moved to another location after the exhibition.. The building, which used light and cheap materials such as iron, wood, and glass, was designed by Sir Joseph Paxton in less than two weeks and constructed in only a few months. The palace, which consisted entirely of prefabricated components, was taken apart, piece by piece, and moved to another location after the exhibition.

Figure 2.4. Crystal Palace by Sir Joseph Paxton, London (Britannica, 2024)

Before the industrial revolution, construction was mostly craft production where parts were handmade and unique (Sacks & Partouche, 2010). But even then, the construction industry had developed many standards such as floor height, stairs, doors and windows, tile dimensions, height of a counter, timber work details, and furniture (Herbert, 1984). During the industrial revolution, all these handmade components were replaced with factory made items, which became objects of agreed standard dimensions (Herbert, 1984). Standardization of building components simplified projects and the construction processes, basing construction on typified assemblies (Pereira-De-Oliveira et al., 2022). It also reduced the information flow on site, speeding up workflow and potentially reducing errors (Partouche et al., 2008). However, these changes were not always welcome, even found "brutal" from time to time, and many a times hindered by government agencies and regulations (Herbert, 1984).

With the establishment of Bauhaus in 1919, the relationship between art and industry, and the standardization of dimensional and typological norms became two basic issues of the general concept of industrialization (Herbert, 1984). Walter Gropius firmly believed in standardization and thought that machines could provide mass-produced products that are cheaper and better than those manufactured by hand. The first attempts in Bauhaus were experiments examining variability within a standardized system, such as the Masters' Houses at the Bauhaus in Dessau in 1925-26, rather than an overall system of prefabrication (Herbert, 1984).

Figure 2.5. Masters' Houses at the Bauhaus in Dessau (Bauhaus Kooperation, 2024)

On the other side of the Atlantic, Aladdin "built in a day" house became popular in the United States in 1930s (Boafo et al., 2016). The Aladdin House consisted of a metal sandwich panel wall system, and it was followed by George Fred Keck's "House of Tomorrow" and the "Crystal House" for the Chicago World's Fair.

Figure 2.6. Aladdin Homes Catalogue (*Aladdin Homes Built in A Day Catalog*, 1918)

The standardization movement promoted by Bauhaus could be observed in iconic buildings around the world. For instance, the metal spandrels of the Empire States Building were standardized in only eighteen variations in a total of 5,704 elements (Partouche et al., 2008). Similarly, Charles-Édouard Jeanneret, the famous architect known as Le Corbusier, used only fifteen measurements in L'Unite d'Habitation (Le Corbusier, 1954), one of his masterpieces.

Le Corbusier tried to establish a standard measurement system, which is explained in his book "The Modulor – A Harmonious Measure to the Human Scale Universally applicable to Architecture and Mechanics". It was first published in 1948 as Le Modulor in French. The English version came in 1954. In a book exhibition at the ninth Triennale in Milan in 1951, a graphic demonstration of the Modulor was made, announcing it as "*the pivot around which revolve all the problems of proportion in modern architecture*" (Le Corbusier, 1954).

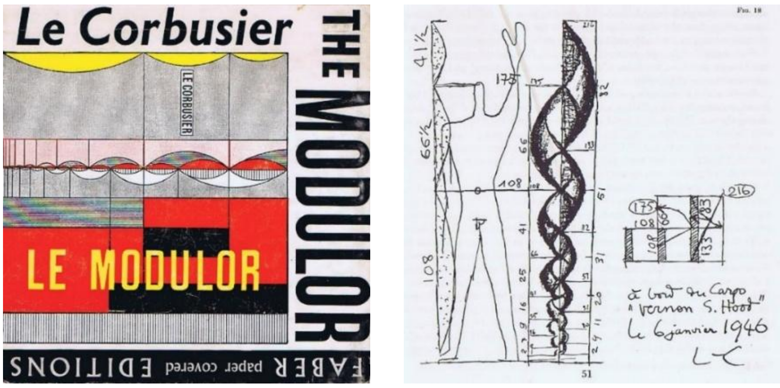


Figure 2.7. English Edition of the Modulor (Le Corbusier, 1954)

Le Corbusier defined Modulor as a measuring tool based on the human body and on mathematics. In the Modulor, Le Corbusier sought a way to unite two virtually incompatible systems, the imperial system of feet and inches with the metric scale and establish a relationship with the human body. He believed that building construction was the concern of heavy industry, and the parts of houses had to be mass-produced, for which standardization was necessary. He developed a proportioning grid according to the human body and thought that one day it could serve as a basis for prefabrication if it could be set above both imperial and metric systems.

Japan was influenced by the Bauhaus movement as well. After the introduction of the dry assembly structure in the early Showa period (1926-1945), "Wood Panel Assembled House" was developed in 1941 under the guidance of an architect who researched and practiced the dry construction method (Japan Prefabricated Construction Suppliers and Manufacturers Association, 2024). In a country which was traditionally no stranger to these building techniques, this led the way to the birth of the wood-based prefabricated buildings in the post-war reconstruction. The Factory Production Housing Association was established in 1946 to cope with the housing shortage after the war. Their aim was to achieve mass production of high-quality standard housing. These were wood-based buildings of either frame assembly type or panel type, or a combination of both. Soon after this, the scarcity of wood and the pursuit for a non-combustible material led to experiments with concrete, which included precast concrete members for foundations, columns, floors, and exterior walls joined by bolting (Japan Prefabricated Construction Suppliers and Manufacturers Association, 2024). In 1955, Japan Lightweight Steel Building Association was established, which started research and development on the use of lightweight steel for small-scale buildings.

Before World War II, many attempts were made in Germany such as the Steel House, the Timber House, and the Copper House, promoted by the steel, timber, and copper industries of Germany respectively (Herbert, 1984). Walter Gropius was personally involved in the Copper House Project. Mostly consisting of framing and panel systems, these ventures still included too much sitework. The steel house and the timber house were never practically consummated. The Copper House was a financial failure accelerated by the effects of the Great Depression in the late 1920s and the rise of National Socialism in Germany (Herbert, 1984). With the rise of National Socialism, many German intellectuals including many Bauhaus architects left the country. They continued their work in other countries, mostly in the USA.

Prefabrication of dwellings was still seen as the potential solution of the housing crisis, but it meant different things for America and Europe (Herbert, 1984). Whereas prefabrication meant mass housing in the European context, it meant mass production of single-family houses in the USA.

During World War II, there was a massive need for quickly deployable building systems for accommodation of troops and migrant workers (Imperiale, 2012). Emigrating to the United States during WWII, Konrad Wachsmann and Walter Gropius worked on a prefabricated modular construction system, the “Packaged House” for long years. The system consisted of prefabricated panels that could be configured in infinite ways on a single-story rectangular plan. Wachsmann also developed a “universal joint,” a wedge connector, that would enable the joining of prefabricated panels giving them great structural stability. Wachsmann aimed this system to be mobile, scale-less, flexible/adaptable providing for material reuse, and accessible to the unskilled laborer (Andrzejewski, 2019). Unfortunately, Wachsmann was so obsessed with improving the system that the project could never be finished (Imperiale, 2012). Thus, an engineering genius resulted in a financial failure. When the traditional housing industry regained its momentum in the competitive free-enterprise system of the USA in late 1940s, “prefab” houses were put aside for a while (Herbert, 1984). However, the mobile home industry became the most efficient building industry in the United States in the 1950s (Bernhardt, 1980).

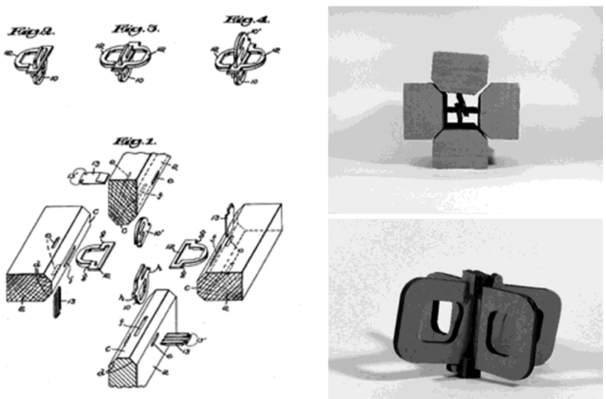


Figure 2.8. Universal Joint by Konrad Wachsmann (Andrzejewski, 2019)

After WWII, several prefabricated building systems were extensively developed in Eastern and Western Europe to satisfy the massive demand for housing reconstruction (Jelenic & Petrovcic, 2021). A shift towards industrialized buildings was observed within the construction industry in the 1950s and 1960s brought forth by the philosophies of the Bauhaus movement. Although this factory manufacturing methodology was more dominant in social housing, other areas of construction took their share as well. For instance, in the mid-1950s, 25% of all single-family houses in the United States were mobile homes built on a chassis (Jelenic & Petrovcic, 2021).

In the USSR, introduction of the prefabricated panel caused a boom in the industry, although early experiments with prefabrication goes back as far as the Bolshevik Revolution (Malaia, 2020). Nikita Khrushchev's housing campaign in the late 1950s, aiming to deliver an apartment to every family, was the driving force behind this boom. Khrushchev had a view to transforming a chaotic and backward construction industry into one that operated with industrial methods. Thus, 13 million apartments were built between 1956 and 1965. K-7 panel series developed by architect Vitaliy Lagutenko were the most famous of a series of prefabricated concrete panels. The use of reinforced concrete in housing was made obligatory with a decree so that steel could be reserved for industrial construction.

In 1969, the US Department of Commerce issued a report titled "Industrialized Building in the Soviet Union" (National Bureau of Standards, 1970). This report was based on the observations of a US delegation sent to the USSR. The standardization approach of the Soviets was based on sets of coordinated modular dimensions to allow the lowest possible number of system components, with little or no component interchange from one system to another. Model changes were very infrequent. There were twelve basic designs for apartment houses in the entire USSR with fixed height, fixed plan, and fixed exterior appearance. Thus, it was a closed system in contrast to the open industrialized building systems that offer flexibility.

The centrally planned economy and institutional bureaucracy of the communist state facilitated the implementation of prefabricated housing at the beginning, but then it went into stagnation in the late 1980s and 1990s (Malaia, 2020). Poor governance and lack of investment in technological upgrades led to inefficient production and low-quality products. The falling apart of the USSR in 1991 marked the end of state commissioned housing, and thus the end of industrial prefabricated housing production. The limited spans and small spaces of prefabricated houses failed to satisfy the purchasers after that.

Figure 2.9. Prefabricated panel construction in 1961 and 1964 (Malaia, 2020)

In the Western side, volumetric buildings emerged in late modernity in 1960s and 1970s with movements like Japanese Metabolists and British Archigram, symbolized with projects like Arata Isozaki’s Cities in the Air, Moshe Safdie’s Habitat 67, Paul Rudolph’s Oriental Masonic Gardens, and Kisho Kurokawa’s Nakagin Capsule Tower (El Messeidy, 2018).

Figure 2.10. Habitat 67 by Moshe Safdie, Montreal (GKV Architects, 2024)

Figure 2.11. Nakagin Capsule Tower by Kisha Kurokawa, Tokyo (GKV Architects, 2024)

In his book “Design for the Real World”, Victor Papanek (1971) defines the contemporary architect as a master assembler fitting together a puzzle, which is a building, by plugging in components. This is an appropriate interpretation for the process of putting together modules to create more complex structures. Acknowledging that the answer for meeting the requirement of millions of housing units around the world lie in mass-production techniques and totally new concepts, Papanek argued that Habitat 67 was the first intelligent attempt to use a modular building system although this project was criticized for being too expensive and too complex. According to Papanek, it would be the least expensive and most varied system, if it could be built. The system would begin to pay for itself as more units were built after making an initial investment.

Volumetric construction continued to be extensively used throughout the 1970s, employing prefabricated construction in the form of frames (timber or steel) or concrete boxes (Jelenic & Petrovcic, 2021). By the mid-1980s, many countries had begun using prefabrication together with standard modular designs in public housing projects.

2.1.2 Types of Modular Construction

Although there is no uniform definition of modular design in scientific literature, a common principle is shared by most sources, which is a simple design approach separating a whole into smaller independent or interconnected parts (Jelenic & Petrovcic, 2021). There are different approaches in modular construction, where standardized components of a structure are produced in an offsite factory, and then assembled onsite (McKinsey & Company, 2019). These prefabricated modules may be delivered as volumetric components of complete or partial rooms or units, or as two-dimensional elements like walls and columns (Goh & Goh, 2019).

Three-dimensional modules may be produced in factory with decoration, piping, insulation, heating, ventilation and air conditioning or other equipment, and even facade, avoiding or simplifying onsite work (Ye et al., 2021). 3D volumetric approach, in which units are produced in the factory with full fit-out, enables the highest efficiency and time saving, but constraints related to road transport may be a hindrance (McKinsey & Company, 2019). This approach is more suitable for buildings with repetitive units such as hotels, hostels, or mass housing, and especially for rooms with more intricate finishings like bathrooms and kitchens.

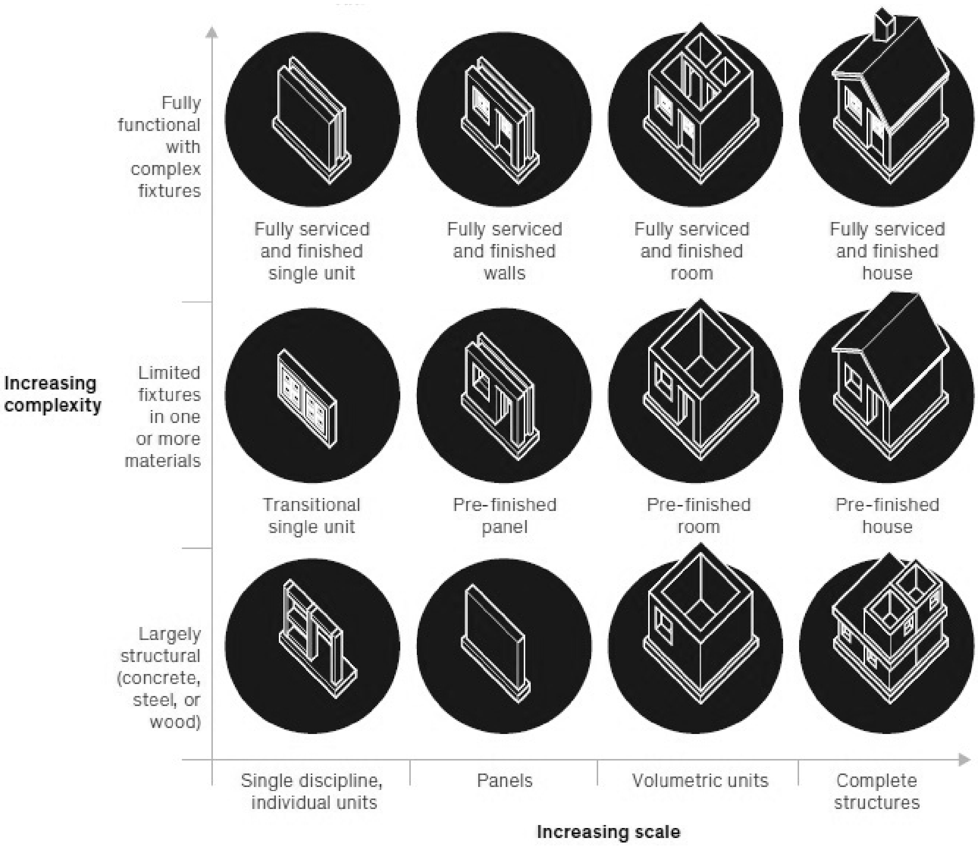


Figure 2.12. Complexity vs. Scale in Modular Construction (McKinsey & Company, 2019)

The figure above shows complexity vs. scale in modular buildings. 2D panelized solutions are similar to the flat-pack assembly method used in home furniture. It makes onsite assembly work simpler than conventional construction, but it is more complex than putting together 3D modules (McKinsey & Company, 2019). Yet, the greater flexibility enabled by 2D panelized solutions make them more suitable for non-repetitive structures. The two approaches may be used in combination as well, taking advantage of both as required by the project.

The figure below shows the decision factors related to selection between 2D panels and 3D modules.

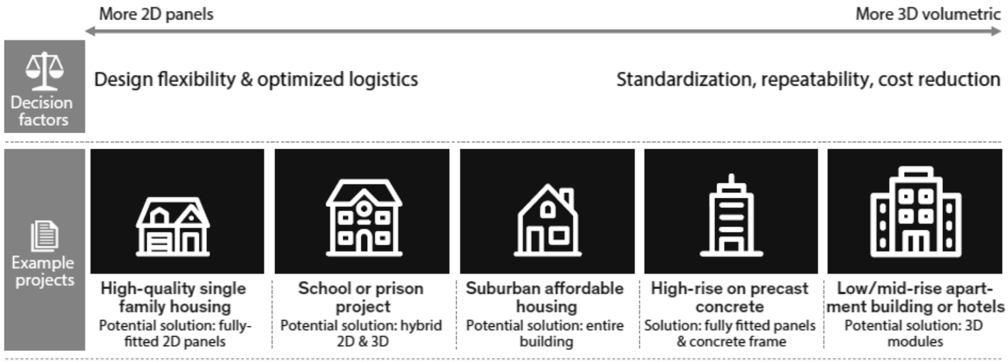


Figure 2.13. Decision Factors in Modular Construction Approaches (McKinsey & Company, 2019)

In the UK, the Modern Methods of Construction (MMC) definition framework was developed by a specialist sub-group of the MHCLG MMC (Ministry of Housing, Communities and Local Government of the United Kingdom) to regularize and refine the term ‘MMC’ by defining the broad spectrum of innovative construction techniques (MHCLG MMC, 2019). The definition framework identified 7 MMC categories shown in the figure below. These categories have many sub-categories as well.

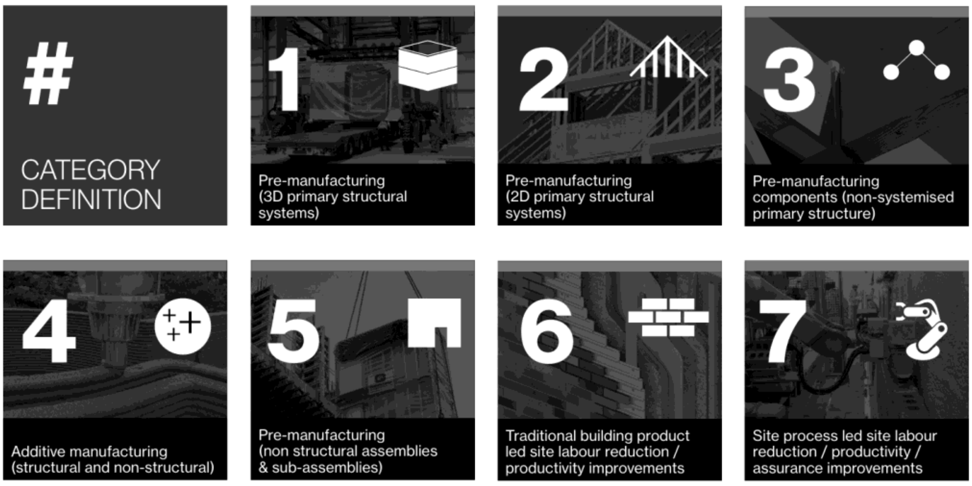


Figure 2.14. 7 MMC Categories (MHCLG MMC, 2019)

Many terms have been produced lately such as “Modular Integrated Construction (MiC)” in Hong Kong, “Prefabricated Prefinished Volumetric Construction (PPVC)” in Singapore, “Permanent Modular Construction (PMC)” in the United States, “Industrialized Building System (IBS)” in Malaysia, and “Offsite Construction Technique (OCT)” in Australia and Pakistan, which all refer to prefabricated volumetric modular construction (PFVMC) (Chen et al., 2021).

PPVC is a method gaining high popularity especially in places with restricted land and reliance on low-skilled imported labor such as Hong Kong, London, New York, and Singapore (MGI, 2017). As a matter of fact, Government of Singapore has made it mandatory to use prefinished volumetric modules. Building and Construction Authority of Singapore defines PPVC as “*a construction method whereby free-standing 3-dimensional modules are completed with internal finishes, fixtures and fittings in an offsite fabrication facility, before it is delivered and installed on-site*” (BCA Singapore, 2022b). In PPVC projects, modules are produced with finished walls, floors, and ceilings in offsite factories to be transported to construction site for installation (Hwang et al., 2018). In volumetric approach, up to 95% of the building may be fabricated off-site (AIA, 2019).

Wuni & Shen (2020) argue that a manufacturing business model is embraced in PPVC, in addition to the Design for Manufacturing and Assembly (DfMA) philosophy, which is an engineering methodology that simplifies design processes to facilitate the manufacturing and assembly of building modules. The authors define three major benefits of adopting a DfMA approach in PPVC projects: selection of cost-effective manufacturing-compliant raw materials, reduction in the complexity of manufacturing operations during design phase, and reduction in manufacturing time, cost, and assembly time. On the other hand, Y. S. Li et al. (2019) state that construction becomes easier to control in PPVC, and there is an environment-friendly and safe working environment for workers because the structural body is completed in the factory.

Wuni & Shen (2020) further argue that design stage is very critical for a PPVC project as the decisions at this stage will have a substantial impact on later stages of the project. PPVC may not be suitable for all projects because it requires unique specifications of module jointing, tolerance limitations and space allocation for buffering of the modules (Wuni & Shen, 2020). Yet, it is very beneficial for projects with repetitive design such as hotels, apartments, student residence, hospitals, and prisons (Hwang et al., 2018).

2.1.3 Design Processes and Use of BIM in Modular Construction

It is predicted that more prefabricated components will be used in buildings, and factory-made products will be incorporated into construction projects using tools that enable parametric remodeling of buildings (MGI, 2017). However, a different design-thinking must be adopted to make full advantage of the production efficiencies, opportunities of standardization, mass customization, and ease of transport and assembly enabled by these tools (McKinsey & Company, 2019). In conventional construction, design phase is mostly rushed, and construction starts before design is finalized (MGI, 2017). However, early design decisions must be made in modular projects, and later changes are more costly and difficult compared to conventional construction (McKinsey & Company, 2019). Wuni & Shen (2020) identify early design-freeze and early consideration of modularization as the two critical success factors for modular projects. The authors argue that inclusion of module fabricators and suppliers in the design team is essential for providing a smooth workflow in modular projects in addition to collaboration among stakeholders.

Digital technologies such as building information modeling (BIM), computer aided design (CAD), computer aided manufacturing (CAM), and computer numerical controlled (CNC) machinery play a central role in the fabrication of modular components (AIA, 2019). As a matter of fact, an online survey of 809 industry professionals attributes the reemergence of prefabrication and modular construction to the influence of Building Information Modeling (BIM) on design and construction processes and the collaboration between project teams (McGraw-Hill Construction, 2011). BIM, which is defined as *"an innovative technology to virtually design and manage construction projects by simulating a virtual model of a building",* allows all project members to collaborate efficiently throughout the entire lifecycle of a building (Oesterreich & Teuteberg, 2016).

Considered as one of the pillars of Industry 4.0 approach in the construction industry, BIM has evolved from an initial strategy of information sharing into an information management strategy supporting design, construction, and operation processes (Işıkdağ, 2015). BIM not only offers revolutionary design management tools such as fluent visualization, coherent shop drawings, fast coding, and accurate interference detection, but it also facilitates the work of quantity surveyors and contractors with its built-in cost estimating features (Papadonikolaki et al., 2016). In a time when the construction industry had never been so challenged for innovation, BIM is identified as a significant opportunity to change the sector rigidness towards change and innovation that had been a barrier against modernization of the construction industry (Ahmed & Kassem, 2018). BIM is being recognized as a worldwide industry standard. Government of Germany has announced a plan to make BIM mandatory for large-scale infrastructure projects from 2020 onwards, and the governments of the USA, the UK and the Scandinavian region are heavily investing in BIM programs (Oesterreich & Teuteberg, 2016).

Due to its highly repetitive nature, modular prefabricated construction can significantly benefit from BIM applications (Ramaji & Memari, 2015). It is reported that there are design firms developing module libraries which can accelerate and speed up design processes (McKinsey & Company, 2019). However, the number of research on the subject is limited (Xu et al., 2020).

Prefabricated construction is an interdisciplinary process where complex products are manufactured in a facility and then transported to the site for assembly (Xu et al., 2020). For this, coordination and sharing of information has always been a challenging task in this process. The need to solve the general interoperability problem in BIM applications led to development of US National BIM Standard (NBIMS) consisting of three major parts: 1) Information Delivery Manual (IDM), 2) International Framework for Dictionary (IFD), and 3) Industry Foundation Class (IFC) file format (Ramaji et al., 2014). IDM is a standard for the processes of the work, IFD is a standard for the terminology that is used in the processes (Ramaji et al., 2014), and IFC is an open standard that includes data specifications for the individual building elements and their relationships (Xu et al., 2020). Ramaji et al. (2014) argue that it is more advantageous to use an open standard for interoperability compared to direct translation because it decreases the number of required translators.

Among the few attempts at BIM implementation in the prefabrication area, Xu et al. (2020) developed a conceptual model for modeling the information delivery among stakeholders to achieve an integrated management of prefabricated construction. The authors proposed an expansion to IFC to represent design information of the prefabricated construction, listing several prefabricated component properties for the different attributes between prefabricated components and conventional components.

Ramaji et al. (2014) started a long-term study to examine standardization in modular building construction. The authors aimed to achieve a standardization of information exchanges in modular construction, which has a rather low level of information integration and no specific code or standard for the modules or the processes. Current BIM tools and frameworks did not address modular construction as an industrialized type of construction (Ramaji et al., 2017). Its additional stages of manufacturing and transportation made the processes different from site-built projects (Ramaji et al., 2014).

In continuation of this study, Ramaji & Memari (2015) presented a method to standardize the information exchanges in modular construction. In this method, the authors incorporated production information management techniques in NBIMS to organize the product information, addressing the interoperability issue in this industry. To evaluate the modular buildings from the production point of view, the authors used a Product Architecture Model (PAM) as the key element blended in the NBIMS method and used it as a core for all standardization. Modular buildings were broken down to assemblies and subassemblies by the PAM which contained all physical and non-physical attributes and properties at different stages of the project. The authors worked on different Model Views for different disciplines and uses to support software development and facilitate use of the present BIM software and tools for multi-story modular building projects.

In the later stages of this work, an information delivery framework was developed for multistory modular buildings addressing both the project-based and product-based nature of these buildings (Ramaji et al., 2017). The methodology used by the authors for development of such framework included four steps: 1) recognizing different modular systems, 2) defining hierarchy of modular systems in terms of assemblies and subassemblies, 3) defining attributes of components required during the lifecycle of the building, and 4) categorizing the components and related attributes. Although this framework is designed for modular buildings, it can be used for defining project-specific exchange requirements as well.

Thus, the information framework proposed by Ramaji et al. (2017) presents a new methodology for standardization of information exchanges in industrialized types of construction and facilitates the execution of BIM in multistory modular buildings. In addition to this, the framework addresses interoperability in modular building projects by outlining the basis for standardization of digital representation of building information models, provides a design guide for modular building companies and can also be beneficial for software developers to add required features to their software packages to support modularization.

Another study was conducted by Gan (2022), which aimed to develop a comprehensive BIM-based graph data model for representing the essential characteristics and interrelated elements in modular buildings. With this graph data model, it was intended to automatically generate and plan design options for precast modular construction by establishing Industry Foundation Classes (IFC) model view definitions (MVD). The graph data model explicitly formulated the spatial, topological, and geometric characteristics essential for design generation in modular off-site construction, addressing spatial attributes of volumetric modules such as position, area, space boundary, adjacency, and connectivity (with other modules). The author asserted that this study contributed to the standardization of design information for modular buildings in the precast industry.

Review of the literature shows that there is a pursuit for a common design language serving prefabricated modular construction. Cao et al. (2022) argue that module libraries containing prefabricated parts and assemblies would be very beneficial for construction firms eager to shift to a more industrialized and product-oriented approach. However, current information delivery frameworks mostly do not contain such product-related components (Ramaji et al., 2017) and the existing libraries usually serve single-use projects (Cao et al., 2022). Thus, a more flexible data structure is needed to support storage, analysis, and reuse of design information in industrialized construction (Cao et al., 2022).

2.1.4 Benefits of Modular Construction

Many authors agree that modular construction is more advantageous compared to conventional building methods in terms of construction waste, cost, time, safety, water usage and pollution (Haque et al., 2022). The table below shows a summary of benefits and constraints related to Modular Construction, gathered from the literature.

Table 2.1 Benefits of Modular Construction

Benefits of Modular Construction	
Management & Schedule	Accelerated construction schedules by 20-50%
	Greater certainty on both building times and costs
	Good coordination of activities
	Increased levels of automation
Cost & Revenues	Reduced and controlled construction cost and overall lifetime cost of the building, up to 20%
	Earlier revenue collection and higher internal rates of return due to shorter project schedules
	Labor savings
	Lower site overheads
	Lower waste in factory
Quality	Improved quality of the building, including better energy or seismic performance
	Easier quality control
	Less rework
	Easier identification of defects
	Increased precision of construction in a factory environment
Environmental Aspects	Reduction in GHG emissions
	Lower carbon footprint
	Utilizing comparatively eco-friendly materials like timber, steel, plywood, and gypsum boards
Human Aspects	Working in an enclosed and controlled factory environment
	Reduction in health and safety incidents
	Based in a fixed factory location instead of living a transient lifestyle, working outdoors exposed to all kinds of weather conditions

Off-site construction allows simultaneous performance of work that would normally be sequenced; thus, it increases productivity (AIA, 2019). Compared to site intensive building construction, modular construction may reduce onsite time by over 50% and site wastage up to 70% with other advantages like high quality control, work safety due to shortening of work-at-heights, rapid introduction of new technologies, and a decrease in noise levels (Haque et al., 2022). Reduction of production time, which is 45% in average, is the greatest advantage offered by modular construction

(MBI et al., 2015). While the site is prepared and the foundation is built, modules can be prepared in the factory. The increased amount of time saved on-site increases the amount of savings as well. Even if no significant cost reduction is achieved, modular construction enables higher cost control (MBI et al., 2015).

Construction and operation stages of a building cause significant environmental issues. Globally, construction industry is responsible for 40% of the primary energy consumption with a higher share in developed and urbanized countries (Jin et al., 2020). Embodied energy of construction materials, which covers energy consumed during raw material production, transportation, and onsite construction processes is very high (Jin et al., 2020). Optimal use of materials enabled by off-site production of building components reduces material input and waste and allows capturing and recycling of a significant amount of surplus material and fall-off that can be used in other projects (AIA, 2019). Similarly, the reduction in worker travel and small material deliveries reduce transportation emissions. Key contributions of modular construction in terms of sustainability are significant waste reduction, lower carbon footprint/embodied carbon, ability to relocate, renovate, and repurpose, and greater energy efficiency/tighter building envelope (MBI, 2023).

Modular construction can help to mitigate the climate crisis by enabling a circular economy by Narrowing, Slowing, and Closing of Loops in the construction industry (Sajid et al., 2024). A circular economy keeps the resources in the loop for the longest possible time (Kazmi & Chakraborty, 2023) and aims to increase material efficiency through the adoption of the 3Rs: reduce, reuse, and recycle (Minunno et al., 2020). Modular construction allows easy adaptation and modification of buildings to be used for different purposes over time (AIA, 2019). Especially design for disassembly and reuse increases the time a building is kept in the loop, because even if a building is not reused, a modular building designed for disassembly can be decommissioned and removed in a more controlled and undisruptive way compared to traditional demolishing. As a matter of fact, steel is the highest-ranking construction material in terms of circularity, and steel technologies offer the highest degree of circularity because the high durability of the material allows repeated assembly and disassembly of modules (Gallo et al., 2021). Reclaiming structural elements such as beams, columns, slabs, and walls, and reallocation of these in new projects is likely to gain more attention as the industry evolves (AIA, 2019). In the future, buildings may have assembly and disassembly guides like machines to maximize the efficiency and smoothness of these operations.

Table 2.2 Circular Economy enabled by Modular Construction (Sajid et al., 2024)

Circular Economy Enabled by Modular Construction		
	Advantages	**Achievements**
Narrowing of Loops	• Precision manufacturing • Reduced variances through standardization of modules • Utilization of recycled materials • Enhanced quality control, mitigated need for rework and corrections	• Reduced consumption of resources • Minimized construction waste • Lower demand of raw materials
Slowing of Loops	• Prolonged functional lifespan • Effective refurbishment and maintenance of modules • Detachable components of modular units • Adaptability and repurposing	• Decelerated overall consumption of resources • Easy replacement • Extended service life
Closing of loops	• DfD (Design for Disassembly) principles • Streamlined remanufacturing process	• Easy recovery of products, parts, and materials when a building is disassembled or renovated • Restoration of products at the end of their lifecycle

2.1.5 Barriers

Construction culture and late design changes are the most significant barriers against modular construction according to the Report of the Results of the 2018 Off-Site Construction Industry Survey conducted by National Institute of Building Sciences (2018). Communication, or the lack of it, between stakeholders is a major barrier as well.

Table 2.3 Constraints of Modular Construction

Constraints of Modular Construction
Longer design period
Early design decisions needed
New and unfamiliar for the industry
Transportation constraints
Additional logistics costs
Additional material cost due to the need for greater precision
Units need to be structurally sound for transportation
Just-in-time delivery to sites is critical because modules cannot be stacked in site

There are no special provisions related to modular construction, and modular projects must comply with the same building codes that apply for conventional on-site construction (AIA, 2019). Because of this, the approvals and inspections may take much longer than conventional construction.

Upfront costs of modular buildings are higher than their traditional counterparts due to different sequencing but shortened construction time offers opportunities to reduce overall cost (AIA, 2019). Cashflow in a modular project is different due to the manufacturing side, and this must be taken into consideration during preplanning stages, financial arrangements, etc.

Modular construction is sometimes perceived as an all-or-nothing strategy. On the contrary it may be used in a hybrid way together with conventional methods (AIA, 2019). For instance, bathroom pods may be used to reduce construction time, improve quality, and eliminate bathroom defects (MBI, 2016).

As each module of a modular building will have its own walls, floor, and ceiling, the result may be a bulkier structure with deeper floors and thicker walls (AIA, 2019). Because of this, modular construction is not convenient for buildings with large spans. Also, the increased use of cranes should be taken into consideration (AIA, 2019).

Preliminary meetings with industry professionals demonstrated that modular construction works better for projects with repetitive units like mass housing, hotels, hospitals, etc. and using modular construction for customized buildings or high-end products is not very satisfactory yet. Also, to benefit from economies of scale, factories have to supply units for larger projects instead of small and customized projects. Modular construction is very effective in reducing labor costs in places where there is a lack of skilled workers or onsite workmanship is very expensive. However, in countries where onsite workmanship is relatively low, modular construction may have difficulty in competing.

Transportation of modules is one of the most important aspects because road transportation is a significant constraint due to maximum lane width. Modules exceeding the lane width need police escorts to be transported and the regulations may differ from country to country. A modular construction company may choose to directly transport modules or transport flat-packed units to be assembled in an interim facility to be installed near the project area. However, under such circumstances, a detailed feasibility analysis must be made so that transport and logistics costs do not outweigh the benefits to be gained from modular construction.

2.2 Realized Modular Projects

It is observed that the popularity of modular buildings is increasing across the world due to the wide variety of benefits offered by modular construction such as improved speed of construction, product quality, efficiency of materials, and worker safety while reducing environmental impacts. Some of the outstanding projects have been selected and presented below demonstrating that there is a shift in the construction industry towards prefabricated modular buildings. Instead of the ugly, cheap, and poor-quality image modular buildings had in the past, nowadays they bring sustainability, aesthetics, and high precision to the market.

Figure 2.15. Star Apartments by Michael Maltzan (Michael Maltzan, 2024)

As the selected projects show, buildings made of steel modules are more prevalent in the USA and the UK. In Singapore, concrete structures using PPVC method are more popular, and they have already included prefabrication in their legislation. It is also observed that there is fierce competition to build higher in a shorter time. Thus, six projects are presented below, three of which are made of steel modules, built in the USA and the UK, and the other three are made of concrete modules, built in Singapore.

In the last part of this section, examples of ISO container-based buildings are presented. Four projects have been selected, one of which is a seven-story apartment building. One is a student housing project, another one is a mix-use complex, and the last one is a hotel building. These projects show that ISO containers may offer diverse options for different projects, and proper buildings with convenient spatial organization can be produced using ISO containers. This is a critical aspect for this study, because the ISO container was selected as a sample material for this research. Selected projects show that successful buildings can be produced using ISO containers which are appreciated by their inhabitants.

2.2.1 High-Rise Modular Steel Buildings

2.2.1.1 461 Dean Street – New York

461 Dean Street is the first of many residential buildings at the Pacific Park Brooklyn development. The building, which has 32 floors above ground and 2 floors below ground, was designed by SHoP Architects and engineered by Arup and Partners (Turner Construction Company, 2023).

Clad in glass and multi-colored metal panels, the building is 359 feet (109 meters) high with 363 rental apartments consisting of 930 steel modules (McKnight, 2016). When it was constructed, 46 Dean Street was the highest modular building and the first modular high-rise building in the world. The steel modules, arranged in a total of 23 different configurations, were fabricated off-site at a factory in the nearby Brooklyn Navy Yard and shipped to the site by truck, along with each apartment's countertops, stone backsplashes, and stainless-steel appliances (McKnight, 2016).

The success of the project was attributed to effective pre-planning of construction activities and introduction of new construction means and methods, including an efficient transportation plan that ensured timely delivery of modules to the site (Turner Construction Company, 2023). Turner web page informs that a Tuned

Liquid Mass Damper was installed to reduce structural vibrations and sway during high winds on the site, where the modules were staged, inspected, and hoisted into place to be bolted together. The building was granted an Award of Excellence in 2018 by CTBUH (Council on Tall Buildings and Urban Habitat) (The Skyscraper Center, 2023).

Figure 2.16. 461 Dean Street (Turner Construction Company, 2023)

2.2.1.2 Apex House – London

The web site of the design company, HTA Design, informs that the Apex House building accommodates 558 student rooms on 29 stories (HTA Design, 2023). Construction of the building was completed in 2017, in a record time of 12 months. It was the tallest modular building in Europe then. The self-supporting modules of the building are made from steel frames and a concrete floor, and they were delivered as fully finished internally. The modules were then connected to each other as well as a slip-formed concrete core after being craned into position.

There are a variety of room types and shapes to suit different requirements including wheelchair units and shared social spaces. The facade of the building is finished with terracotta tiling with aluminum cladding infill panels for the flanking wings and polished Glass-Reinforced Concrete with aluminum cladding infill panels for the tower. The building, which has become a local landmark, was granted the following awards:

- Winner, Offsite Awards: Best use of volumetric – Apex House, Wembley
- Winner, Offsite Awards: Offsite Professional of the Year
- Best Residential High-Rise Development
- Winner, Offsite Awards: Offsite Professional of the Year
- Winner, Offsite Manufacture Awards: Housing Project of the Year
- Winner, Building Awards: Offsite of the Year – Apex 2018
- Highly Commended, Student Accommodation Awards: Private Halls of Residence (London) of the Year – Apex 2017
- Shortlist, WAN Awards: Best MMC Project – Apex 2017
- Shortlist, Offsite Awards: Housing Project of the Year – Apex House 2016
- Shortlist, Offsite Awards: Best Use of Concrete – Apex House 2016
- Shortlist, Offsite Awards: Best Use of Steel – Apex House 2016

Figure 2.17. Apex House – London (HTA Design, 2023)

2.2.1.3 Ten Degrees, Croydon – London

With its two towers of 38 and 44 stories, the 135-metre-high Ten Degrees, designed by HTA Design, is currently the tallest modular residential building in the world. There are 546 rented apartments in the building along with a wide range of shared amenities. Completed in 2021, the project was constructed in 39 months with a 67% reduction in carbon and a significant reduction in waste compared to traditional construction methods. In addition, improved quality control ensured high performance during operation. (Architecture Today, 2023)

The towers incorporating almost 1,500 modules were manufactured off-site (Parkes, 2021). Then the modules were delivered to site and stacked on top of each other in a streamlined construction process and reduced disruption to the surrounding area (Architecture Today, 2023). There are seven flats on each residential floor ranging from one to three-bedroom homes, shared spaces such as a rooftop lounge, private dining spaces, a gym, social and leisure facilities, and co-working spaces at the base and top of the building (Parkes, 2021).

Figure 2.18. Ten Degrees Module Layout (Architecture Today, 2023) and Flat Layout (Housing Design Awards, 2024)

Figure 2.19. Ten Degrees, facade construction and exploded window detail (Architecture Today, 2023)

Virtual reality and 3D printing were extensively used for rapid prototyping at the planning stage, especially for the angled modular facade and large format glazed terracotta diamond cladding panels. HTA Design refers to their building "*as a clear demonstration that building tall can be beautiful, whilst challenging any perception that modern methods of construction need be a limit on design quality*" (Architecture Today, 2023).

2.2.2 High-Rise Concrete PPVC Buildings

2.2.2.1 Clement Canopy – Singapore

Clement Canopy is a residential condominium housing 505 two-, three- and four-bedroom apartments spread over two 40-storey blocks, a multi-story car park and a swimming pool at the basement (Block, 2019). 1,899 prefabricated and pre-finished modules were made from concrete, cast in Senai, Malaysia, and then fit out to a nearly finished stage in a factory in Tuas, west Singapore. The fit-out was totally finished before the modules arrived at the site including painting, window frames and glazing, doors, wardrobes and MEP (mechanical, electrical and plumbing) including water and sanitary pipes, electrical conduits and ducting. The modules of the building are connected to a concrete core, which was built in parallel to stacking and installation of the modules. The facades of the towers are made from rendered and painted concrete with aluminum window frames.

Building and Construction Authority of Singapore informs that the basement floor, multi-story carpark and first floor of the blocks are of conventional construction, but the typical floors from 2 to 40 are built with PPVC method (BCA Singapore, 2023). Six-sided concrete PPVC modules were used in the project weighing between 26 tons to 31 tons (BCA Singapore, 2023). Clement Canopy is the first project to use full concrete PPVC units in a building as high as 40 stories, but this made the modules very heavy, so two 48-ton capacity tower cranes had to be used instead of moderate heavy duty tower cranes (Carlisle, 2017).

Figure 2.20. Clement Canopy – Singapore (Block, 2019)

2.2.2.2 Avenue South Residences – Singapore

Avenue South Residences designed by ADDP Architects consists of two 56-story towers, each 192 meters high, with 1,074 residential units (BCA Singapore, 2022a). The building is the highest residential tower built in PPVC for the moment. The PPVC method allowed each tower to be completed in 18 months, at least seven months shorter than conventional methods. The PPVC method also allowed the construction company to work effectively during the pandemic. The modules were manufactured offshore and then installed on-site in Singapore complying with each country’s safety measures. Thanks to precise scheduling, most of the supply disruption challenges during the COVID period were overcome, achieving a seamless and efficient production and installation process.

Pan-United Corporation’s CarbonCure, which is an environment-friendly type of concrete providing 50% reduction in carbon emission, was used in the project in parallel with the Singapore government’s net-zero carbon targets (BCA Singapore, 2022a). Also, the Robotic Installation System for Elevators (R.I.S.E) of Schindler Lifts was applied in which robots drilled holes and set the elevators’ anchor bolts quickly and systematically instead of having workers do such tasks.

Figure 2.21. Avenue South Residences (BCA Singapore, 2022a)

2.2.2.3 Student Hostel at Nanyang Technological University of Singapore

The Student Hostel at Nanyang Technical University of Singapore was completed in 2017 using Prefabricated Prefinished Volumetric Construction (PPVC) method by Santarli Construction Company. According to the web site of the company, *"NTU Residential Hall is the first public high-rise building in Singapore constructed using "Lego-style" that allowed prefabricated individual rooms to be stacked on top of each other"* (Santarli Construction Company, 2023). Up to 25 to 40% of manpower and 15 to 20% of construction time were saved by using PPVC method.

Converted to a design and build contract, the project was re-designed from conventional reinforced concrete structure to a modular system for PPVC in a tight timeline of 20 months including re-design, re-submission to authorities and construction. The team had several challenges in the project such as the inability to change the design once PPVC modules were manufactured, transporting the modules from China where they were manufactured, and optimizing installation efficiency and the cost of site operations. (Zheng Keng Engineering & Construction, 2023).


Figure 2.22. Student Hostel at Nanyang Technological University of Singapore (Santarli Construction Company, 2023)

2.2.3 Buildings Made of ISO Containers

2.2.3.1 Drivelines Studios, Maboneng, Johannesburg

Drivelines Studios project, which is a seven-story apartment building in the Maboneng district of Johannesburg, was opened in September 2017 (Chemaly, 2022). It was constructed with 140 shipping containers. Ranging between 37 m² and 134 m², each apartment supports alternative energy methods including solar panels, geysers, and rainwater collection systems (*Joburg's New Container Homes Open in Maboneng*, 2017). The project was designed by LOT-EK, a New York- and Naples-based company, that is known for reusing retired shipping containers (Chemaly, 2022).

The project offers 104 affordable apartment units and three retail spaces. Whereas the designers normally use a second site for preparing the modules, all works were done in-situ in Drivelines project due to size (Chemaly, 2022).

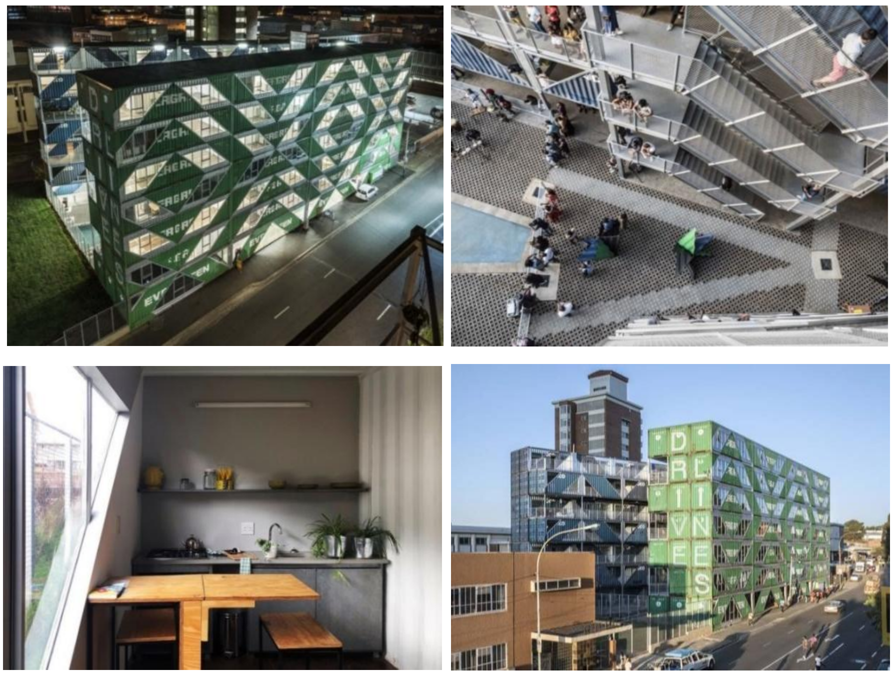


Figure 2.23. Drivelines Studios, Maboneng, Johannesburg (L. Wang, 2018)

2.2.3.2 Keetwonen Student Housing Complex, Amsterdam

Keetwonen is a student housing project in Amsterdam built by TempoHousing (Christensen & Worzala, 2010). It was originally planned as a five-year temporary solution for the students in Amsterdam, but it became so popular that its relocation was postponed. Initiated in 2005, the project has become one of the most popular student housing centers in the city, consisting of 1034 modules in total and including student homes, a cafe, common areas, and a laundry (Martinez, 2017).

With the help of a dedicated production line in China, the project was completed in eight months (Martinez, 2017). Built with 40 ft. containers, the project has a construction area of over 30,000 m^2. The container homes provided an affordable housing alternative for the students, and they were safe enough to satisfy the high building standards in Europe.

Figure 2.24. Keetwonen Housing Complex (Livin' Spaces, 2014)

2.2.3.3 Trinity Buoy Wharf, London

Located on the River Thames, Trinity Buoy Wharf is a center for arts and cultural activities offering studios for rent (Trinity Buoy Wharf, 2023). The web page of the project informs that Trinity Buoy Wharf was an empty and derelict site until it was taken over by Urban Space Management Ltd in 1998. The existing brick buildings were preserved as heritage sites and new buildings were constructed using retired shipping containers by Container City Ltd, a company specializing in container buildings. All fit out works were carried out off site at the Container City warehouse and craned to the site only when the site and the units were ready (Container City TM, 2023).

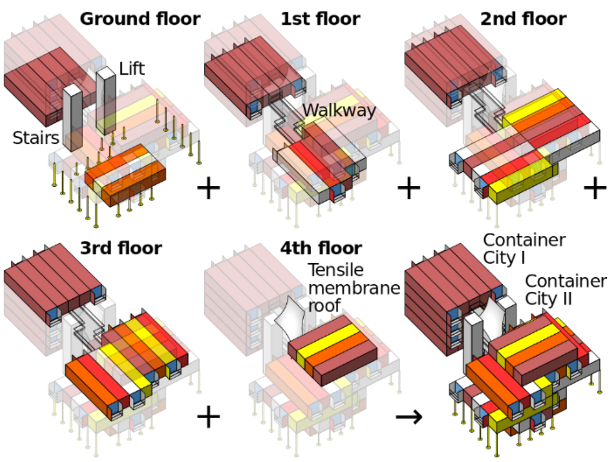


Figure 2.25. Container City I & II, container layout (Wikipedia, 2024)

Figure 2.26. Container City II, London (Trinity Buoy Wharf, 2023)

2.2.3.4 The Travelodge Shipping Container Hotel – Uxbridge, UK

This project was completed by Travelodge, a budget hotel company, using retired shipping containers in August 2008 (Eco Container Home, 2023). It is reported that the 86 container units used in the hotel building were prepared in China with plasterboard walls, and electrical and sanitary installations. The containers were then shipped to the UK, to be stacked and assembled at the site like Lego pieces. After installing the units with bolted connections, windows were fitted, the modules were decorated and furnished, and then the exterior of the building was clad.

It is also reported that Travelodge Company could achieve a 10% reduction in cost and a 25% reduction in time by using container units in its hotel buildings.

Figure 2.27. The Travelodge Shipping Container Hotel – Uxbridge, UK (Eco Container Home, 2023)

2.3 ISO Freight Containers

2.3.1 Introduction

It is unknown how many shipping containers are out there in the world, but there are different estimations such as 65 million (Porta-Stor, 2022) and 37 million (MBI & NPSA, 2017). UNCTAD (United Nations Conference on Trade and Development) reported that 815.6 million TEUs (Twenty-Foot Equivalent Units) of containers were handled in ports worldwide in 2020, and this was even 1.2% lower than 2019 figures due to COVID-19 pandemic (UNCTAD, 2021). The same report expected a 10.1% increase for 2021. International seaborne trade carried by container ships has reached 1.85 billion metric tons compared to 0.1 billion in 1980 (Statista, 2020). 95% of the world's cargo is carried by ships (Saunders, 2017). Another estimation claimed that there were approximately 20 million containers in the world, equivalent to about 30 million TEUs (SG Blocks, 2022a). 5.5 million of these were standard 40' units equaling 2 TEUs, 7 million were 40' HC (high cube) units and 5.5 million were 20' units. More than 90 percent of all containers worldwide are produced by Chinese companies, and half of all containers worldwide belong to container leasing companies (Klose, 2015).

In the book *The Container Principle: How a Box Changes the Way We Think*, containers are defined as the "core and the crowning element of a logic of modularization" under the name globalization—leaving no place on Earth untouched (Klose, 2015). Klose (2015) argues that containers, which cannot be restricted to the realm of transportation of goods and logistics, appear in cultural domains like architecture and urban planning, psychology, philosophy, pedagogy, business administration, communications and information, film, television, theater, and art, in addition to their physical appearance in every imaginable place in the city.

On the other hand, Klose (2015) points at how easily it may be forgotten within the smooth processes of container transportation that it is "*a matter of heavy metal, a* *gigantic technological system of steel and silicon that requires tens of thousands of human workers to function*". It is estimated that several thousands of containers go overboard each year in storms and shipwrecks. Although this is an infinitesimally small figure compared to the total number of containers in circulation, each of them poses danger of environmental pollution or poisoning, collisions with ships, loss of transported goods, etc.

The average life expectancy of shipping containers is about 30 years, but most of the time they are not used for more than 10 years (Berbesz & Szefer, 2018; Cerro, 2015). Most of the time, they are not used for that long (Zhang, 2016). Once retired, a shipping container is classified as "waste" (Christensen & Worzala, 2010). Many authors argue that dockyards are full of empty cargo containers that are ready for sale because sending the empty containers back is more costly than using new containers for export (Anagal & Dhongde, 2017). Berbesz & Szefer (2018) state that 30 million containers are stored in harbors around the world because transporting them to their homeports without a cargo is not cost-effective. It is cheaper to build a new container compared to transporting an empty container (Christensen & Worzala, 2010). In addition, abandoned containers occupy useful space in ports (Nduka et al., 2018).

Zhang (2016) reports that only in 2005, 12,880,000 TEUs went to the United States from Asian regions with 4,540,000 TEUs returning, and the remaining 8,340,000 TEUs waiting for a solution. Mostly caused by unequal cargo volumes in European and U.S. transport from and to east Asia (Klose, 2015), and trade imbalances between countries (Zhang, 2016), these containers pose an environmental issue. Recycling them is not a very environment-friendly option since they are made of steel, which carries a lot of embodied energy (Anagal & Dhongde, 2017). For this, reusing or up-cycling ISO containers is a better choice compared to recycling them as scrap steel, and using these containers as building blocks may be a viable option as well (Zhang, 2016).

According to Mammadov (2015), using shipping containers as structural components of a building can reduce the market demand for structural steel, reducing environmental pollution. Grębowski & Kałdunek (2017) argue that the future of housing lies in prefabrication and fully recyclable materials, and that reusing shipping containers will reduce the concrete waste. Similarly, El Messeidy (2018) defines repurposing cargo containers into homes as a sustainable construction practice because majority of the structure comes from reused materials. Thus, a global surplus item may be reused in a beneficial way (Christensen & Worzala, 2010). Modified shipping containers have been used in the construction industry for a long time, and they may be a potential candidate to solve the housing problem (Ling et al., 2020).

Berbesz and Szefer (2018) identify container architecture as a contemporary type of architecture that makes use of steel shipping containers as the primary construction element. The authors noted that the growing interest in using containers in architecture led to a new term that is "cargotecture". Coined in 2003 (Tiger Containers, 2016), cargotecture is defined as "*the partial or complete reuse of ISO-certified shipping containers, also called cargo containers, for constructing fully operational buildings, commercial spaces, and housing*" (Wilson, 2020). Wilson (2020) argues that these buildings economically utilize used shipping containers, which would have otherwise simply been discarded. Thus, the need for expensive raw materials requiring environmentally destructive processes to extract and refine is eliminated. Wilson (2020) further argues that cost-effective, time-effective, versatile, and secure modular buildings are produced by cargotecture, fitting together in unique and customizable ways. The biggest advantage cargotecture provides is utilizing containers that would otherwise be sent for scrap (Tiger Containers, 2016).

Klose (2015) argues that the key principle of modern logistics is rationalization, which means modularizing, standardizing, and mechanizing, and automating the promotion and processing of goods according to the principles of Ford's factory. Thus, the same principles may be applied in finding solutions to the housing problem in the world. At this point, Klose refers to Le Corbusier and the concept of the architectural cell, with biological connotations of the cell as the basic building block of life. According to Klose (2015), Le Corbusier saw the future of building in industrialization, in the use of rationalized working methods and mechanized mass production, similar to the factories of Ford Motor Company. Klose argues that Le Corbusier's quest for a new architectural aesthetic brought him to the prefabricated, standardized modular room. Thus, long before its technological realization in transport logistics, Le Corbusier showed how cells could be stacked in the container principle. He called the houses he designed as "machines for living" (Wolfe, 1981). This should not be misunderstood as a mechanistic 'machine aesthetics', because it means rationality in planning, a capacity of serial-production, and function (Thames and Hudson, 1963).

In his book, Klose (2015) addresses objections against a dictated from above building culture, unresponsive to the actual needs of residents and local conditions. Although there are many who claim that container and box architecture of high-rise ghettos is largely responsible for the social ills, he argues that it is more relevant how they are managed, rather than how they are built. He exemplifies cases from Berlin, Paris, and the USA, stating that East German slab housing complexes allowed a high degree of social mixing, but large high-rise buildings on the fringes of Paris and many of the housing projects in U.S. cities became spatially isolated and crime-prone areas.

2.3.2 Definition of ISO Containers

Although a container is a general expression for all kinds of objects, such as a bowl, a barrel, a bucket, a box, or a car, or even a bag, pouch, or pack that can enclose something (Klose, 2015), it has been widely associated with the steel box used to carry cargo in different modes of transit. Bureau International des Containers (BIC), which distributes the codes for all containers worldwide, defines a container as follows (Klose, 2015):

> *"Means of transport (box, removable tank, or similar transport vessel), that*
>
> a. *is of durable construction and resilient enough to be used repeatedly;*
> b. *is especially constructed to ease the transport of goods through one or several modes of transport without repacking the cargo;*
> c. *is equipped for easy handling, particularly when transferring from one mode of transport to another;*
> d. *is built such that it can be loaded and unloaded easily…."*

Klose (2015) argues that the container is not a vehicle or an ordinary packaging material, but it is a means of transport, which separates the transport vehicle and the cargo, eliminating the interruptions caused by the intermodal transfer processes. Different names, such as "shipping container", "ISO container", and "Conex box", may be used to designate cargo containers, but they are called as Intermodal Steel Building Unit (ISBU) when used in construction (El Messeidy, 2018).

ISO compliant shipping containers are made of corrugated steel, resistant against weathering and corrosion, with double leaf doors at one end (Grant, 2013). Frames and transverse elements are made of 4 mm-thick steel profiles, and the outer walls are made of trapezoidal metal sheet with 28 mm wood plates or plywood used as flooring (Berbesz & Szefer, 2018). Cor-ten (corrosion resistant and high tensile) steel is used in the production of ISO containers (Anagal & Dhongde, 2017), which is a genericized trademark for weathering steel. Weathering steel is defined as "*low-alloy* *steels with a carbon content of less than 0.2 wt. % to which mainly Cu, Cr, Ni, P, Si and Mn are added as alloying elements to a total of no more than 3-5 wt. %*" (AZO Materials, 2016). These alloys have a specially formulated chemical composition that allows an early formation of a rust/iron oxide layer which acts as a weather protective coat to the underlying steel. The corrosion rate of weathering steel is so low that a 120-year design life can be achieved with minimal maintenance without any need of protective painting. Elimination of the requirement of paint reduces production time as well as the amount of volatile organic compounds released into the atmosphere (AZO Materials, 2016).

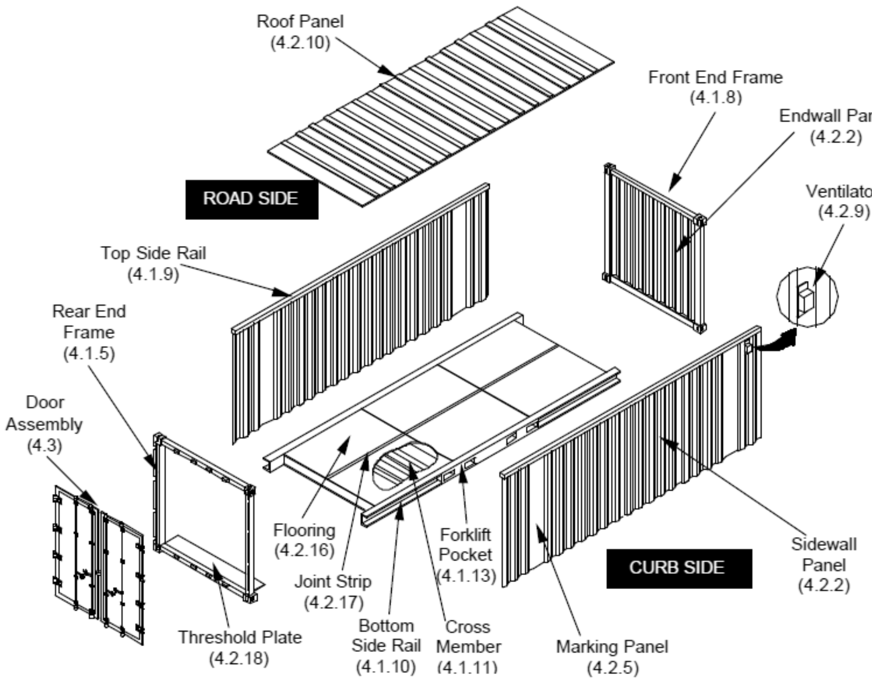


Figure 2.28. Components of Containers (US Department of Defense, 2002)

Shipping containers, which are watertight and airtight structures designed to withstand extreme climates, are used for transporting cargo from one place to another by road, air, or waterways (Anagal & Dhongde, 2017). The whole unit is sealed by the gate at the end, which is equipped with bolt locks, and the high-quality materials that are used in the construction of units allow resistance to all atmospheric conditions, heavy load, and transportation (Berbesz & Szefer, 2018). Shipping containers' specifications, structural strengths, serviceability, and applications are regulated by the International Organization for Standardization (ISO) and the International Convention for Safe Containers (CSC) (Giriunas et al., 2012).

2.3.3 History of ISO Containers

Klose (2015) argues that the myths of various peoples support the thesis of containers as creators of culture. He states that most creation stories have a container metaphor, which is often equated with a womb. In the book 'The City in History', written by Lewis Mumford (1961), the author compares the masculine nature of Paleolithic tools and weapons to the feminine dominance of the Neolithic period, when containers emerged as important tools of civilization. During this era, containers were important to preserve and store any surplus. According to Klose (2015), the amphorae were the containers of ancient times and barrels were the same for Middle Ages. The author calls the Roman amphora, which had coded inscriptions telling place of production, ownership, contents, and transport routes, as the first "modern" transport container. However, he adds that neither amphorae nor barrels had the standardization that is the core structural element of the modern transport container.

Before intermodal shipping containers became an industry standard in maritime trade, boxes of various sizes were used for shipment of goods, carried by workers manually (Placek, 2022). This was an inefficient, expensive, and time-consuming way, and it made loading cargo on different modes of transport very difficult. The need for standardization of container equipment for handling goods goes back as far as 1780s (Brandt, 2011). Brown Industries, which is credited for having built the first shipping containers for use on trains and ships, started experimenting with lightweight aluminum trailer bodies in 1926, and the first refrigerated container was created by Henry Werner and Joe Numero in the 1930s (Brandt, 2011).

The World Automobile Congress held in Rome in September 1928 was a decisive point where ways to integrate railway and road transport into a transport association were examined for the first time (Klose, 2015). This led to the introduction of the transport container, a box detached from the chassis, which could be carried on both railway platform cars and truck trailers. Soon, ships would be "built around the cargo", evolving into container ships. Bureau International des Containers (BIC) was founded in Paris on 22 February 1933, which still distributes all serial and identification numbers of containers in the world (Klose, 2015).

Figure 2.29. Sea-Land Company's FAIRLAND container ship in 1966 (Buitendijk, 2016)

The first standardized intermodal shipping container was introduced in the 1950s, when Malcolm McLean, a trucking giant from North Carolina founded the Sea-Land company and introduced the world's first container ship (Brandt, 2011). Time and cost of shipping were reduced, and easy movement of containerized goods between different means of transport was enabled (Placek, 2022). Thus, standardized container dimensions of McLean made loading and unloading freight faster and more organized, reducing the costs by more than 90% and ultimately reducing consumer prices (Christensen & Worzala, 2010). And the traditional view of a port, which remained more or less the same since the Phoenician trade ships in the Mediterranean some 3,000 years before with a clutter of bags, bales, barrels, and crates, turned into one with large, standardized containers (Klose, 2015). When the International

Standards Organization (ISO) shipping container was introduced in 1970, the worldwide container design became standardized (Grant, 2013). After around 1970, container transport expanded as a sea-land network and became the dominant form of cargo shipping (Klose, 2015).

2.3.4 Structure of ISO Containers

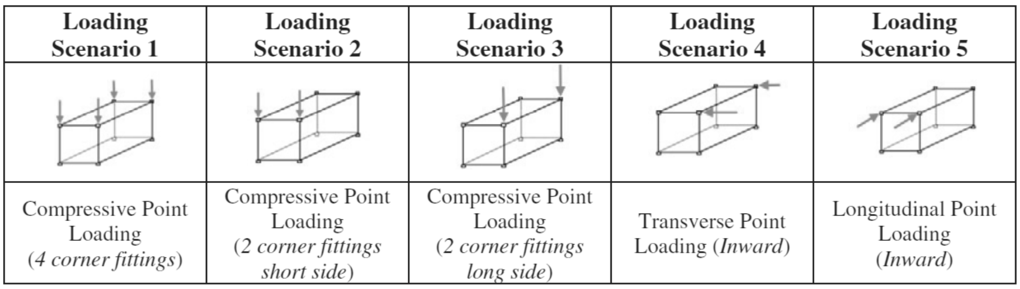
To meet structural and architectural demands, off-site manufactured modular building systems or hybrid-modular building systems usually require additional support structures, a lot of on-site assembly and a considerable amount of post construction finishing works (Srisangeerthanan et al., 2020). However, a container is a monocoque structure, which means that structural support is provided by the exterior skin of the unit (Anagal & Dhongde, 2017). Unlike a traditional frame structure where load is transferred to the frame and the skin only acts as a safeguard against external conditions, the load is carried by the whole unit in a monocoque structure, including the skin (Anagal & Dhongde, 2017). The skin is made of corrugated steel sheets, ranging between 25, 30, and 50 mm, depending on the model and surface of the container where deeper corrugation provides higher inertia and more rigidity (Elrayies, 2017).

Thus, the frame and the walls enable load bearing reinforcement, withstanding dynamic and static loads (Grant, 2013). In this way, load bearing skin of a monocoque structure reduces the weight of the unit significantly without compromising the load bearing capacity; however, modifications in the skin of the container will affect the structural integrity of the container (Anagal & Dhongde, 2017). Therefore, each hole in the skin will compromise the structural integrity, and minor reinforcements need to be made if entire panels are to be removed (Gręgowski & Kałdunek, 2017), and it is advised to place the openings rather far from the corner posts (Zafra et al., 2021).

In the ISO containers, vertical loads are transferred through the corner columns, which are laterally restrained by the steel walls against buckling, whereas horizontal loads are transferred through the sidewalls (Anagal & Dhongde, 2017).

Figure 2.30. Transfer of vertical loads in containers (Anagal & Dhongde, 2017)

Starting with an argument that shipping containers' structural integrity, modification properties, foundation requirements, building code regulations, and reinforcing limits are mostly unknown, Giriunas et al. (2012) published an article called "Evaluation, modeling, and analysis of shipping container building structures", with a view to develop structural guidelines for International Organization for Standardization (ISO) related to shipping containers used for non-shipping applications. The authors conducted finite element computer model simulations of shipping containers, modeling and analyzing the containers in SolidWorks, Hypermesh, and Abaqus/CAE programs, and examined the behavior of ISO containers under 5 loading scenarios given in the figure below.



Loading Scenario 1	**Loading Scenario 2**	**Loading Scenario 3**	**Loading Scenario 4**	**Loading Scenario 5**
Compressive Point Loading (*4 corner fittings*)	Compressive Point Loading (*2 corner fittings short side*)	Compressive Point Loading (*2 corner fittings long side*)	Transverse Point Loading (*Inward*)	Longitudinal Point Loading (*Inward*)

Figure 2.31. Five loading scenarios simulated on shipping container models (Giriunas et al., 2012)

Analysis results were as follows (Giriunas et al., 2012):

- In Loading Scenario 1, removal of sidewalls or the roof did not affect the maximum applied loading values. Most critical load resisting components under Scenario 1 were the end walls, carrying loads more effectively compared to the sidewalls. The impact of removing only one end wall was higher than removing both sidewalls.
- In Loading Scenario 2, the most critical load resisting components were the sidewalls, where the end walls had a lower effect. The roof did not have a significant effect on stiffness or strength in Scenario 2.
- In Loading Scenario 3, the most critical load resisting components were the end walls. The sidewalls also carried a significant load and provided stiffness, especially in the absence of the end walls.
- The roof had no significant contribution in carrying vertical point loads (Scenarios 1 – 3).
- In Loading Scenario 4, the most critical lateral load resisting components were the end walls. Lateral capacity of the sidewalls and the roof was very low, and the roof had little resistance without walls.
- In Loading Scenario 5, the most critical lateral load resisting components were the sidewalls. The existence of the roof significantly increased the rigidity.

Thus, Giriunas et al. (2012) reached the following conclusions:

- Axial/vertical loads applied on the top corner fittings: the end walls are the strongest load resisting components, the sidewalls are the next strongest load resisting components, and the roof has no structural contribution.
- Transverse lateral loads applied on the top corner fittings: end walls are the strongest load resisting components.
- Longitudinal lateral loads applied on the top corner fittings: the sidewalls are the strongest load resisting components.

- The roof generally has no structural contribution for lateral loads.
- When the walls in the direction of loading are removed, lateral resistance of the container structure is significantly reduced.

Giriunas (2012) states that shipping container structures usually do not require strong foundations because they are structurally very stable. They usually must conform to standard foundation requirements. Giriunas' work on the structural attributes of shipping containers was used by others such as Ntumi (2018), who aimed to develop a computer model that can reasonably predict the structural behavior of ISO containers. Later, some other researchers performed their own finite element analyses. Although the results were mostly similar, there were some discrepancies. For example, Zafra et al. (2021) found that the roof of the container also contributes to resisting the load, contrasting to the results of Giriunas who argued that the roof did not have any structural contribution for lateral loads.

2.3.5 Connections of ISO Containers

Srisangeerthanan et al. (2020) argue that connections of modular buildings should (i) endure the required level of stress without losing function, (ii) maintain function at the beginning of degradation, (iii) be simple enough for easy recovery, and (iv) be easily replaceable to achieve structural resilience.

Klose (2015) found the similarity between containers and Lego blocks striking. An infinite number of solutions may be produced, starting from a very rigid given. Compared to other modes of modular construction, volumetric modules may have the greatest potential to achieve complete building systems by reducing on-site work to foundations, module assembly and finishing module-to-module interfaces, but they have certain technical, logistical, and regulatory issues as well (Srisangeerthanan et al., 2020). Inter-module connectivity is one of the issues in container buildings, because stiffness, strength, ductility, and other mechanical properties of connections influence overall serviceability, strength, safety, and stability of structures to a high degree (Srisangeerthanan et al., 2020).

Stacked containers are either connected to each other or to the foundations (Shen et al., 2020). The most common connection to foundations is using a steel base plate with welds, with reinforcing bars (anchor bolts) on the underside of the base plate, which are cast into concrete foundations (Giriunas, 2012). To connect two containers, twist locks and latch locks are used for securing the containers during stacking, transporting, or lifting empty containers (Giriunas, 2012). They may be permanently welded as well (Shen et al., 2020).

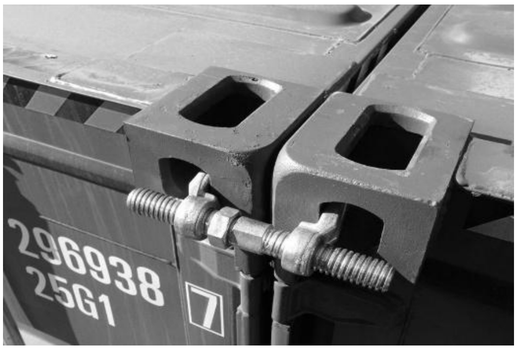


Figure 2.32. Container bridge fittings (Twistlock Africa, 2024)

Table 2.4 ISO 3874 Structural Limitations for Container Connection devices (Giriunas, 2012)

	Tensile Strength	**Tensile Strength (Lifting)**	**Compression Strength (Intermediate Plate)**	**Compression Strength (Cones)**	**Shear Strength**
Twist Locks	150 kN (33.7 kip)	178 kN (40 kip)	850 kN (191 kip)	150 kN (33.7 kip)	300 kN (67.4 kip)
Latch Locks	150 kN (33.7 kip)	178 kN (40 kip)	850 kN (191 kip)	150 kN (33.7 kip)	300 kN (67.4 kip)
Stacking Fitting	0 kN (0 kip)	0 kN (0 kip)	850 kN (191 kip)	150 kN (33.7 kip)	300 kN (67.4 kip)

2.3.6 ISO Container Types

Shipping containers have a wide variety of available sizes such as universal/standard, HC (High Cube), PW (Pallet Wide), and Open Top containers (Berbesz & Szefer, 2018). However, the most widely used containers measure 2.44 m wide by 2.44 m high, and 6.1 m (20 ft.) or 12.19 m (40 ft.) long (Grant, 2013). Dimensions of the cargo containers are necessitated by the requirements of intermodal transport, which may be a ship, a train, or a truck (Edis, 2022). The most suitable type for construction is the 40’ High Cube.

Table 2.5 Dimensions of 40’ HC ISO Container (Ling et al., 2020)

Dimensions		**40’ HC**
External (mm)	Length	12,192
	Width	2,438
	Height	2,896
Internal (mm)	Length	11,998
	Width	2,330
	Height	2,655
Rating (kg)	30,480	

20' General Purpose

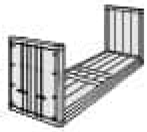
Inside Length	Inside Width	Inside Height	Door Width	Door Height	Average Weight
5.882m	2.332m	2.387m	2.332m	2.261m	2350Kg

20' Open Top

Inside Length	Inside Width	Inside Height	Door Width	Door Height	Average Weight
5.890m	2.311m	2.340m	2.286m	2.184m	2680Kg

20' Flat Rack

Inside Length	Inside Width	Inside Height	Door Width	Door Height	Average Weight
5.620m	2.200m	2.219m	-	-	2960Kg

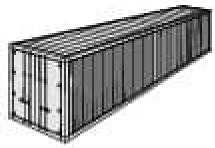


20' Reefer

Inside Length	Inside Width	Inside Height	Door Width	Door Height	Average Weight
5.456m	2.294m	2.273m	2.290m	2.264m	3050Kg

40' General Purpose

Inside Length	Inside Width	Inside Height	Door Width	Door Height	Average Weight
12.022m	2.332m	2.385m	2.333m	2.260m	4020Kg



40' High Cube

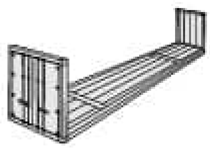
Inside Length	Inside Width	Inside Height	Door Width	Door Height	Average Weight
12.031m	2.350m	2.667m	2.336m	2.585m	4200Kg

40' Open Top

Inside Length	Inside Width	Inside Height	Door Width	Door Height	Average Weight
12.028m	2.348m	2.331m	2.337m	2.274m	4250Kg

40' Flat Rack

Inside Length	Inside Width	Inside Height	Door Width	Door Height	Average Weight
12.080m	2.438m	1.978m	-	-	5480 Kg



40' High Cube Reefer

Inside Length	Inside Width	Inside Height	Door Width	Door Height	Average Weight
11.584m	2.294m	2.294m	2.284m	2.437m	4900Kg

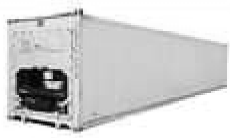


Figure 2.33. Container Sizes & Dimensions (SLR Shipping, 2024)

2.4 Use of ISO Containers in Construction

Using shipping containers for architectural purposes is not a brand-new concept, as they have been used in a widespread manner especially for temporary buildings such as post disaster housing, site buildings, etc. There have been attempts to use containers as building blocks for permanent buildings as well. In 1989, Phillip C. Clark issued a patent application for a "Method for converting one or more steel shipping containers into a habitable building at a building site and the product thereof" (Berbesz & Szefer, 2018). This patent provides step by step instructions for assembling shipping containers on a foundation, removing inner sidewalls, and installing a roof, ceiling, windows, and doors (Brandt, 2011).

Containers are exposed to harsh sea conditions and handling when used for transportation purposes, and the average life span is 10 to 15 years (Grant, 2013). Most containers are retired after 10 years of use (Cerro, 2015). Each year, around one million containers are retired from the transport sector, and approximately 300,000 to 500,000 of these are reused in various areas, one of which is modification of shipping containers for building purposes (Grant, 2013). Containers used in building construction or storage are called as ISBU (Intermodal Steel Building Unit) Module or a GreenCube (Grant, 2013). Using containers in building construction has two main advantages as follows:

1. Reusing ISO containers in building construction mitigates the environmental burden created by disposal of these container units.

2. Using retired containers instead of new construction materials creates economic benefits.

There are disadvantages, such as the need for insulation to achieve thermal comfort and avoid corrosion and condensation, related to using retired containers. They restrict the flexibility of design due to standardized container forms. Mammadov (2015) argues that both the energy consumption required to sustain indoor comfort and the construction cost of using shipping containers as a building envelope must be taken into consideration when studying the feasibility of using shipping containers as a cost-efficient source in building construction.

There are opposing views with respect to reusing ISO containers in building construction. For example, Grant (2013) negates the idea arguing that "*the transformation of a steel box is an eco-romance where one takes the excesses of capitalism and through human ingenuity transforms them into a serviceable object*". Similarly, Anagal & Dhongde (2017) state that containers are not manufactured for architectural application, although they have a potential for providing a habitable space. However, the same authors also argue that retired cargo containers can be upcycled to be used for housing purposes, and this will reduce the environmental impact of these containers by extending their useful life. The embodied energy of using new containers may be higher than other building materials because the containers are made of materials which require large amounts of energy for production (Grant, 2013), but hundreds of thousands of ISO containers are retired each year, and disposal of these is a big environmental issue. Similarly, Cerro (2015) claims that despite the amount of energy required to make a container habitable, building with container units is still a good idea, because it solves the essential pre-requisites of production at a minimum cost. And El Messeidy (2018) argues that buildings made from repurposed containers have a smaller carbon footprint and create less landfill, creating a lower environmental impact compared to traditional buildings. AbuMoeilak & Taleb (2018) further argue that shipping containers are "*outstanding modular units with intrinsic strength, weatherproof capability, and availability, which make them ideal for conversion into cost-effective housing units*". The authors see the shipping container as an intrinsically sustainable unit that can be used to resolve the housing shortage.

Thus, the idea of reusing ISO containers in building construction has more potential to explore, and it shouldn't be discarded so lightly. Turning old industrial objects like shipping containers into living space has many benefits including sustainability, eco-friendliness, cost-effectiveness, quick installation and durability, flexibility, customizability, and safety (Wilson, 2020). The industry has already started organizing for reuse of idle containers. For example, Maersk Line established a business area for the sale of used containers (Shen et al., 2020). In addition, many conversion projects have already been realized in several sectors such as commercial, social, residential and even education, without compromising building aesthetics (Risnandar & Primasetra, 2021).

A study conducted in Nigeria explored the perspectives of construction industry professionals on the reuse of shipping containers in house building (Nduka et al., 2018). In this study including architects, builders, civil engineers, and quantity surveyors working with construction firms engaged in containerized buildings, the authors questioned the “enablers of use of shipping containers in building” and the “challenges limiting the use of shipping containers for building construction”. The highest-ranking enabler was the “speed of construction”, and the highest-ranking challenges were “low awareness of public to the use of containers as building material” and “low acceptability by general public”. The study also recommended the development of competency in construction of shipping container homes in the industry professionals, as well as awareness among related professional bodies and government agencies towards ISBU, especially developing countries.

Using shipping containers as housing creates psychological and sociological challenges such as concerns related to individual privacy, crowding, human territoriality, and spatial behavior (Brandt, 2011). However, they also have the potential to manifest unique and outstanding architectural features, when creatively designed as a whole building (Pereira-De-Oliveira et al., 2022). Thus, these are aspects that need to be mitigated by the quality of architectural design and good technical solutions. The complex relationship between the perceived space and real size of a dwelling unit is very dependent on proper organization of space and rooms (Jelenic & Petrovcic, 2021).

2.4.1 Advantages of ISO Containers

Shipping containers can be considered as a structural frame, into which the architectural and engineering design can be integrated in accordance with the requirements (H. Islam et al., 2016). A US based manufacturer website indicates that they can work with any facades used in traditional construction including limestone, stucco, shingles, brownstone, brick, and aluminum siding (SG Blocks, 2022b). They can work with standard or custom finishes, and fit doors and windows to meet the customer's design. Anagal & Dhongde (2017) identify seismic stability, modularity, transportability and demountability as the benefits of using steel containers in construction. The authors indicate that most of the work is carried out off-site, which saves time and labor on on-site works. Similarly, Trancossi et al. (2018) argue that container based modular construction is 40-60% faster, produces 70% less onsite waste, and reduces cost substantially compared to traditional construction. Thus, major advantages of using shipping containers in building construction are given below.

2.4.1.1 Environmental Performance: Energy Saving and Waste Reduction

Negative effects of the construction industry, such as resource extraction and infrastructural development are major causes of concern that may damage fragile ecosystems (AbuMoeilak & Taleb, 2018). It is reported that the construction industry is responsible for 36% of overall energy utilization and 40% of CO_2 discharges globally and manufacture and transportation of materials have a significant share in this (Haque et al., 2022). Tumminia et al. (2018) argue that material production phase alone is responsible for 70-90% of the total environmental impact of a building, therefore it is important to choose construction materials with lower environmental impacts.

A major environmental benefit of using shipping containers in construction is the solution it provides for the problem of how to dispose of the thousands of redundant containers around the world. Container steel is not a decomposing material to be used in landfill and melting it into raw steel requires very high amounts of energy and emits greenhouse gases (H. Islam et al., 2016). Reusing the containers keeps them out of the waste stream (Wilson, 2020), so it is a more environment-friendly option compared to scrapping them because they carry a lot of embodied energy (Anagal & Dhongde, 2017). Reusing the steel container reduces the environmental impacts associated with melting them down (Haque et al., 2022), in addition to reducing the energy used in the prefabrication (welding) of new containers for house building (Satola et al., 2020). This also reduces the consumption of energy and natural resources required for the production of construction steel (Pereira-De-Oliveira et al., 2022), as well as the need for other construction materials such as brick, mortar, wood, etc. (Haque et al., 2022). H. Islam et al. (2016) report that the ratio of recycled materials used in a container house can be as high as 75%.

H. Islam et al. (2016) report that a 3.63 t shipping container requires 8000 kWh of electrical energy to be converted into steel blocks, whereas it takes only 400 kWh of energy to reuse that entire container for building a house, which is only 5% of the energy required to melt it. The authors further state that 2 t of CO_2 and 40 kg of other gaseous emissions are released during production of one ton of steel, which later requires 24.4 GJ of embodied energy to be recycled.

Zhang (2016) conducted a life cycle assessment on utilizing used shipping containers in the building sector and concluded that it is a more environment-friendly solution than re-melting them for steel. Although there are uncertainties in the estimations, results of this study showed that reusing shipping containers as steel frames for housing could save 90MWh (34%) in embodied energy, compared with using virgin steel, and 2.9MWh per year (26%) to 3.9MWh per year (34%) operating energy if well insulated. Zhang also found that one reused shipping container structure with four containers could save 346.2GJ embodied energy compared to four new shipping containers or virgin steel frame. And the embodied energy needed for re-working the shipping container and removal of hazardous materials was much less than the savings from steel. Zhang concluded that it would be clearly energy-efficient to build houses using retired shipping containers.

Shen et al. (2020) endorse this view by arguing that reuse of containers in building construction reduces the embodied energy compared to conventional buildings. Similarly, H. Islam et al. (2016) report that reusing shipping containers is an ultimate step in sustainability due to the drastic drop in embodied energy compared to conventional buildings, and the reduction in the new materials required. In a comparative LCA performed by Bertolini & Guardigli (2020), results showed that up-cycling of shipping containers delivered overall environmental benefits in all impact categories compared to steel frames in any climate condition. A potential reduction in general global warming ranging from 15% to 19% could be achieved by up-cycling of shipping containers with a reduction of 20–25 tons of CO_2 equivalent in comparison to steel frames, but it was critical to reduce transport distances to maximize the benefits.

Another advantage provided by using shipping containers in construction is the elimination of wet construction and water use (Nduka et al., 2018). Contemporary container architecture allows sustainable growth by designing objects that are respectful of the natural environment (Berbesz & Szefer, 2018). A significant amount of natural resources may be preserved by using container units in construction because the construction doesn’t have to start from scratch and the need for raw materials is reduced (Wilson, 2020). For instance, the building industry cuts down hectares of forests every year, uses $1/6^{th}$ of fresh water and $2/5^{th}$ of liquid fuel resources (Berbesz & Szefer, 2018). Using shipping containers can balance CO_2 emissions and reduce the demand for natural resources (Berbesz & Szefer, 2018).

Schiavoni et al. (2017) made another life-cycle analysis of using end-of-life or disused containers in terms of primary energy consumption, greenhouse gas emissions, lighting, and acoustic criteria. The authors examined three different materials for external coating: Corian, Corten and Plywood. The authors found that plywood coating was the best configuration in terms of energy efficiency, and the specific consumption decreased as the building size increased. The authors attributed this to the reduction in the S/V ratio.

Research related to the full life cycle of prefabricated buildings is limited for the moment (Satola et al., 2020) and most of the studies focus on construction stage. However, operation and end of use stages are starting to attract more attention as well. In a paper exploring innovative approaches and methodologies for sustainable container designs in different climatic zones, AbuMoeilak & Taleb (2018) concluded that the main objective of sustainable building design had to be to reduce total primary energy needed for ensuring comfort by using renewable resources. Similarly, Trancossi et al. (2018) claimed that with an accurate design process, A+ class energy saving could be achieved.

In a life cycle assessment comparing various energy efficiency designs of a container-based housing unit in China, Satola et al. (2020) found that the end-of life stage impacts of all designs they worked on were represented by negative values, which meant that the environmental benefits created by recycling of construction materials were higher than the environmental impacts of building demolition, waste transport and treatment, and landfill processes. However, demolition-related data concerning prefabricated buildings is scarce for the moment because most of the prefabricated buildings are still in operation (Jin et al., 2020). Satola et al. (2020), who based their research on a single building pointed at the necessity to also assess an interconnected group of buildings.

Dara et al. (2019) made a life cycle assessment on container housing in Canada, using nine impact categories: global warming potential, smog potential, primary energy use, fossil fuel consumption, acidification potential, human health particulate, ozone depletion potential, eutrophication potential, and solid wastes generation. The assessment was based on a case study comparing the life cycle impact of a container-based modular house to that of the conventional lightwood house built in Canada, covering phases of pre-use (production and manufacturing), use and operation, end of life, and total LCA. The analysis made by the authors shows that results are very close between a container and a lightwood house, and between an improved container and an improved lightwood house. This shows that retired shipping containers may well be used as a structural replacement for conventional methods. The results also show that use/operation phase dominates the life cycle environmental impacts with 95%, which is consistent with the general literature (Tumminia et al., 2018). Dara et al. (2019) state that the impact of the end-of-life phase is negligible, and the ratio of the impact of the pre-use phase increases in improved models because the impact of use and operation phase significantly decreases in these models.

2.4.1.2 Structural Stability of ISO Containers

Shipping containers are built against the harsh conditions of seafaring. They must bear extreme dynamic loads from all directions created by the waves. Miller (2019) argues that steel containers are "virtually indestructible" because they are designed to carry tons of merchandise across rough ocean tides. He states that containers are an excellent choice for building construction in areas prone to natural disasters as they are resistant against earthquakes and hurricanes. Wilson (2020) similarly argues that containers are extremely secure against breaking in and safe against natural disasters. Corrugated steel walls used in shipping containers resist highly against external forces (Chen et al., 2021), and the structural composition of the containers allow generous cantilevers (Elrayies, 2017). In addition, container structures have a robust seismic response even during significant earthquakes (Chen et al., 2021).

Anagal & Dhongde (2017) indicate that there is no consensus in the literature about how many units may be stacked on top of each other. However, they found that up to 9 containers would be stacked above each other in ships, and 5 containers would be stacked above each other in ports. Several other sources confirm that containers may be vertically stacked up to 9 levels (Cerro, 2015; El Messeidy, 2018). In any case, ISO norms require that containers should be able to support at least six other containers over with maximum load (Bernardo et al., 2013).

Zhang (2016) argues that used shipping containers are particularly advantageous over other alternative building materials because they are inherently strong. He reports that a shipping container is strong enough to bear loads of 1.7 t/m^2 whereas the expected strength of a normal building is only 0.25 t/m^2. He further argues that physical properties of shipping containers satisfy the technical and regulatory requirements as building frames, and it is especially advantageous to reuse shipping containers for housing near ports, where there are many surplus shipping containers.

Bernardo et al. (2013) argue that calculation of structural projects related to container buildings is not easy using the currently available resources due to lack of tabulated values and lack of experience about the structural behavior of shipping containers. Still, there is a general understanding in the literature that shipping containers are structurally quite fit to be used in building construction.

2.4.1.3 Cost-effectiveness and Construction Speed

Most researchers in the area argue that using shipping containers in housing construction provides both time and cost reduction. A manufacturer web-site claims that using containers and prefabricated construction options can reduce construction time by 40%, and construction costs by 10-20% (SG Blocks, 2022b). Wilson (2020) argues that the cost of a cargotecture construction project is around 30% less than a traditional project. Studies have also revealed that using shipping containers becomes more feasible as the number of stories increase, compared to single story construction (Nduka et al., 2018).

Berbesz & Szefer (2018) advocate using shipping containers in building construction due to the wide choice of available sizes and ease of modification. The authors argue that the containers are ideal for designing buildings for housing, service and commercial, office, recreational, cultural, and even medical functions. Similarly, AbuMoeilak & Taleb (2018) view the container as an ideal unit to be used in social housing due to its modularity. According to Berbesz & Szefer (2018), container-based construction has an undeniable advantage from an economic point of view due to lower building costs, easy transportation, and short assembly time. The authors claim that significant reduction in construction cost and time can be achieved through use of shipping containers, such that a traditional house of 135 m^2 which costs about $115,000–$126,000 in Poland can be produced at around $15,000 using containers.

Whereas it takes months to build a traditional structure, a container structure may be built in weeks because it is basically a prefabricated building (Miller, 2019). Especially in cold climates, where long and cold winters make it difficult to carry out construction works, using standardized prefabricated modules will shorten construction time significantly (Sun et al., 2017). In addition, the inherent design of containers, which is made according to intermodal shipping requirements, provides ease of transportation (Wilson, 2020).

Flexibility and customizability are further advantages of container structures and stacking multiple containers to design various layouts offer spatial flexibility (Wilson, 2020). Further extensions may always be added due to the modular nature of the shipping containers (Radwan, 2015). Sawyers (2005) states that if trimmed neatly, the steel squares removed from side walls for openings may be used for other purposes such as shower stalls, new interior walls, porch coverings, small roofs, small outbuildings, storages, and miscellaneous utility parts, thus providing additional cost savings.

A study made to explore the potential of using shipping containers as low-cost housing for resettlement projects in Sri Lanka showed that 60% of construction costs could be saved by using containers instead of traditional construction methods (Ishan et al., 2019). 68,812 families living in 1,499 underserved settlements were identified by the Urban Development Authority of Sri Lanka in a survey conducted in 2010 and 2011. These families lacked a healthy environment and access to basic infrastructure facilities such as clean water, electricity, and sanitation. Thus, a program was planned to construct 68,000 housing units for resettlement of these dwellers with an intention to increase their living standards in addition to liberating the prime lands presently occupied by them. In this project, the average costs of conventional and container-based housing units were calculated as 4,200,000 Rupees (7,336 Rs/ft^2) and approximately 1,745,000 Rupees (3,878 Rs/ft^2) respectively.

In South Africa, Botes (2013) found that a single-story solution was more costly than a small brick and mortar home, but the multi-story solution was more feasible than the concrete three-story structure. Also, ISBU houses could be built 3 times faster compared to the traditional house.

2.4.2 Considerations Related to ISO Containers

2.4.2.1 Preparation of the Containers and Labor Requirements

Sawyers (2005) compares buying used containers to buying cars. He recommends a complete visual inspection checking the following points:

- There should be no cracks, breaks, cuts, tears, punctures, corrosion in the corner fitting joints, sidewall joints, and floors.
- There should be no missing, cracked, or broken welds at any major structural juncture.
- There should be no loose or missing fasteners at any major structural juncture.
- There should be no deformations such as dents, bents, or bowing.
- Old repairs such as welded steel patches should be checked.
- It should be checked that the container is square with no warping.

Preparatory works may include sandblasting of the structure, floor replacement, cutting openings with a torch or saw, and steel rust protection (Zhang, 2016). Hazardous chemicals used in production of shipping containers, such as lead-based paints on the walls and arsenic in the flooring material (Wilson, 2020) need to be removed as well as the harmful chemicals used in coating the body and preserving the wooden floor against infestation in the ocean (Nduka et al., 2018). One container may produce around 450 kg hazardous waste in this process (AbuMoeilak & Taleb, 2018), and converting one 40’ High Cube container into a housing unit may consume around 400-430 kWh electrical energy (Satola et al., 2020). Sanitation may be required according to previous use (Wilson, 2020). To prevent corrosion, steel surfaces of containers should be painted with a rust-inhibiting urethane enamel on the exterior, and an acrylic rust-inhibiting enamel on the interior (Sawyers, 2005).

Pereira-De-Oliveira et al. (2022) argue that refurbishment of shipping containers must be carried out in factories for quality control purposes, and all details must be considered in the project. As prefabricated units are used, labor is directed at modification rather than production or assembly (Brandt, 2011). Although some researchers argue that such work may be performed by unskilled workers (Elrayies, 2017; Ishan et al., 2019), converting containers into habitable units requires higher skilled labor compared to traditional construction workers because the works involve a lot of cutting, welding, addition of structural members, fixing up services, door and window fixtures, weather sheds, insulation works, and finishes on the corrugated metal sheets (Anagal & Dhongde, 2017; Grębowski & Kałdunek, 2017).

2.4.2.2 Dimensional and Structural Constraints of ISO Containers

Dimensions of the cargo containers are necessitated by the requirements of intermodal transport, which may be a ship, a train, or a truck (Edis, 2022). Internal width, which is 2.352 m, is very restrictive in terms of spatial design, but joining two containers along its length for certain rooms such as bedrooms and living rooms may solve the issue (Anagal & Dhongde, 2017). However, the skin needs to be removed for this, which compromises the structural integrity of the container (Anagal & Dhongde, 2017) because lateral resistance of the module dramatically decreases without the walls (Chen et al., 2021). Reinforcement of top rails and addition of vertical supports may avoid this problem, but this will restrict the internal spatial planning (Anagal & Dhongde, 2017). Cuttings and openings should not be placed near edges because they may cause a reduction in strength due to stress build-up

(Zafra et al., 2021). Zafra et al. (2021) argue that moving an opening even 20 cm away from the edge will decrease the stress.

Figure 2.34. Deformation due to removal of side panels (Anagal & Dhongde, 2017)

To create complex habitable spaces from ISO containers, many units need to be stacked horizontally and vertically in different ways. Anagal & Dhongde (2017) argue that there are no structural issues related to horizontal connection of the containers, but vertical stacking may be a problem. Units may be stacked on top of each other up to 9 levels along the same axis, but structural safety related to stacking in different arrangements would need to be further studied.

When used for non-shipping applications, ISO containers are modified from their original design (Giriunas et al., 2012) and certain parts of the side panels need to be removed for architectural uses. When an opening is made for light, ventilation or access, the opening needs to be framed out with steel framing (Anagal & Dhongde, 2017). Additional reinforcement is provided in most cases because the structural strength of a modified container is mostly unknown (Giriunas et al., 2012). Anagal & Dhongde (2017) argue that end panels of a container are more critical compared to side panels in terms of structural integrity. Similarly, findings of Giriunas et al. (2012) show that end walls are the most critical load resisting components under evenly distributed vertical loads, carrying loads more effectively compared to sidewalls. Also, modifications require a lot of steel cutting, addition of supports and welding processes (Anagal & Dhongde, 2017), which may be very costly

(Mammadov, 2015), therefore, the lesser the modifications are made, the lesser the environmental impact will be.

2.4.2.3 Thermal and Acoustical Comfort in ISO Containers

Although using shipping containers provides a lot of energy saving during the production stage, they need some adjustments for the operation stage, and there is a general consensus in the literature that thermal comfort is the weakest side of buildings made of shipping containers. Yet, the 6-star energy rating compliance given by the Building Code of Australia shows that container homes may be quite energy efficient (Taleb et al., 2019).

As containers are not intended for home building, turning containers into residential space requires a certain level of operational energy (H. Islam et al., 2016). In spite of the conflicting results regarding energy and environmental performance of container buildings (Nduka et al., 2018), it is widely accepted that they need to be adjusted to climate and geological conditions in a given place, when being converted into habitable spaces (Berbesz & Szefer, 2018). All structural components of an ISO container are made of steel, which is very low in thermal and acoustic comfort because it is a good conductor of heat and sound (Anagal & Dhongde, 2017). High density of Corten steel promotes easy sound propagation within the internal spaces (Nduka et al., 2018). The high thermal conductivity causes condensation when there is moisture (Zafra et al., 2021), and the high electric conductivity is an aspect that requires attention because of the high risk of lightning (Ishan et al., 2019). For these reasons, container buildings need to be well insulated for habitation (Elrayies, 2017).

Roof and side panels of containers need to be acoustically and thermally insulated to provide the desired comfort levels (Anagal & Dhongde, 2017). Although it requires additional initial expenditure, adding a double roof slows down heat transfer into the building envelope and maintains a consistent temperature (H. Islam et al., 2016). Poor airtightness may cause condensation within building components, increase thermal transmittance, and subsequently increase heating and cooling requirements (Tanyer et al., 2018). It is of the utmost importance to make the containers more energy efficient, especially in harsh climates (Taleb et al., 2019), but simple modifications may provide high heat resistance in shipping containers (Kristiansen et al., 2020).

Traditional energy saving and passive cooling strategies such as ventilation, orientation, windows, thermal mass, shading, and insulation are recommended for container housing as well (AbuMoeilak & Taleb, 2018). Using active and passive strategies in the design will provide indoor thermal comfort and decrease energy consumption (Taleb et al., 2019). Using passive design strategies could create an energy saving of 79% in the operation stage compared to a standard container (Dara & Hachem-Vermette, 2019). Container houses can be designed like standard houses, using insulation materials, glazing and other building components similar to standard houses but with different methods of application (Taleb et al., 2019). Berbesz and Szefer (2018) recommend the following insulation methods for shipping containers to increase the efficacy of the building envelope:

- Internal batt insulation where it is essential, selecting high-density materials such as glass wool
- Sprayed insulation with low-toxicity materials like polyurethane foams
- Blown-in technique which minimizes thermal bridges
- SIP (Structural Insulated Panel) as an alternative to traditional insulation materials which is composed of OSB plates with a polymer foam insulation core

Good planning is required in terms of electrical, plumbing and drainage services before insulation works are done, because the internal height of the units is already limited (Anagal & Dhongde, 2017). El Messeidy (2018) favors outside protection over inside protection, because internal insulation reduces internal volume and creates thermal bridges. However, outside protection is more costly because it requires water insulation on top. In addition, external and internal ventilation is required in container buildings because condensation may have detrimental effects on the insulation (Nduka et al., 2018). Stacking containers reduces thermal insulation requirements (El Messeidy, 2018). Oviya et al. (2023) found that open-cell spray polyurethane was the most cost-effective of all the insulating materials with the least heat gain/loss (4.2 Wh/sq.m), and it outperformed the traditional brick wall by 83% in U-value, 81% in heat gain-loss.

Orientation of the container blocks is another subject of interest related to thermal comfort, but there are opposing views in this regard. Berbesz & Szefer (2018) argue that it is best to place the blocks longitudinally in the east-west axis so that the southern part, where light requiring spaces should be situated, faces the Sun between 9 am and 3 pm. Similarly, results of Suo et al. (2023) show that eastern and western sides of containers should be blinded for energy conservation in hot climates, taking in daylight from northern and southern facade openings. Shen et al. (2020) recommend a building orientation perpendicular to the direction of the prevailing wind during summer months for thermal comfort. On the other hand, Zafra et al. (2021) argue that the orientation of the container does not improve thermal comfort, and glazed windows, scheduled natural ventilation, or closed windows may even increase the indoor temperature and indoor relative humidity. However, findings of Risnandar & Primasetra (2021) show that optimized shading and window settings increase thermal performance by providing thermal comfort and reducing energy consumption.

Hassan et al. (2022) studied the effect of stacking in container houses and found that especially in hot weather conditions, stacking influenced thermal performance. According to their results, vertical stacking worked best in hot climates and horizontal stacking worked best in cold climates.

Bertolini & Guardigli (2020) reported that using containers as building components delivered the best environmental advantages in cold climates due to emission reductions. They argued that the choice of secondary materials was crucial for obtaining similar benefits in hot and temperate climates where the thermal mass of the buildings needed to be improved. The authors' work and other research in literature may imply that it is not easy to achieve thermal comfort in container buildings in tropical climates without air-conditioning. Findings of Suo et al. (2023) show that the heat gains due to the thermal transfers through the envelope and the ones due to hot air infiltration have an equivalent contribution to the cooling load, which will be further elevated by the future extreme climates. However, considering the housing deficit in many underdeveloped countries located in tropical climates, further research is recommended there.

2.4.3 Regulations Related to ISO Containers

Shipping containers' specifications, structural strengths, serviceability, and applications are regulated by the International Organization for Standardization (ISO) and the International Convention for Safe Containers (CSC) (Giriunas et al., 2012). For instance, load tests of containers are regulated under ISO 1496-1:1990 (Robinson, 2017). However, there are no ISO standards yet specifying the conditions for using shipping containers as building materials (Shen et al., 2020). According to U.S. federal law, existing and new containers must meet the standards of Convention for Safe Containers (CSC) (Giriunas, 2012). Giriunas (2012) listed some of the ISO standards related to shipping containers:

- ISO 668: dimensions, tolerances, and weight of containers
- ISO 830: terminology and components of containers
- ISO 6346: coding, identification, and marking of containers
- ISO 1496: structural tests that ISO containers must pass before operation
- ISO 1161: corner fittings' terminology, dimensions, and structural strengths
- ISO 2308 and 3874: methods for handling and securing containers

According to ISO 6346, containers need to have an information plate including an owner code (three letters) followed by an equipment category (one letter), a serial number (six numbers), a check digit (single number in a square), and a size and type code (combination of four letters and numbers) (Giriunas, 2012).

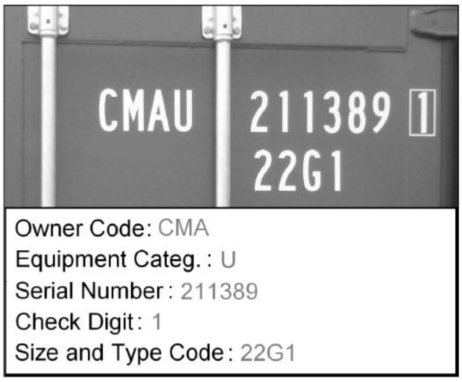


Figure 2.35. ISO 6346 Container Character Definitions (Giriunas, 2012)

Giriunas et al. (2012) published an article called "Evaluation, modeling, and analysis of shipping container building structures", with a view to develop structural guidelines for International Organization for Standardization (ISO) related to shipping containers used for non-shipping applications. The authors argued that no guidelines for safely using shipping containers for building applications existed. The authors also argued that a shipping container's structural integrity, modification properties, foundation limits, building code regulations, and reinforcing limits were mostly unknown.

In addition, although the units are subject to certain international standards, the regulations related to using shipping containers in building construction may vary from country to country. Modified shipping containers must be recertified and structurally retested according to CSC requirements (Giriunas, 2012).

Polish regulations classify a container as a temporary building object "dedicated to temporary use over a period shorter than the container's technical durability, designed to be moved to another location or deconstructed, not connected to the ground permanently" (Berbesz & Szefer, 2018). According to this, they do not require a building permit when used temporarily, but they must be deconstructed or relocated within 180 days. On the other hand, permanent connection between shipping containers and the ground requires a building permit, provided that the building's durability and ability to withstand external conditions can be guaranteed (Berbesz & Szefer, 2018).

A regulation titled "Cargo Container Conversion to Modular School Buildings: 2019 CBC" was issued by the State of California, USA, in 2016, and revised in 2020. As the name implies, the purpose of this regulation is to clarify the requirements for the conversion of cargo containers to modular school buildings, and it covers selection, verification of structural integrity, and other basic requirements of the cargo containers (Cargo Container Conversion to Modular School Buildings: 2019 CBC, 2020). The basis of this regulation was the growing use of cargo containers in building construction for reasons of sustainability and economy. It regulates the eligibility of cargo containers to be used in school building construction, inspections and tests to be made, required documentation, structural requirements, and other special requirements.

Zhang (2016) reports that in the UK and China, using shipping containers in construction is mostly subject to local construction laws because there are not specific laws for shipping container houses.

In the United States, the Modular Building Institute (MBI) and the National Portable Storage Association (NPSA) are working on creation of certain regulations, which may potentially be building codes related to ISO containers, providing a clear path to compliance (which may vary from state-to-state), and providing guidelines for future productions of modified containers (MBI & NPSA, 2017). These institutions propose to divide container-based buildings into four industry segments as given below, and to establish codes and regulations according to these segments.

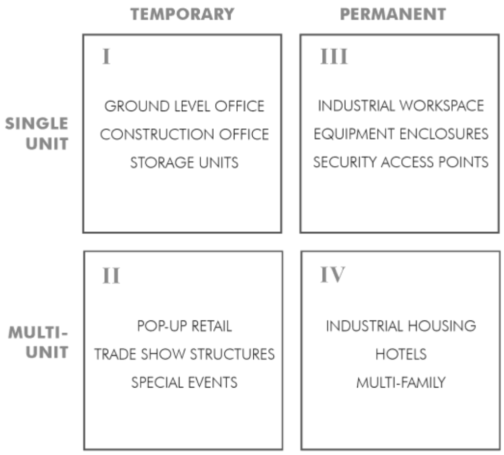


Figure 2.36. Four industry segments for container-based structures (MBI & NPSA, 2017)

2.5 Existing Research on ISO Containers

Although converting retired ISO shipping containers into dwelling units and other building types is a very popular topic, the research in this area is limited for the moment as affirmed by several researchers in the area (Anagal & Dhongde, 2017; Christensen & Worzala, 2010; Giriunas et al., 2012; Mammadov, 2015; Pereira-De-Oliveira et al., 2022). Christensen & Worzala (2010) argue that most of the research in the area has been undertaken by private firms with the purpose of creating a niche market. The following dissertations and project proposals were found in the literature search about the topic.

2.5.1 Life Cycle Analyses

2.5.1.1 Whole Life Energy Analysis of Recycled Shipping Containers for Housing

Lejin Zhang (2016), Glasgow Caledonian University, the School of Engineering and Built Environment

This PhD study aimed to assess the viability of utilizing used shipping containers in housing, especially regarding whole-life-cycle energy consumption. Main objectives of the study were to define a whole life boundary, prepare and confirm robust data for estimating energy usages, quantify embodied energy savings, validate operational energy savings, assess possible developments for shipping container framed houses, and discuss the life cycle energy consumption of container houses under different insulation and location scenarios. It was examined whether utilizing used shipping containers in housebuilding could save life cycle energy and had any potential as a sustainable building form through two case studies in Glasgow and Beijing.

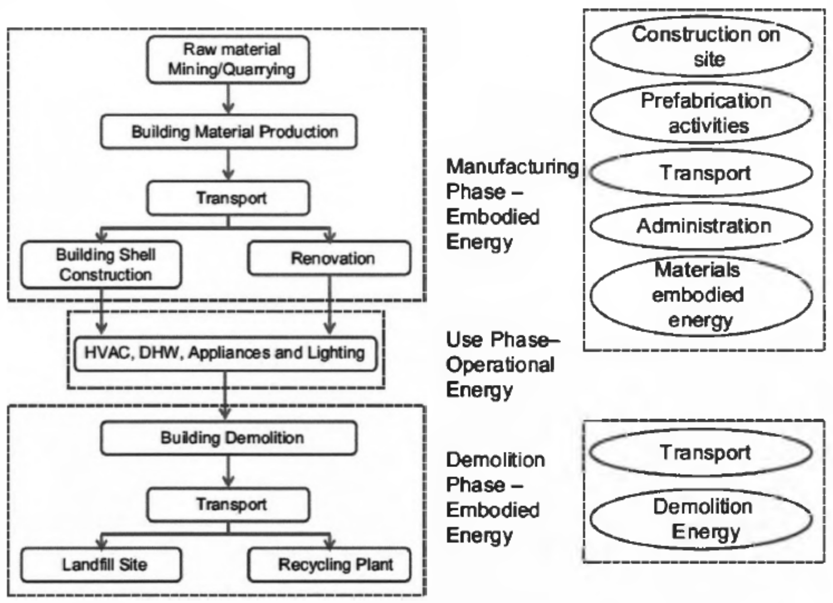


Figure 2.37. Life cycle energy flow in the building sector (Zhang, 2016)

Many assumptions and decisions needed to be made for a broad and robust life cycle assessment, including life cycle assessments of any product or process, and all previous constituent materials and processes. Zhang (2016) argues that LCA data can be very uncertain as well. For this study he assumed that the only difference between a conventional steel-framed house and a container house would be the structure and made his analysis according to this. Thus, the main objective of this study would be to compare a residential house using standard virgin steel frames and one made from used shipping containers.

Zhang (2016) concluded that building houses in both locations is clearly energy efficient. The savings are mostly from embodied energy, and they are quite significant compared with new steel frames or containers. Thus, a steel shipping container may be reused as a building frame with a contribution for energy conservation in the building sector under the present building regulations in UK and China. In addition, utilization of retired shipping containers as building frames has the potential to be applied in other regions, especially near port cities that have shipping container accumulation issues.

2.5.2 Structural Analyses

2.5.2.1 Evaluation, Modeling, and Analysis of Shipping Container Building Structures

Kevin Giriunas (2012), The Ohio State University, Department of Civil Engineering

In this master's thesis, Giriunas (2012) aimed to develop structural guidelines for ISO shipping containers used for non-shipping applications. The author argued that no guidelines for safe usage of shipping containers for building applications existed, and the shipping container's structural integrity, modification properties, foundation limits, building code regulations, and reinforcing limits were mostly unknown. The author further argued that published information on shipping containers used for non-shipping applications could rarely be found, and many of the available publications lacked information about structural strength or response of shipping containers under abnormal loading scenarios or modifications. Thus, the author started by investigating the structural limitations of the shipping containers.

Stating that most of the structural testing on ISO containers used blast loading, the author designed loading scenarios and examined how both modified and unmodified containers responded. Structural engineering considerations, foundation and connection design, and future research suggestions were given related to utilization of shipping containers in building construction.

The author conducted finite element computer model simulations of shipping containers, modeling and analyzing the containers in SolidWorks, Hypermesh, and Abaqus/CAE programs, and examined the behavior of ISO containers under 5 loading scenarios. Findings and conclusions of the author are summarized in Section "2.3.4 Structure of ISO Containers" herein.

The author recommends further research on the topic including nonlinear and dynamic responses of shipping containers, consulting the container and engineering industry to improve modeling accuracy. He argues that additional loading scenarios should be considered such as uniform pressure loading applied on the wall surfaces. In addition to optimum modifications for shipping containers, further research should be conducted to determine which container damage, modifications, or defects are too dangerous to keep the container operational. Also, an in-depth foundation design should be examined to define optimum container orientations.

2.5.2.2 A Simplified Structural Analysis Method for a 20-Foot Cargo Shipping Container

Dzijeme A. G. Ntumi (2018), University of New Hampshire, Department of Civil and Environmental Engineering

This thesis aimed to develop a simplified beam analytical model of a typical cargo container to compare to the finite element shell model of a twenty-foot cargo shipping container created by Giriunas (2012) in terms of displacement and stress. Ntumi (2018) intended to explore the structural behavior of a cargo container under a variety of loads and develop a computer model that can reasonably predict the structural behavior of it. In this structural investigation of the cargo container, the author attempted to find out how the container behaved under different applied loads, what structural components in the containers controlled the supporting of loads applied and understand the critical load path to transfer the load from the top of the container to its support points. Thus, information on the structural behavior of a cargo container would be provided for those who would use ISO shipping containers as the primary structural building component.

Coupon testing was carried out using ASTM E8/E8M-16a "Standard Test Methods for Tension Testing of Metallic Materials". Then, mathematical models of the structural components of containers were produced and compared to FEA shell mathematical models.

Results of study showed that the simplified beam method could predict the displacement and stress of an FEA shell model within 10% and 15% respectively.

An additional benefit of the simplified beam method was that it could be run on different software. Thus, the author concluded that this method could be used to simplify the analysis of cargo shipping containers used as structural components for non-shipping applications.

2.5.3 Feasibility Studies

2.5.3.1 A Feasibility Study of Utilizing Shipping Containers to Address the Housing Backlog in South Africa

Antoni Willem Botes (2013), Stellenbosch University, Faculty of Engineering, Civil Department, Construction Management Division

In this study, Botes (2013) aimed to test the feasibility of container-based homes as an alternative to brick-and-mortar homes in South Africa for the low-income groups, because the backlog of cost effective and high-quality housing units in South Africa grew rapidly. Social acceptance and environmental sustainability were examined as well as the triple constraints of project management: cost, time, and quality. The author used two case studies for feasibility analyses, one of which was a single-story house and the second was a multi-story, medium density residential building for multiple families. The test cases were compared to traditional brick and mortar solutions.

Examining the cost, construction time and quality of the end products, the author found that a single-story solution was more costly than a small brick and mortar home, but the multi-story solution was more feasible than the concrete three-story structure. Also, ISBU houses could be built 3 times faster compared to traditional houses. As for quality, it depended on the quality system used by the contractor and its correct implementation.

Regarding sustainability, the author examined economic, environmental, and social aspects of ISBU houses. In terms of the economic parameter, ISBU was cheaper per square meter, took less time to construct and delivered higher quality compared to conventional construction methods. As for the social parameter, a survey made by the author showed that beneficiaries still preferred conventional homes unless the container-based houses looked like their conventional counterparts. So, there was a negative perception in the beneficiaries against container houses. Lastly, the author found that ISBU houses had a lower life-cycle environmental impact than conventional construction methods.

Thus, the author concluded that a single-story container house was ineffective because it was more expensive per square meter than a conventional house, but a multi-story container solution was lower in cost, faster to construct, and more environment-friendly.

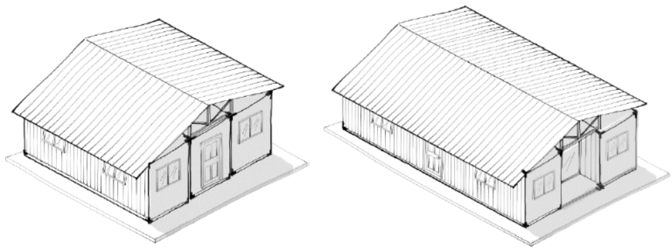


Figure 2.38. Low-density (2 families), single-story hybrid-ISBU housing with a galvanized roof (Botes, 2013)

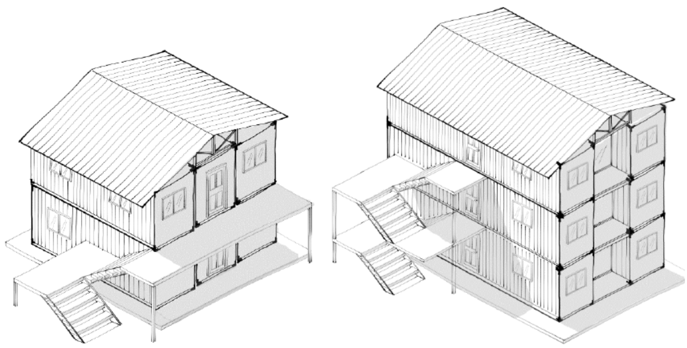


Figure 2.39. Medium-density (6 families), multi-story hybrid-ISBU housing with a galvanized roof (Botes, 2013)

2.5.3.2 Feasibility Study of an Alternative Approach to Recycle Shipping Containers

Tofig Mammadov (2015), Illinois State University, Department of Technology

The starting point of this thesis was that using retired shipping containers for dwellings, offices or other buildings was an environment-friendly idea. In this study, Mammadov (2015) investigated if using shipping containers as a structural component could reduce cost and energy consumption. The author made several analyses and comparisons with traditional construction methods and concluded that it would be feasible to develop midrise student residences with 4-7 stories using shipping containers. Project cost estimations showed that using shipping containers as structural components could significantly reduce construction costs. The author noted that one concern here would be the attitude of the users towards buildings made of shipping containers.

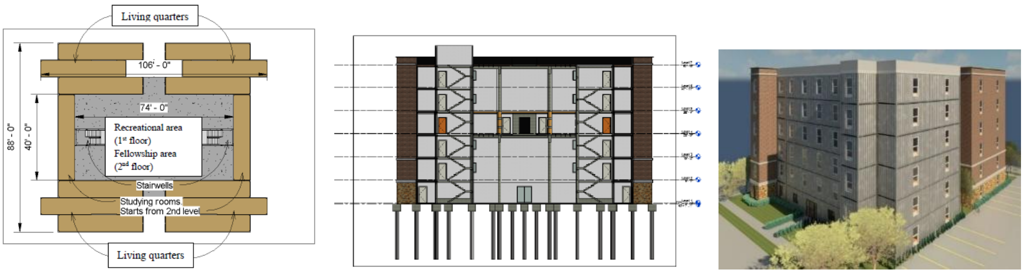


Figure 2.40. Layout, section, and 3D view of the proposed student residence building (Mammadov, 2015)

2.5.4 Design Proposals

2.5.4.1 A Housing Proposal Based on Intermodal Freight Container Dimensions

Craig Seiya Kagawa (1974), University of Hawaii, Department of Architecture

Completed in 1974, this M. Arch Thesis explored how a mobile house for a single family could be produced using freight containers, including transportation, handling and storage. In the study, construction sequencing and a cost analysis are included as well.

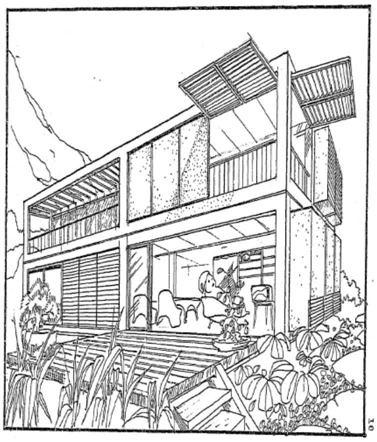


Figure 2.41. 3D view of the proposed project (Kagawa, 1974)

2.5.4.2 Plugging in: Reinterpreting the Traditional Housing Archetype within a Community Using Shipping Containers

Kathryn Ann Brandt (2011), The University of North Carolina at Greensboro, Faculty of the Graduate School

In this study, Brandt (2011) investigated shipping containers with a focus on the process involved in transforming the containers into a housing module. She explored community settings and the way in which both the interior and exterior could be adapted for the user and the surrounding context. The goal of the author was to show that the shipping container was a viable resource for housing in a variety of situations and that containers could be modified and adapted to accommodate the users' needs, creating a sense of community.

The author studied Christopher Alexander's book, *A Pattern Language*, and tried to create her own customized language related to Housing and Community. She argued that shipping containers could be viewed as building blocks that could be combined for creation of meaningful spaces and connections within a community and a home. Using the pattern language she created, the author explored designing a student housing complex, disaster housing proposals, and a military housing unit made of shipping containers in her study.

The author concluded that shipping containers would be a viable solution to satisfy the need for a home and shelter without compromising the quality of the experience within the interior. The ease of transport and availability would enable design in a variety of incomes, and as the cost of converting a shipping container was less than building a house with traditional methods, a larger amount of interior space and a higher quality of interior furnishings could be achieved for the same cost.

Figure 2.42. Proposed student housing (Brandt, 2011)

2.5.4.3 ISBU Modular Construction and Building Design Prototypes

Adrian Robinson (2017), Loughborough University, Department of Civil & Building Engineering

Divided into two parts, this study was commissioned as part of some on-going initiatives to address the lack of efficiency in design and construction. The first part investigates the development of an Intermodal Steel Building Unit (ISBU) used in multi-story construction and the second part is about a pre-designed modular station that is repeated on four station buildings.

The first part of the research is based on the ISO container, the standardized nature of which is favorable for large-scale mass manufacturing. However, the standard width needs to be investigated because it is too narrow for architectural purposes. Robinson (2017) argued that the container needed to be modified to enable better spatial arrangement, and this led to the development of an over-sized modular product based on the container platform. The width was increased to 3.6 m. Steel frame and corrugated infill panels of an extended 20 ft or 40 ft dry freight container were used with addition of insulation, plywood, and plasterboard layers. In this design, there are multiple corner fittings, bolt boxes for vertical and horizontal connections, and steel plates to fix cladding in the exterior with a built-in riser to connect floor to floor between units. This built-in riser enables pre-installation of some vertical pipework with flexible couplings.

Starting with a standard domestic house, the ISBU prototype was improved from project to project continuing with Queen Mary College student housing, a Social Housing complex, Merton Abbey development, Travelodge Hotel in Uxbridge, Heathrow Travelodge, and Gatwick Premier Inn. Thus, the majority of the work was carried out in these hotel projects. Two sets of structural tests were applied on the prototype units, the first being a non-destructive ISO 1496-1:1990 test for intermodal transportation to prove the capacity of the units, and the second an ultimate load capacity test.

2.5.4.4 Supportive Housing: Prefabricating Supportive Communities for the Homeless

Andrew Watson (2019), Graduate School of the University of Cincinnati, College of Design, Architecture, Art, and Planning

This master's thesis explores the potential of utilizing shipping containers to create and sustain socially responsible permanent supportive housing for the homeless within the city of Seattle. Supportive Housing is defined as "affordable housing with supportive social services in place for individuals and families who are homeless or at risk of homelessness" (NYC Human Resources Administration, 2024). (Watson, 2019) argues that homelessness is a major issue in many high populated cities of the United States, mostly caused by the inadequacy of the minimum wage against increasing living costs.

The author reports that 553,742 people were identified as homeless in the United States in 2017. He argues that this has two major causes: shortage of affordable rental housing and an increase in poverty. In addition, many others are on the verge of being homeless because people living on the minimum wage typically pay 50% of their income for housing, and the slightest extra cost, such as health expenses may cause such families to be evicted.

Thus, after exploring different prefabrication options, the author proposes using shipping containers for designing supporting housing. He argues that the inherent mobility of these units makes them convenient for moving, rearranging, stacking, and removing. And they easily fit in the dense urban fabric. He argues that mass produced components can be fitted into the container, and streamlining the production process will make construction more energy efficient and sustainable.

Watson (2019) proposes using each prefabricated container as a single-room module that can be combined with others to create bigger modules. A repetitive grid system can be used for integrating modules, and containers in certain locations may be omitted to obtain variations. For the avoidance of doubt, the containers have certain structural limitations, and additional load bearing may be required, as well as architectural modifications. The author proposes to have a fixed location, like a workshop for making these modifications and the outfit. Units may be taken to the site on flatbed trucks when all prefabricated components are placed and installed. Thus, the sitework is limited to lifting the unit off the truck and putting it in its place and joining the collective parts.

Watson (2019) concluded that supportive housing was a preferable way to deal with homelessness, and utilizing shipping containers would be beneficial as they present endless options of arrangement in addition to the precision and quality enabled by prefabrication.

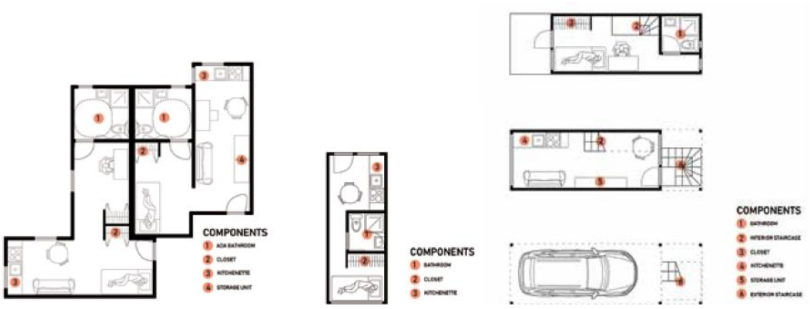


Figure 2.43. Horizontal organization of modules (Watson, 2019)

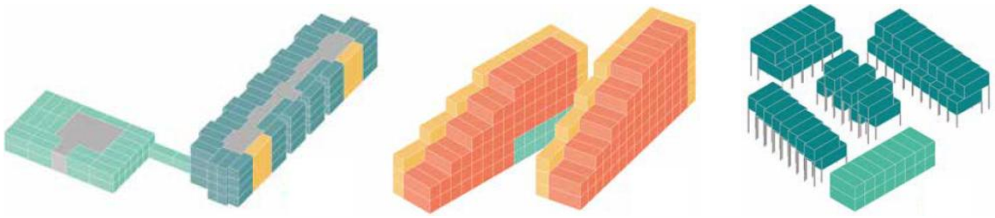


Figure 2.44. 3D massing arrangements of proposed housing (Watson, 2019)

2.5.4.5 Design Studio for Jaitapur Atomic Power Project in Konkan Area of Maharashtra, India

Vaishali Anagal and Sharvey Dhongde (2017), Dr. Bhanuben Nanavati College of Architecture for Women

This was a student project developed for housing of a large team of people ranging from scientists, engineers, managers, various specialized consultants, contractors, administrative personnel, supervisors, skilled workers, and laborers to be employed in Jaitapur Atomic Power Project in India, reported in a conference paper by Anagal & Dhongde (2017). The aim of the project was to transform the containers into habitable spaces. The students explored different ways of combining units so that the completed project would not look like a container yard.

Figure 2.45. Container Housing for Jaitapur Atomic Power Project – Student Projects (Anagal & Dhongde, 2017)

The outcomes of this design studio were as follows:

- The students used 20 ft. and 40 ft. containers, which allowed different mass compositions.

- Students achieved better interior spaces by joining the containers laterally rather than longitudinally.
- Perpendicular placement of containers allowed a better configuration of internal spaces compared to placing them in one direction.
- Many students staggered the containers to form terraces, creating a more humane and interactive housing cluster.

The authors concluded that there is a lot of scope for exploration and research related to using up-cycled containers for housing, and this would be a viable option in India.

2.5.4.6 Low-income Sustainable Dwelling

Camilo Cerro (2015), College of Architecture, Art and Design, American University of Sharjah, UAE

This conceptual project, presented at the Tenth International Conference on urban Regeneration and Sustainability, Sustainable City X, explores the potential of using retired shipping containers for developing sustainable shelter building. Made of stackable shipping containers, this unit is designed to house families of low-income. The ground floor is reserved for commercial use, and the top floor is an urban farm which is designed for producing plants to be consumed by the inhabitants as well as creating income. Many other elements such as solar panels and solar heaters, grey water storage and filtration systems, and utilizing organic waste to produce compost are designed to fulfill sustainability principles.

Figure 2.46. Display board of the Low-income Sustainable Dwelling Project (Cerro, 2015)

2.5.4.7 Post-Hurricane Housing Solution Using Surplus Shipping Containers

Pernille Christensen and Elaine Worzala (2010), Clemson University

This paper examines a case study of the Sustainable, Environmental and Economic Development (SEED) Alternative Post-Disaster Housing project in Haiti, aiming to teach students about sustainability and to think outside the box. The project was developed for a studio course including architecture and landscape architecture students. The objective of the course was to design sustainable housing solutions for post-hurricane victims using surplus shipping containers, developing safe, hurricane-proof, low-energy, and low-cost sustainable housing alternatives in those parts of Haiti affected by hurricanes. The authors point at the tremendous need in the Caribbean region for affordable, hurricane-resistant housing.

Based on the hypothesis that reuse possibilities of the ISO container are yet to be fully explored, this design studio aimed to develop a container modification strategy using retired containers. In addition to meeting immediate post-disaster emergency housing needs, this strategy also aimed to be flexible enough to further evolve into permanent hurricane-resistant housing solution for families in the Caribbean.

Figure 2.47. SEED, an emergent housing solution for the Caribbean Region (Jordana, 2010)

This housing solution needed to be strong enough to resist being overturned by high-force winds and maintain its structural integrity under wind forces of a Level 5 hurricane. Christensen & Worzala (2010) argue that the ISO container is the strongest modular structure in the world with its corrugated steel walls. It is waterproof and strong, and it can stand 140 mph winds in its unaltered form. The authors argue that even after removing a large portion of the corrugated steel, the module keeps its structural integrity. These qualities make it an ideal building module resistant against water, fire, mold, wind, and vandalism.

With this project, a second life was given to retired shipping containers, eliminating the need to transport them to another location, and reducing fossil fuel consumption and greenhouse gas emissions. This project also eliminates the need to continually rebuild after hurricanes because it is already hurricane resistant. Thus, a sustainable solution was proposed to the world problem of hurricane-resistant housing.

A similar study was carried out by Haque et al. (2022) in Bangladesh, focusing on a coastal area exposed to cyclonic storms, which leave local communities devastated. Existing housing structure in the area was unstable with poor space quality leading to an unlivable environment and lacking a dedicated community space and basic infrastructure. Based on the shipping containers' potential of enhancing mass housing development, this study focused on re-arrangement of the built form, economic sustainability, and environmental sustainability analysis in the said area of Bangladesh.

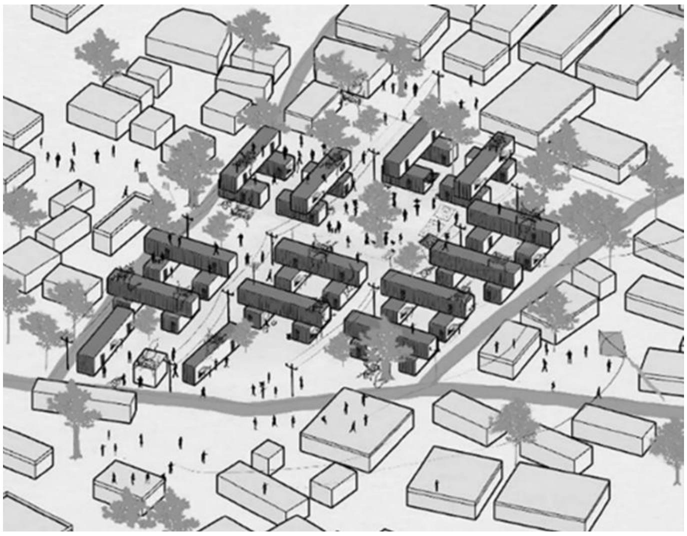


Figure 2.48. Proposed housing clusters (Haque et al., 2022)

Haque et al. (2022) reported that properly anchored containers would stand against wind pressure up to 289 km/h, and their structural stability provided a safe and disaster resilient option for housing construction. The hypothetical container housing proposed by the authors provided a robust infrastructure that could reduce tropical disaster risks. The project reduced electricity consumption by increasing daylight intake and reduced cooling loads by proper insulation. Traditional courtyards were generated in the project that could enhance domestic works or works to generate income by producing items or rendering services to others, thus encouraging communal activities and promoting cultural sustainability. Most importantly, the hypothetical mass housing project created a high financial return by reducing both hard costs and the interest load.

The two mass housing projects given above demonstrate the potential of using surplus shipping containers in hurricane-resistant housing in areas prone to hurricanes. In addition to the many benefits such as hurricane resistance, waterproofness, and durability, ISO shipping containers also have the unique advantage of multi-story constructability compared to other types of refugee shelters (Tan & Ling, 2018). As they are inherently made for stacking on top of each other, this is a major advantage enabling free land for common and rehabilitation activities when land is limited.

2.5.4.8 Procedural architectural settlement generator for container housing: A study on Marmara and Mediterranean Regions

Asena Kumsal Şen-Bayram (Maltepe University), Belinda Torus (Bahçeşehir University), Oğuz Orkun Doma (Istanbul technical University), Sinan Mert Şener (İstanbul Technical University) (2023)

Şen-Bayram et al. (2023) developed an innovative digital tool called bBox that utilizes procedural architectural generations to produce realistic solutions for settlement design problems. The authors used a game engine to develop the tool with high-quality, real-time renders, and procedural modeling to generate designs of complex urban structures.

bBox tool requires three inputs, which are an image map with geographic information (land/water/vegetation), an elevation map with height information, and a population density map of a location. Then it designs a settlement using predefined container configurations of 20- and 40-feet containers.

There are also three predefined scenario options as ecological, post-disaster, and agriculture. The algorithm makes decisions in each scenario prioritizing related criteria. In the ecological scenario, the carbon footprint of the settlement is minimized. In the post-disaster scenario, the number of living spaces is maximized in a specific land area. In the agriculture scenario, it is aimed to create adequate farming areas around each living unit. In the final phase, the program calculates and generates 3D models.

The case study made by the authors showed that the tool could generate up-cycled shipping container settlements for different real-life scenarios in a short period.

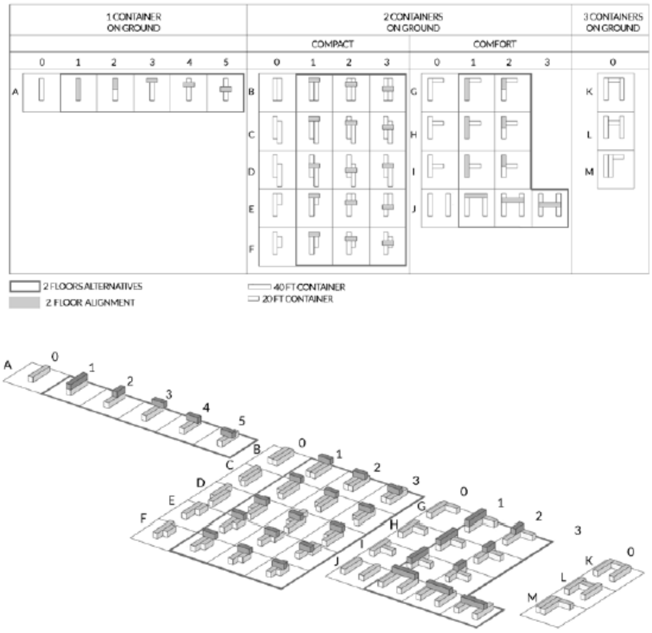


Figure 2.49. Predefined container configurations (Şen-Bayram et al., 2023)

2.6 Learning from the Freight Container

As might be expected, the pursuit of standardization is not a short-run process. The standards of the ISO container itself did not come out overnight, and it was a long and challenging process narrated in detail in Marc Levinson's book "the Box: How the Shipping Container Made the World Smaller and the World Economy Bigger" (2016). Telling the story of the shipping container from a boring box to a trend topic, Levinson asserted that containers would not help to reduce the total cost of shipping as long as they came in different shapes and sizes. He also pointed at the fact that academics ignored the container for a long time due to its "prosaic nature".

Until the 1950s, freight, loaded piece by piece on trucks or railcars, had to be unloaded separately at the waterfront, recorded on a tally sheet, and carried to warehouses on docks (Levinson, 2016). This was an inefficient, expensive, and time-consuming way, and it made loading cargo on different modes of transport very difficult. The job of loading and unloading would be done by longshoremen, or dockers, with countless maneuvers of hooks and winches. Dock work was dangerous with a high injury rate. There may be a lesson to be learned here for the construction industry, which is doing more or less the same now. This shift made by the shipping industry could be an example for the construction industry on the path to industrialization. So, how did the shipping industry make this shift?

An entrepreneur, Malcom Purcell McLean, started McLean trucking Company in 1934 in North Carolina (Levinson, 2016). Although McLean introduced the world's first container ship, Ideal X (Brandt, 2011), he was not the "inventor" of the shipping container, but he had the right management mindset, and he saw the opportunities and took risks (Levinson, 2016). As a result of this disruptive technology, time and cost of shipping were reduced, and easy movement of containerized goods between different means of transport was enabled (Placek, 2022). This eventually changed the shape of the world economy in which the container was placed at the core of a highly automated system (Levinson, 2016).

2.6.1 Container Standards

A short while after McLean started container shipping in the 1950s, this became a hot topic for the transportation world. However, a container did not have the same meaning around the world. It was a 4-5 feet tall wooden crate with steel reinforcements in Europe, but the US Army considered it as a steel box (Levinson, 2016). If containers of a transportation company failed to fit on another's ships or railcars, that company would need a large fleet of containers exclusively for its own customers. According to Levinson (2016), this would be the end of containerization in the bud because *"containers would be more of a hindrance than a help"*. So, there was chaos at the beginning, the sizes and standards of containers, trucks, and railroads being different and incompatible on the two sides of the Atlantic.

Amidst the standardization wars, Marad, the United States Maritime Administration, decided to put an end to this anarchy in 1958 and established two expert committees, one for standards for container sizes and the other for studying container construction (Levinson, 2016). However, Materials Handling Sectional Committee 5—MH-5 created by the American Standards Association (ASA) imposed 10-, 20-, and 40-foot lengths and deleted other lengths from the list of standard sizes with the help of government subsidies as incentives. The International Organization for Standardization (ISO) was also involved in the standardization project, which aimed to establish worldwide guidelines before firms made large financial commitments. Eventually, the 10-, 20-, 30-, and 40-foot containers were formally adopted as ISO standards (Levinson, 2016) and the worldwide container design became standard (Grant, 2013). Levinson underlines the fact that neither Sea-Land Service (the former Pan-Atlantic) nor Matson, the two leading containership operators of the time, owned a single container conforming to these new standard dimensions. Today, dimensions of shipping containers are governed by "ISO 668 – Series 1 freight containers – Classification, dimensions and ratings" which was introduced in 1968. Currently, the seventh edition is used that was enforced in 2020.

Another battlefront in the standard wars was related to the lifting and locking devices (Levinson, 2016). Some companies patented their systems, forcing other ship lines and trailer manufacturers to develop their own locks and corner fittings. In this way, no two company's containers would fit together even if container sizes were standard. Seeing that common technology would stimulate the growth of containerization, Sea-Land of McLean released its patents to be used by the MH-5 committee as the basis for a standard corner fitting and twist lock. Eventually, US National Castings system was adopted, and ISO approved the American design as the international standard for corner fittings in 1965. Standards for Container sizes and lifting methods were set with international agreements, so that carriers would be able to handle one another's containers.

2.6.2 Container Ships

As container standards were being set, the ships had to be converted to accommodate them and new ships had to be built accordingly (Levinson, 2016). Ship lines acquired old WWII tankers and converted them to haul truck trailer bodies. A lashing system had to be developed as well, allowing stacking containers on board with new winch systems to lift the containers. More containers required bigger ships and bigger ships required bigger ports.

2.6.3 Container Ports

Ports had to be transformed to accommodate the new ships (Levinson, 2016). Wharves were specially designed for container handling with proper docks and winches. Land and railroad connections needed to be made. As a result, the port system of the entire world has changed. Forgotten ports moved to front ranks, old ports fell out of favor. New and deeper ports were built at the fringes with highway and railroad connections instead of old city center ports. The new maritime geography brought new trade patterns. All the manufacturing systems have changed to compete in this new system. Small manufacturers selling locally were replaced with big international sellers. “Intermodal” freight became the new norm switching trailers and containers from one conveyance to another.

The first transatlantic container service opened in March 1966 using combination ships that carried truck trailers, containers, and mixed freight (Levinson, 2016). The pressure for bigger ships and faster cranes to reduce handling costs led to the development of huge cranes, simultaneously emptying and filling the ships. All movements were choreographed by computers, making transportation so efficient that freight costs were almost negligible.

During Vietnam War, the US military adopted container shipping as well. Levinson (2016) argues that the United States could not *prosecute a large-scale war halfway around the world* without containerization. After the war, ports in Asia opened to containerization one by one, such as Philippines, Japan, etc. Singapore became a hub in Southeast Asia.

2.6.4 High-skilled Labor

Before containerization, dockworkers were unskilled labor, similar to the construction industry. Computerization necessitated fewer workers with higher skills. According to Levinson (2016) loading and unloading time of container ships was reduced to one-sixth of conventional cargo ships in 1958 with fewer workers. During the early decades of containerization, there was a continuous struggle between unions and employers. A massive job loss among dockworkers was inevitable, but dock work became a safe and well-paid job in time, one of the highest paid blue-collar occupations.

2.6.5 Consequences of Containerization in the Shipping Industry

Standardized container dimensions made loading and unloading freight faster and more organized, eventually reducing the costs and consumer prices (Christensen & Worzala, 2010). The traditional view of a port with bags, bales, barrels, and crates turned into one with large, standardized containers (Klose, 2015). It was a rocky way because in addition to the challenges mentioned above, McLean also had to struggle with the competition laws of the United States and devised ways to circumvent them. However, after 1970, container transport expanded as a sea-land network and became the dominant form of cargo shipping (Klose, 2015).

Combined with the computer, the container enabled the development of just-intime manufacturing by companies like Toyota and Honda (Levinson, 2016). Thus, goods could arrive at a specified time as required by the customers. Thanks to the high precision of timing allowed by the container, manufacturers' inventories were minimized, and huge cost savings were achieved. Nonfreight costs fell as well because custom-made wooden crates were no longer necessary, and theft dropped abruptly, reducing insurance costs.

To summarize, the shipping industry went through a massive shift in about two decades. This shift included the container itself, the ships, the ports, workforce, and regulations. Trucks, trains, and related road and railway networks were affected by this shift as well. At the end of the bumpy ride, global standards were achieved to which all companies conform. The question we must ask here is how we can make the same shift in modular construction. Can we reach the same level of automation achieved by the shipping industry? How can we move beyond the prevailing case-based approach and create definitive standards?

2.6.6 Lessons for the Construction Industry

There are certain similarities between the shipping industry and the construction industry. Before containerization, transportation was an inefficient, slow, costly, and dangerous job, carried out by an unskilled workforce. The situation is more or less the same in conventional construction. Containerization increased efficiency and speed, decreased costs, and provided safety. As mentioned above, containerized transportation requires fewer but high-skilled workers to manage the automated transactions. Thus, if the same level of standardization can be achieved in modular construction, we may reap similar benefits. For this, we must define the framework of standards to be applied worldwide.

Basic standards used in containers are as follows:

1. Operational environment
2. Dimensions
3. Corners & Joints
4. Frame & Walls/Roof/Floor
5. Structural properties & Ratings (weight)
6. Materials, Surfaces, Sealing
7. Doors (Openings)
8. Compliance with regulating authorities: testing & inspections
9. Coding, identification, and marking
10. Handling and Transportation (marine, rail, and road)
11. Types & Special features

It was mentioned before that modular construction is more favorable when the type of structure has a degree of repeatability, the unit sizes suit land transport, and savings allowed by shifting activities outweigh logistics costs (McKinsey & Company, 2019). Having standard modules has the potential to solve these problems, because then, products of different companies would fit together. There could be specialized companies producing specific modules. All production work would be carried out in the factory, and the construction site would operate like the modern ports, cranes lifting and placing modules, instead of workers moving things around.

There have been similar attempts in the history of the construction history, but they failed to be widely adopted by the industry. Today, the construction industry seems to be ready for such a shift like never before. The road may be bumpy, just as the container seemed to be more of a hindrance at the beginning, but at the end of the day, a globally standardized modular construction system could be the long-awaited solution for the unproductivity problem of the construction industry.

Figure 2.50. ISO Containers on Ship (RonSped Worldwide, 2024)

Figure 2.51. ISO Containers on Train (FESCO Transportation Group, 2024)

Figure 2.52. ISO Containers on Truck (T.P. Trailers & Truck Equipment, 2024)

2.7 Modular Housing as a Solution for the Housing Problem

Several researchers address the housing deficit in the world, which is attributed to miscellaneous causes such as the increasing population, high cost of building materials, aversion to modern building technology, lack of infrastructure, stringent land acquisition processes, and occurrence of natural and manmade disasters (Nduka et al., 2018).

According to UN-Habitat (2022), 33% of the urban population in the developing world, or about 863 million people, lived in slums in 2012, and the major reason for this is the lack of dignified affordable housing. Accordingly, 54% of the world's population lived in cities in 2014, more than 80% of some cities lived in slums, and about 3 billion people, making about 40% of the entire population of the planet, will be in need of shelter and access to water, energy, food and sanitation in near future.

Even in developed countries, the housing problem is experienced in different ways. For example, Watson (2019) argues that the lack of affordable housing was not such a critical problem before 1980 in the United States, and there were many options for the low-income families. However, affordable housing is no longer funded by the government, and it is scarce due to the low number of existing rentable housing. Thus, there is a great need for new affordable housing in the United States.

World Cities Report of UN-Habitat (2022) states that provision of affordable and adequate housing and addressing the challenge of slums should be future urban priorities in developing countries. The flee from large cities during the early days of COVID-19 pandemic was a temporary response, and the course of global urbanization is expected to continue, with an increase from 56% in 2021 to 68% in 2050. This means 2.2 billion additional urban residents, living mostly in Africa and Asia, where the levels of poverty and the lack of adequate infrastructure are highest. According to Habitat report, 1.6 billion people, making up 20% of the global population, live in inadequate housing including slums and informal settlements. This ratio increases up to 90% in poor countries. In addition, although slums and informal settlements are mostly associated with cities in low- and middle-income countries, some major cities in developed countries, such as London, are also experiencing inequalities in housing. The report mentions an emerging vision which should seek to make cities more equitable, greener and more knowledge-based by embodying a new social contract providing a universal basic income, universal health coverage, universal housing, and basic services for all human beings.

Affordable housing has been a problem throughout human history. Walter Gropius addressed this issue in an essay in 1938. He argued that the main task of the building profession was to build up an adequate service to provide sufficient, decent, up-to-date dwellings for the community, at a price average people could afford (Gropius, 1943). Gropius further argued that this kind of dwelling was not on the market, and even government-supported housing with public subsidy was still too high to be afforded by the lower-income class. In the same essay, Gropius pointed at the doubling of building prices in the 1920s whereas car prices halved. He attributed this to one industry still using handwork, and the other using mass production methods. These observations still seem to be valid today, and one of the motivations of this study has been to investigate how modular construction could be a solution to this problem.

With its potential to significantly increase the speed of delivery, modular construction is seen as a well-suited strategy to address the issue of housing shortage (AIA, 2019). Modular construction is especially favorable when the type of structure has a degree of repeatability (McKinsey & Company, 2019), which is an inherent characteristic of mass housing. Many authors promote the advantages of modular construction in terms of reduced cost and time, lower construction waste, reduced water usage and pollution, and increased safety (Haque et al., 2022). Prefabrication may provide up to 50% reduction in waste production and 20% reduction in energy consumption (Satola et al., 2020), all of which lead to reduced costs. Therefore, mass housing projects may benefit highly from the advantages offered by modular construction.

On the other hand, we should not have to compromise urban quality and the specific needs of urban dwellers while producing social housing. We should seek ways to promote community engagement and enhance the quality of life in urban environments. Modularity may provide uniqueness and flexibility at the same time, and it is apt for creating richness of space with a given set of elements.

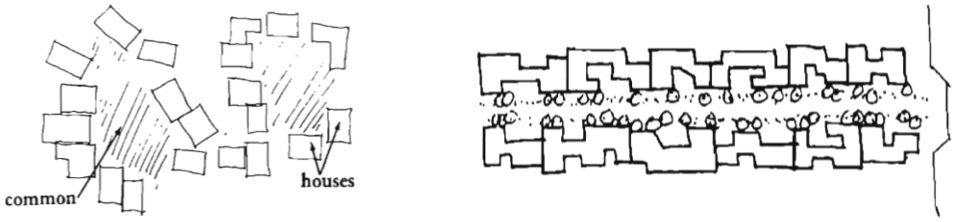


Figure 2.53. Clusters and row houses (Alexander, 1977)

Many urban patterns evolved in time such as periphery blocks, row houses, clusters, etc. If we can design repeatable modules, which can be combined in different ways to form such patterns, then we may create the identifiable spatial units people need to belong to. Alexander (1977) argues that people would feel more comfortable in their houses when a group of houses form a cluster with the public land between them jointly owned by all the householders. He advises to arrange houses to form identifiable clusters of 8 to 12 houses around some common land and paths. In this way, the hierarchy of open space can be achieved with living courtyards and activity pockets. In addition, Alexander (1979) believes that majority of buildings in any urban area, especially those for human habitation, should be maximum four stories high, which is quite achievable in modular construction.

Sustainability is defined as *"meeting the needs of human beings and society, without compromising the future of the next generations"* (Souvandy et al., 2023). In that, it is critical to preserve the environment for present and future generations. Sustainability has three pillars as the economic pillar, which refers to quality, time, and cost, social pillar meaning minimum standards of housing quality, and environmental pillar referring to natural resources used, pollution generated, and waste produced (Souvandy et al., 2023). As a matter of fact, the construction industry does not have a good reputation in terms of sustainability. However, modular structures are more environment-friendly and generate fewer emissions of greenhouse gases (Balasbaneh & Ramli, 2020). In addition, reduced construction times enabled by modular construction has economic advantages (Goh & Goh, 2019).

A design system using predefined modules to combine different types of buildings such as apartment blocks, row houses, periphery blocks, etc. would be beneficial for disaster housing as well. Such a design system would allow accelerated project development with all facilities regardless of the location. As a common practice, emergency response containers are erected after a disaster to accommodate people in need of shelter. These are of temporary nature until permanent housing is provided. However, delivery of permanent housing is usually delayed and there is an extended stay in these emergency containers. On the other hand, prefabricated modular homes can be built in weeks, which is impossible to accomplish in traditional construction methods. Huoshenshan and Leishenshan hospitals were designed, built, and commissioned in a record time of 9–12 days in response to COVID-19 outbreak in China (Luo et al., 2020). This shows the capabilities of modular construction. If fully functional houses could be built in a very short time after a disaster instead of temporary shelter, this would be beneficial in all aspects for all stakeholders. Building modules could be produced in a safe factory environment while preparing the site, which would save further time. It may even be possible to keep a certain stock of disaster housing to provide people with immediate and permanent shelter. Percentage of completion could be defined for interior and exterior, minimizing sitework. Governmental agencies would benefit from such a system.

2.8 Critical Review of Literature

As mentioned in earlier sections of this work, it is widely acknowledged that the construction industry has a productivity problem. Although the construction industry has a huge economic impact as one of the most important industry sectors in many countries, it is amongst the lowest R&D intensity sectors with less than 1% of net sales, with a decline in the labor productivity (Oesterreich & Teuteberg, 2016). It is also acknowledged that the solution to this productivity problem lies in streamlined and more collaborative design processes and repeatability of designs to benefit from scale in production (MGI, 2017).

A comprehensive literature review was made to find out the hot topics in current research and recent developments in the industry, in addition to assessing the nature of the problem. Both academicians and professionals of the industry seem to be at a consensus about the potential held by modular construction to be a remedy for the productivity crisis suffered by the construction industry. It was observed that there is usually a case-based approach in current research without any attempt at standardization. No definitive work could be found for the architects to build their projects on. There are certain drawbacks slowing down the adoption and implementation of modular construction as well. For instance, modular construction is more convenient in buildings with repeatable units.

It is widely acknowledged by both academic community and field professionals that industrialization and automation would be the solution to the productivity problem of the construction sector, in a manner like the automotive and aerospace industries. On the bright side, data gathered from construction companies show that companies are already investing in prefabrication facilities (McKinsey & Company, 2019), and new approaches such as DfMA (Design for Manufacturing and Assembly) herald a change of heart in the industry. Although prefabrication used to have the image of an ugly, cheap, and poor-quality option, it is now attracting new interest after long years of a dormant period, because it brings sustainability, aesthetics, and high precision to the market (McKinsey & Company, 2019).

Construction Industry’s inability to catch up with the manufacturing industries in terms of efficiency and productivity made it imperative to revisit modular and prefabricated solutions. Countries such as China and Singapore have already included prefabrication in their legislation. To promote building prefabrication technologies, the Chinese government has mandated that 15% of new constructions should be produced with prefabrication techniques by 2020, and they are targeting 30% for 2025 (Satola et al., 2020). In Singapore, where the land is restricted and the country relies on low-skilled imported labor, the Government has made it mandatory to use prefinished volumetric modules (MGI, 2017).

As the inferior image of prefabricated buildings changes, we observe a fierce competition to build the highest modular building of the highest quality in the shortest time possible as in the examples like 461 Dean Street in New York, Apex House and Ten Degrees in London, and Clement Canopy and Avenue South Residences in Singapore. On the other hand, when people appreciate a building and establish a good relationship with it, they preserve, improve, and sustain it, regardless of the image. Keetwonen Student Housing Complex in Amsterdam and the Trinity Buoy Wharf in London are good examples in this regard. Especially Keetwonen Student Housing, which resembles military barracks, was originally planned as a five-year temporary solution but it became so popular that its relocation was postponed (Christensen & Worzala, 2010).

There are failures in the modular construction field as well. There is a myriad of arguments about why modern methods of construction don’t work. Many modular construction companies closed or fell into administration recently including the industry giant Katerra (Wintour, 2023). 461 Dean Street, the first modular high-rise building in the world, was finished quite a bit later than planned due to certain conflicts during construction. However, no transition happens overnight, and these struggles may be expected in a newly emerging industry area.

When we look at the historical icons such as Le Corbusier’s Unité d’Habitation or Moshe Safdie’s Habitat 67, we can observe that these buildings went through several stages. After being described as a concrete monstrosity for decades, Unité d'Habitation is very popular today, and people are ready to pay a high price for the opportunity to live there (Bryant, 2007). Habitat 67, described as a milestone when it first opened, went through growing pains as well, but eventually became one of the most fashionable Montreal residences, offering luxury condominiums for the rich, although its starting point was the idealism and socialism of the 1960s (Lewsen, 2016). Reportedly, Safdie asserted that the measure of success for a residential project is whether people like it. He pointed out that Habitat was never criticized as an undesirable place to live in. In fact, Habitat was given a heritage status by the Quebec government in 2009 (Paiement, 2015). And for those people who asked why Habitat has not proliferated, Safdie resembled his building to "*an idea whose time is yet to come*" (Lewsen, 2016).

In the light of these developments, there will be an attempt to formulate the framework of standards for modular buildings in this study. However, it is also crucial to investigate whether this should be an open or closed system. Copyrights and the pursuit of profit maximization leads to closed systems as experienced in the automotive industry. Although brands merge under parent companies, there is no drop in the automobile prices that the end-users can benefit from. Should the construction industry, which has been an open system before, embrace a silo mentality to increase its efficiency and productivity by exploiting proprietary know-how? Can it imitate the platform system of the automotive industry to benefit from the economy of scale? Would this lead to monopolization in the modular construction industry?

According to a report prepared by the American Institute of Architects (AIA, 2019) and National Institute of Building Sciences, more integrated and interdisciplinary operating systems are expected to succeed the traditional silos in the areas of design and construction. To that effect, construction companies involved in prefabrication may need to collaborate with free-lance designers other than their in-house design teams. Examples of this collaboration were seen in leading brands of the automotive industry such as Peugeot having its 406 Coupé designed by Pinin Farina in 1996.

This applies to the construction industry as well. Even certain construction companies, which used to have in-house design offices, had to collaborate with well-known architects at one point to improve their company image.

To summarize, the philosophical position of this research is to investigate the potential of standardization for modular buildings. And the aim of this dissertation is to explore the common criteria and develop a framework of standardization for modular building manufacturing. To that end, the standard ISO freight container was examined as an exemplary material. Although it cannot be called the ideal construction material, as explored in previous sections, the ISO container may offer a good example with the standardization story it offers, because this single unit transformed an entire shipping industry.

CHAPTER 3

MATERIAL AND METHODOLOGY

3.1 Material

The material of this study is the transcriptions of interviews conducted with industry professionals. A 14-question interview was conducted with 15 industry professionals, who are mostly owners, managers, or technical staff of major modular construction companies, or consultants from different countries. These interviews were recorded and transcribed. Turkish texts were translated into English. The total text volume used in the analysis is 88,300 words.

3.2 Methodology

3.2.1 A Qualitative Research Method: Interview

Based on the interpretivist and constructivist paradigms, qualitative research tries to formulate an in-depth understanding of the research subject (Tomaszewski et al., 2020). Qualitative research methods are used for three reasons: (1) to define concepts, (2) to clarify an earlier study, or (3) to build theory (Douglas, 2022). Qualitative studies are specific to situations, context, and location (Douglas, 2022), and they produce findings, which are the categories or themes or answers to the research questions (Merriam, 2022). Although inherently subjective and sensitive to the biases of both researchers and participants, qualitative research may still be consistent and rigorous when conducted thoughtfully (Tomaszewski et al., 2020).

Qualitative research includes many techniques, one of which is interview. An interview is a set of questions asked by an interviewer to a person, the interviewee, who knows something about the topic of interest (Hussein, 2022). Interviews may be examined in three categories as given below (Hussein, 2022):

i. Structured: This type consists of a structured questionnaire and coded answers, where the researcher guides and controls the discussion. A large sample size is needed for reliable statistics.

ii. Semi-structured: Although there is a questionnaire format in this type of interview, the researcher encourages the interviewees to elaborate on their answers so that she can probe deeper into the topic. The interviewee has more control over the answers in this type of interview.

iii. Unstructured: There are a few pre-arranged questions in this type of interview with a list of covered topics. The interviewee not only has control over the answers, but also over the conversation's direction. Although a large amount of valuable data may be collected here, it is harder to control and analyze it.

Unlike positivistic research, data collection and analysis are simultaneous processes in qualitative research (Merriam & Tisdell, 2016). Interviews must be transcribed verbatim, because the answers to the research questions lie in the words and thoughts and responses of the interviewees (Merriam, 2022). As the data collection and analysis process is a recursive and dynamic one, it is important to begin the analysis early (Merriam & Tisdell, 2016). The researcher does not know what she will encounter in each interview, so she may need to make minor revisions within the course of the interviews. For example, in this research, it was observed that the interviewees had difficulty in understanding some of the questions, so they were paraphrased in the following interviews.

Douglas (2022) defines five stages for qualitative data analysis as follows:

1. Review each interview transcript and identify important concepts.
2. Compare the concepts and identify a few important themes.

3. Review the initial analysis by going back to the original texts and ensure that the concepts and themes are truthful for the data.
4. Turn the analysis into robust findings.
5. Write up the findings.

Qualitative data analysis is primarily inductive and comparative (Merriam & Tisdell, 2016). Thus, the major aim of qualitative analysis is to make sense of the data (Weick, 1995). According to Merriam & Tisdell (2016), findings may include organized descriptive accounts, themes, or categories cutting across the data, or models and theories explaining the data. By looking for recurring regularities in the data, categories are constructed (Merriam & Tisdell, 2016). According to Merriam & Tisdell (2016), these categories should be responsive to the purpose of the research, exhaustive, mutually exclusive, sensitizing, and conceptually congruent. The actual names of the categories may be determined by the researcher, by the participant's exact words, or from sources outside the study, but the fewer the categories are, the easier it will be to make abstractions (Merriam & Tisdell, 2016).

3.2.2 Methodology of Research

As mentioned above, transcriptions of semi-structured interviews have been chosen as the material of this study. Many industry professionals were contacted via email, requesting an appointment for an interview. Interviews were conducted with those who responded and accepted this invitation. 40 professionals were contacted. 14 agreed to give an interview, 1 gave written answers, and 2 declined. One of the companies declining the interview provided some short notes expressing their opinions on the subject. There was no response from the remaining invitees.

The interviews were recorded and transcribed. 9 interviews were conducted in Turkish and 5 were conducted in English. The person who gave a written response answered the questions in English. The Turkish texts were translated into English.

The volume of texts used in analysis herein is 88,300 words, breakdown of which is given below.

Table 3.1 Wordcount of the interview texts

Participants	**Wordcount**
Participant 1	6061
Participant 2	6118
Participant 3	5615
Participant 4	3611
Participant 5	3751
Participant 6	8347
Participant 7	5410
Participant 8	8283
Participant 9	5138
Participant 10	4805
Participant 11	12191
Participant 12	5980
Participant 13	4498
Participant 14	1058
Participant 15	7434
Total	**88300**

A qualitative analysis was performed on these texts in accordance with the methodology described by Merriam & Tisdell (2016) in "Qualitative Research: A Guide to Design and Implementation". First of all, it should be noted that although there are different questions within the scope of this interview, it was observed that the interviewees said things in one question that would answer another question in the flow of the conversation. For this reason, in the evaluation of each question, not only the answers to that question, but the entire text was re-read line by line.

During this reading, each word, phrase or sentence that provides an answer to the relevant question was marked and put together in an Excel table. After the reading process was completed, the common themes observed in the text fragments compiled in the excel table were determined. Then, these text fragments were divided into groups according to the themes. Outlier expressions that did not fall into any group were also identified. Subsequently, the common themes that emerged within the scope of each question were discussed together with the various answers contained within each group. The method of analysis described is also shown in the figure below.

The purpose of the interviews carried out here, with a population of 15 people, is to conduct an exploratory study. Apparently, 15 is not enough to make statistical inferences, and the study was planned as a qualitative study, not a quantitative study. It was aimed to investigate concepts and opinions instead of numerical statistics. This is the reason why semi-structured interviews were chosen as the research method. In this way, it was aimed to obtain a wealth of data that cannot be obtained from a multiple-choice questionnaire. Accordingly, in the following section, the themes that emerged during the analysis of the interview questions were discussed without any statistical inferences. Any numbers related to frequency of answers are given for information purposes only.

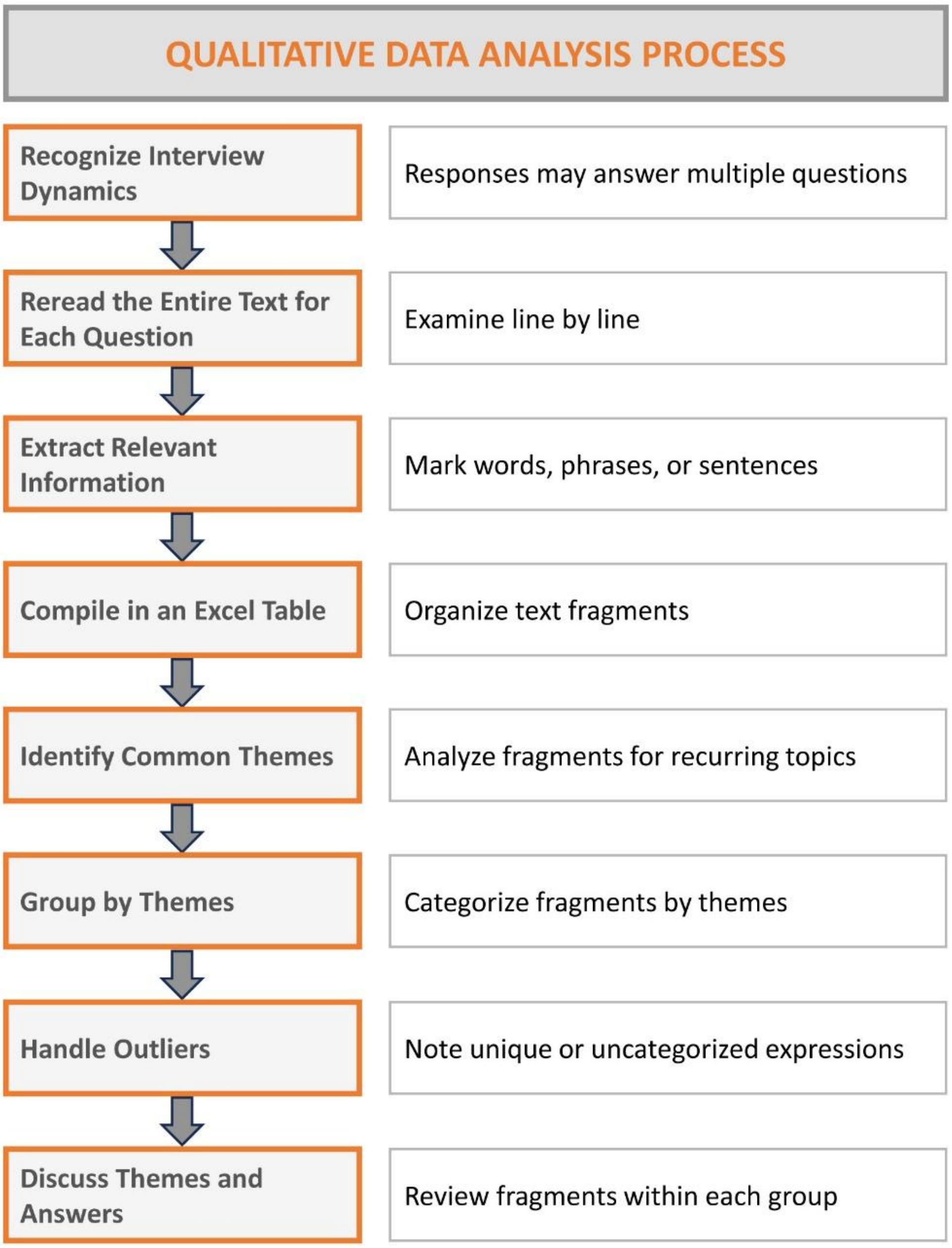


Figure 3.1. Flowchart showing the qualitative data analysis process

CHAPTER 4

ANALYSIS AND FINDINGS

4.1 Analysis of the Interviews with Industry Professionals

To collect data for this study, a 14-question interview was conducted with industry professionals. 40 professionals were contacted. 14 agreed to give an interview, 1 gave written answers, and 2 declined. One of the companies declining the interview provided some short notes expressing their opinions on the subject. There was no response from the remaining invitees. The interview questions were prepared in Turkish and English. The interviews were recorded and transcribed. 9 interviews were conducted in Turkish and 5 were conducted in English. The person who gave a written response answered the questions in English. The Turkish texts were translated into English. The answers to each question are analyzed below in accordance with the methodology defined in Chapter 3.

4.1.1 Question 1: Introduction of the Participants

Can you introduce yourself and give brief information about your experience in the construction industry, particularly in modular construction and prefabrication?

A full breakdown of the participant details is given below including profession, type of institution, position in the institution, and country. The list is given in chronological order of the interviews.

Table 4.1 Industry professionals participating in the interview

Participants	Profession	Institution	Position	Country
Participant 1	Architect	Modular Pod Company	Owner	Turkey
Participant 2	Architect	Steel Prefabrication Company	Design Director	Turkey
Participant 3	Mechanical Engineer	Steel Construction Company	Owner	Turkey
Participant 4	Civil Engineer	Concrete Prefabrication Company	Owner	Turkey
Participant 5	Industrial Engineer	Steel Modular Building Company	Owner	Turkey
Participant 6	Civil Engineer	Steel Modular Building Company	Owner	Turkey
Participant 7	Architect	Steel Modular Building Company	Designer	Canada
Participant 8	Financier	Steel Modular Building Company	Owner	Turkey
Participant 9	Architect	Steel Modular Building Company	Designer	Poland
Participant 10	Architect	Design Company Social Infrastructure Hub	Director / Architect Industry Advisor	UK
Participant 11	Chartered Surveyor	Government Organization	Loans Specialist	UK
Participant 12	Economist	Timber Modular Building Company	CEO	Austria
Participant 13	Mechanical Engineer	Steel Prefabrication Company	CEO	Turkey
Participant 14	Architect	Government Organization / University	Senior Research Fellow / Adjunct Professor	South Korea
Participant 15	Architect	Design Company	Owner	USA

Professionals of various backgrounds participated in the interview from different countries. Of the 15 participants, 7 were architects, 5 were engineers, and 3 were from economic sciences. Breakdown of the professional background of the participants is given in the table below.

Table 4.2 Participants by Profession

Participants by Profession	
Architect	7
Civil Engineer	2
Mechanical Engineer	2
Industrial Engineer	1
Chartered Surveyor	1
Economist	1
Financier	1

11 of the 15 participants represent construction companies, which produce modular or prefabricated buildings or building components. 6 of these are company owners, 3 are company executives, and 2 are designers. 2 participants own their own design company, and the remaining 2 work in government organizations, 1 of whom has been newly retired.

Table 4.3 Types of Organization

Type of Organization	
Steel Modular Building Company	5
Timber Modular Building Company	1
Steel Prefabrication Company	2
Concrete Prefabrication Company	1
Steel Construction Company	1
Modular Pod Company	1
Government Organization	2
Design Company	2

4.1.2 Question 2: Definition of Modular Construction

How would you define modular construction? What are the main characteristics that differentiate modular construction from conventional construction?

The aim of this question was to understand the perception of modular construction among industry professionals, because the literature review has shown that there may be certain variations between countries or regions. When asked to make a definition, all participants were in agreement that modular construction is about producing something in the factory, instead of the construction site. Modular construction is a method of off-site construction under the umbrella term prefabrication. In modular construction, building parts are produced in a closed factory environment, independent from weather conditions, site constraints, etc. And the higher the level of completion, the better.

> *"In fact, modular construction is not the concept at the top. The concept at the top is off-site construction. ... I define modular construction as a term under off-site construction denoting a building system that enables production in the factory at the maximum level." (Participant 6)*

The participants mostly emphasized the mode of production rather than what is produced. So, without taking into account whether these are 3D modules or 2D panels or other prefabricated components, the participants dwelled on the fact that modular construction is something that combines construction and manufacturing. A minority of the participants stressed the use of 3D volumetric modules. However, one participant from the UK gave a very comprehensive answer to this question. As a matter of fact, the explanation provided by this participant shows how elaborately the topic is handled in the UK. The participant pointed at the difference between industrialized construction versus just doing indoor construction. He argued that automation and related equipment needed to be involved in business to talk about industrialized construction. As long as this condition is met, producing volumetric modules or panelized systems are not so different. In his opinion, 2D systems were more important, although they were not quite as popular as volumetric systems.

> *"And from a personal opinion, the factories that were trying to do industrialized construction, so using automation and equipment, as opposed to those that are just doing indoor construction, the difference between Category 2 panelized and Category 1 modular, sometimes, not always, isn't that different. Because effectively, with a Category 2 panelized, you have an automated equipment, which creates walls and floors and ceilings, and either you take those panels and you take it to the construction site and you build the box on site or with the modular people you're building the panels in the same way and then you're building the box in the factory making it into a module… So, the difference in my opinion between Category 2 and Category 1 can sometimes, depending on the model of manufacturing, be really similar, really close." (Participant 11)*

The second part of Question 2 investigated the difference between modular construction and conventional construction in the perception of the participants. Their answers to this question rather revealed a profile of the benefits of modular construction over conventional construction.

Table 4.4 Benefits of Modular Construction

Benefits of Modular Construction	
Time: shortened time, increased efficiency	6
Quality: standard quality and workmanship, easy quality control	5
Cost control	5
Safety: working in a closed space, elimination of site risks	4
Sustainability: reduced waste, proper use of resources	2

The answers given to this question can be categorized under five main topics that are time, quality, cost control, safety, and sustainability. The participants stated that the most important topic was shortened production time enabled by aspects like increased efficiency, distribution of production, parallel production on site and in factory, etc. Delivery speed is particularly important in disaster recovery, as one participant pointed out, and the fact that modular construction allows simultaneous production on site and the factory is critical here. Another critical aspect is that by using industrial methods such as automation, the same amount of work can be done with a smaller manpower.

Another benefit emphasized by the participants is the standard quality and easy quality control enabled by modular construction. As the work is done in a closed and controlled environment, the margin for human error is smaller than on-site construction, and as a result of this, it's easier to maintain a constant level of quality.

Although modular construction is not cheaper than conventional construction, it allows a higher level of cost control. Compared to the unpredictable conditions of the construction site, factory production allows production at fixed prices, in terms of both materials and workmanship, and computable logistics. Site costs are minimized, and this is especially critical in places where on-site workmanship is high. One participant discussed the difference between skilled labor and unskilled labor in this question. He argued that companies using industrial methods such as automation equipment, robotics and manufacturing lines could operate the factory with non-construction skilled workers. Most of the time, even retail workers could do the job. As he has highlighted below, the initial investment to establish a modular building production facility is high. Therefore, the higher the amount of production, the lower the unit cost will be. And elimination of the need for expensive skilled labor is an important aspect here.

> *"It's skilled labor, it's labor we have a shortage of, so you're paying not only for the skilled labor, but then you're going to pay for the factory, the warehouse, all the overhead. So, you're always going to be*

more expensive than on-site construction because you're paying for the same labor plus something else. Whereas with the automation equipment, if you can make it work, you're paying, okay, millions of pounds for the equipment, but then you can deliver so many more housing faster, and if you can get the quantity up, the cost should, in theory, come down." (Participant 11)

The other important issues emphasized by the participants were safety and sustainability. Apparently, working in a fixed and closed environment enabled by modular construction eliminates the site risks, and allows a more efficient use of resources with reduced waste.

4.1.3 Question 3: Examples of Modular Buildings

What are some examples from the world that come to mind when you think of modular construction?

For this question, the winner of the day was contemporary modular residential projects. Especially no name, "non-starchitect" buildings, as one participant put it. High-rise residential buildings, mass housing, social housing, and multi-family housing were the most frequently mentioned examples in this question. Some high-profile examples were given as well: Ten Degrees in Croydon, London, BoKlok of IKEA and Skanska, Boxabl, Avenue South Residences in Singapore, and Holon Building of Broadusa. One of the participants stressed the fact that players from the automotive industry entering the housing industry handled the housing issue like the automotive industry, since they have the perception of a production system.

"I think that in the near future, we will see these automotive brands producing solutions for the housing industry. Of course, I can give many examples of modular buildings, but for example, one of the things that impressed me the most is that Toyota entered this business ten

years ago. A company that has matured and established the issue of lean production in the world has started to produce housing like automotive." (Participant 6)

The second most popular building group was the hotel buildings, especially multi-story modular hotel buildings. Of these, the most frequently mentioned were JW Marriott and sub-brands, Hampton by Hilton, and citizenM Hotels. One participant particularly stressed a hotel building in Arlon, Belgium, which was designed using only two types of modules mirroring each other. He explained his point of view as follows:

"In my opinion, in modular technology, two factors are very important. First is repetition, second is simplicity. Those are two keywords. I like simplicity. I like—maybe this is the reason why I like Scandinavian architecture very much." (Participant 9)

The third group included public buildings such as dormitories, hospitals, prisons, a college, modular industrial facilities, and modular renovation of historical buildings in Europe. The common feature of these buildings is that they have repetitive sections suitable for modular construction.

The last group mentioned by the participants was the cell systems like utility cupboards, bathroom and kitchen pods, bedroom units, etc. It is especially beneficial to prefabricate these small units which are the most problematic ones to build on site with workers from different trades working on top of each other, as one participant put it.

"The bathroom is a cell in the building. ... Why did we choose the bathroom? The bathroom is a unit where 7 different disciplines work one after the other, affecting the comfort of the building the most, and serious costs are incurred after repair. Everybody works in the same place, the insulation worker, floor and wall tiler, electrician, sanitary ware, glassworker, whatever. When you have the most intricate, time-

> *consuming unit built outside… For example, let's think of it as a hotel, let's think of it as a hotel room. When you don't do the whole hotel room and only do the bathrooms, then you only have the woodwork and veneer-work of the hotel rooms. Apart from that, you have completed the entire construction in a sense." (Participant 1)*

Even if only the bathrooms of a hotel are produced in the factory as pods, it will be much more convenient to finish the remaining works on site, compared to building the entire building in conventional ways.

Lastly, some historical buildings such as Nakagin Capsule Tower, Habitat 67, projects of Le Corbusier, and modular buildings of the mid-century were mentioned as well.

4.1.4 Question 4: Perception of Standardization

What does standardization in modular construction mean to you? Do you think it is possible? What is the importance of standardization in the field of modular construction?

Perception of Standardization

The aim of this question was to understand how industry players perceived standardization, what it meant for them, and the importance of it. Although almost all participants defined the topic differently, there were some common themes that emerged. The most basic one is reducing the variability and bringing a certain order for the production facility to work in a flowing system, so that manufacturers will know what they will manufacture and how they will manufacture it. Thus, it is a common fashion of production among different companies, but it will apparently start with the design phase.

"When we say standardization, it is necessary to talk about standardization in many disciplines. In other words, it is necessary to think of standardization in the design phase, standardization in the production phase, standardization in the implementation phase, but perhaps one of the most important differences between modular buildings and conventional buildings is that the design side of modular buildings is a building system that does not accept the logic that the herd is gathered on the road as in conventional buildings. The design process in this industry is perhaps the most critical aspect in all processes, because a production recipe is required for production, and in order to obtain efficiency from that recipe after you give that instruction, you need to have a very finished and correct recipe in order to produce in a system that flows like in an automotive factory." (Participant 6)

One participant from the UK pointed at the difference between interoperability and interchangeability. Here, interoperability means the possibility of using products of different manufacturers together. For example, when a modular manufacturer goes bankrupt in the middle of the construction of a tower building, the remaining part of the building can be finished by another manufacturer. However, interchangeability means swapping manufacturers. In this case, if the same manufacturer went bankrupt while building a number of low-rise single-family houses, then the remaining houses would be produced by another manufacturer. And the modules of the two manufacturers would not have to be interoperable as in the first case. The participant argued that despite all technical challenges, stepping in of a different manufacturer in the first case was more possible compared to the second case because in the second case, a new planning permission would have to be taken, which would delay the project at least two years.

Aspects of Standardization

A review of the wide range of responses to this question has revealed three main aspects of standardization as sizes and dimensions, performance, and interfaces, as shown in the following table.

Table 4.5 Aspects of Standardization

Aspects of Standardization	
Sizes and Dimensions	13
Performance	7
Interfaces	3

Dimensional standardization has many parameters such as external dimensions of modules, weight, spatial dimensions, dimensions of components like doors and windows. This is not a brand-new concept as one of the participants put it, and there have been many attempts, such as Ernst Neufert's Architects' Data in the 1930s, to standardize dimensions in conventional construction as well. The same participant talked about the extensive research in Eastern Europe during the Cold War years trying to answer questions like how many square meters each family needed. Another participant, an architect from the USA, declared that they were already using many standard components, such as windows, doors, sanitary ware, kitchen cabinets, and electrical appliances, and these components definitely influenced spatial design.

The responses of the participants show that two factors are critical, or even decisive, in determining dimensions in modular construction. The first one is road and maritime transport standards. The most basic principle of modular construction is that modules are produced and erected in different locations. For this, the modules must be transportable. Thus, they have to conform to transportation restrictions.

> *"I think that one of the most important aspects of standardization in modular buildings is related to logistics. The dimensions that you can carry logistically actually constitute your limits and grids in design today because when transporting a product, a volumetric product from*

point A to point B, you need to have resolved issues such as transportation conditions, routes, bridges of that country, that geography." (Participant 6)

The second factor is the standard dimensions of the raw materials that are used in the production of modules. Length of steel profiles, drywall frames, pipes, gypsum panels, lumber dimensions, dimensions of cement boards and similar may all be decisive because first, these dimensions are restrictive, and second, module dimensions are arranged such that waste is minimized.

"Light steel systems have already standardized in a sense. You always hear the same dimensions. 40-6 containers, 3-6 containers. Why multiples of three and six? You use three and multiples of three to minimize the waste in steel sections. You want to minimize waste." (Participant 1)

The second aspect is standardization of performance, which is the hidden standards, as explained by one of the participants. The clients or the end users are not aware of these most of the time. Structural standards like the load bearing capacity or earthquake resistance, wall thickness and the composition of walls, the layers they contain, thermal insulation, sound insulation, fire safety, and similar are all included in this category.

"The space doesn't matter, what matters is dimensions, thicknesses of walls, performance and connection details. This is the design." (Participant 11)

The third and last aspect is standardization of the interfaces between modules and subcomponents. First, the connections between modules or connections of modules to the main building should be standardized such that pieces can be installed like plug-in Lego pieces. The second aspect is standardization of the connections in this system, such as ventilation, electricity, water, etc.

> *"There is a plug-in standardization of electrical and mechanical systems. The connection of jacks and pipes are mostly standardized but there is no such standardization for construction elements. This means—I say again—standardization now means standardization of parts that can connect to a main building in a plug-in fashion." (Participant 1)*

Benefits of Standardization

The participants generally stated that standardization can and should be achieved. It is beneficial and has many advantages in terms of cost and time. It speeds up production, reduces material and labor costs, and reduces the generation of construction waste.

> *"The best way to cut costs is to standardize the work when you employ more than one manufacturer." (Participant 1)*

Standardization provides predictability, and predictability increases productivity, because it is much easier to control material and labor costs when a factory always uses the same window and the same door, or the same quantities of materials for flooring, paint, insulation, etc. In this way, more cost-efficient buildings can be produced in a manner similar to the line system in the manufacturing industries. And the more standardized the production is, the faster the products can be produced.

> *"When the products travel from station to station, the daily movements of employees and their walking areas are reduced. Because human movement is a loss. If we can recover these losses, I say that we can actually earn our profits while producing, not selling. If we can regain these losses, we will be content. Where does that come from? It comes from standardization." (Participant 8)*

Despite the challenges which will be examined in Question 5, the participants were of the opinion that at least regional standards or standards based on building type could be achieved in modular construction. It is beneficial for both clients and manufacturers. It is beneficial for the clients because they do not have to stick with a single manufacturer, where they can purchase the same component or the same module from several different companies.

> *"Discrepancies are not welcomed by the clients because they become dependent on a single manufacturer and cannot diversify the risk. For instance, when a project needs to be tendered in two parts, you may come up with different buildings. Thus, standardization is a crucial concept." (Participant 2)*

Standardization is better for the manufacturers as well, because they can engage proactively with the customer.

> *"When you convert these restrictions into established standards, it would be easier for the main contractor to put together products of different manufacturers. Frankly, this will be driven by industry. In other words, it is related to what the industry wants, what it intends to offer." (Participant 1)*

One participant argued that to tackle the current problems such as housing deficit all over the world, we need to think with an industrial mind. We need to define a framework for this, and that is standardization. Thus, it is not a restriction, but an order and a guideline.

> *"The architectural community needs to know something very well—because you are an architect. This is certainly not a constraint. Working in a grid system is not a constraint. On the contrary, working on a grid system provides great advantages." (Participant 6)*

4.1.5 Question 5: Barriers Against Standardization

What are the main challenges associated with the standardization of modular construction processes and components, and in what areas do you think standardization is required?

Barriers

The participants' responses to Question 4 and Question 5 were somewhat intermingled in the course of the conversation. The participants listed several aspects of standardization in Question 4, and when they were asked to declare in which areas they thought standardization was required in Question 5, their answers to these two questions created an opportunity of comparison, which will be made later in this section.

Table 4.6 Barriers Against Standardization in Modular Construction

Barriers		
Human Factor		9
Architects	5	
Clients	4	
Regulations		8
Market Size		7
Technical Issues		5

An analysis of the participants' answers to Question 5 revealed the topics given in the table above as the main barriers against standardization in modular construction. A major topic in this regard is the human factor, which is dominated by two groups, the architects and the clients. Many participants argued that architects needed to take the lead in the spread and standardization of modular construction, but unfortunately, they had a fear of losing control over design. Architects made too many changes during the course of construction, and the architectural community needed to change their mindset to adapt to the modern methods.

"The architectural community is not yet ready for it, at least not in our country. ... architects always change their minds in the process. They say it is a living process and keep changing design. This is acceptable in conventional construction, but when we are on the industrial side, a very definite finish is required somewhere so that there can be a flow where we can feel the production efficiency. I think this is one of the biggest challenges, changing the mindset on the design side." (Participant 6)

The bespoke requirements of clients form the other side of the human factor. As one of the participants put it, "nobody likes someone else's house types", because it is human nature. People are prejudiced against the concept of standardization, because there is emotional fear against it, although most of the time it is simple things like how a wall connects to another wall, or the height of a door. Different expectations of clients obligate companies to keep a flexible production structure. They have to keep their workshop setups and preparations accordingly, but they are mostly off guard. This prevents obtaining the maximum benefit from modular construction.

"When each client has different requirements, companies cannot plan their production or machinery in a certain way. That mindset should be changed. This is mainly caused by the client, but the entire ecosystem should improve each other. An organization including the academia, public institutions, and the private sector must be set up to establish standards." (Participant 2)

The second topic is all sorts of different regulations around the world. Even in the same country, regulations differ from province to province.

"For example, in each municipality in Austria, the roof should have a different angle. And only this angle is possible. Only this. And it might be a different angle 10 kilometers away." (Participant 12)

Although the effect of this may hardly be felt in conventional construction, it can be very challenging for modular building manufacturers because they cannot plan their production or machinery in a predefined way. Thus, the differences between technical specifications required by regulating entities create a significant problem. A related problem is the lack of inspection standards. For instance, in conventional construction, buildings are inspected on site. However, modules manufactured in the factory are delivered to the site almost finished. Thus, they have to be inspected in the factory. When the construction site and the factory are in different places, sometimes even different countries, things get complicated. A further problem is that institutions and their staff lack sufficient knowledge of modular buildings.

Since there is no established inspection system, there is a heightened perception of risk, and this creates regulatory friction such that higher standards may be required for modular buildings in terms of safety, insulation, etc. In addition, lack of standards may create problems of interchangeability. That is, a new building permit may be required when the manufacturer of modules has to be changed.

> *"So, it's a huge delay when the manufacturer delivering the project ... they've gone bust, they've gone, gone. You've then got to find a new manufacturer, you've got to procure them, work with them on the designs, then you've got to go back to the planning process. So, if a modular manufacturer fails, you've got two or three years of disruption before you can bring that project back to life. And there's a huge cost if you have debt finance, you're bankrupt, you know, so it's very high risk in that regard." (Participant 11)*

Market size is the third topic mentioned by many of the participants. A major challenge is that modular construction is a new system in the context we are talking about today. So, the demand is still relatively low. A higher demand is needed even to form the literature about it. Within the logic of manufacturing, something has to be produced in great numbers to achieve standardization. Thus, there should be more manufacturers and more projects so that the industry may reach an agreement on certain standards. And for that, modular buildings should be promoted sufficiently.

> *"There is only one thing required for standardization and that is the market size. If the market grows, it will be easy to achieve standardization, but it is hard to do it with sporadic projects. It also depends on the volume of the project." (Participant 5)*

On the other hand, the participants declared that new modular construction or modular design companies emerged every day.

> *"The more manufacturers do this work, the more they will inevitably go to standardization in line with the demand of the main contractor who buys goods from different manufacturers. ... The first challenge is to increase the number of manufacturers." (Participant 1)*

The last topic in terms of barriers is technical issues. It was said that suppliers are reluctant to standardize because they all have their own methods of construction. They have different productions because their machines are different. For instance, some use hot rolled steel, and some use cold rolled steel. There are discrepancies caused by the in-house processes of companies, and each company has its own set of standards. Also, the land conditions are always different, which makes it hard to standardize. And there are intellectual property rights that companies don't want to share.

> *"There is a reluctance to standardize because of intellectual property rights because each company thinks that they have their own special way or secret way of actually building things." (Participant 10)*

In this question, the participants reiterated their opinion that although it is not very likely to achieve a global standardization, it could be possible to agree on certain standards on a regional basis, or according to building type or function.

Areas of Standardization

In the previous question, when the participants were asked what standardization meant for them, their answers could be categorized under three topics as dimensions, performance and interfaces. However, when they were asked to declare in which areas they thought standardization was required, their answers were slightly different, and a new category was added as standardization of non-structural components. The participants thought that standardization of non-structural components like windows and doors, technical installations such as mechanical and electrical systems, and facade design could facilitate production processes significantly saving time and money. Participants' opinions about the other three topics discussed in the previous question were consistent.

4.1.6 Question 6: Benefits of Standardization

In your opinion, how can standardization increase efficiency and quality in modular construction projects?

Efficiency

Most participants agreed that standardization was beneficial for both the manufacturer and the end user in terms of speed, financial issues and convenience. Efficiency is primarily achieved by design. Keeping the building plans and elevations simple, and repetitive production of the same modules provides efficiency.

One of the biggest cost items in the construction industry is the design changes made during construction, and standardization may be a solution to this problem. In addition, standardization of design provides an efficiency of documents, such that there will be no need for producing new documents each time a project is built.

"So, when we use these standards, there is a higher level of predictability in terms of what it's going to look like, how long it's going to take, and what it's going to cost. ... When you build a home, one of the high costs is the changes while you're building it. If something changes, it takes too long. But if we can coordinate and design everything, which is what we do, before it gets built, then the efficiency of implementation is much, much faster, because they can build a house in a factory in a month, ship it to the site, and then put all the siding on and the flooring in and finish them all." (Participant 15)

In this question, the participants defined three areas in which standardization could increase efficiency. These are speed, cost, and sustainability. As most of the participants stressed, the design phase of modular buildings takes a lot of time, and standardization of design would significantly accelerate the works. If standard designs were used, companies could almost immediately start production. The manufacturers would not have to design everything, and they would be able to prepare project budgets very quickly. Manufacturing processes would speed up as well, because what slows down works is the lack of standardization. Productivity would also significantly increase in terms of electrical and mechanical installations, heating, ventilation, etc.

Standardization, as one participant noted, would lead to a significant increase in efficiency in the areas of social housing, the health sector and the education sector. Standard modular buildings would significantly speed up recovery in disaster zones and urban transformation areas, because production and demolition could start at the same time without waiting for long periods of design and procurement. Tendering processes would be streamlined as well.

"It is ridiculous for the designer to redesign windows for each project. Architects have established codes in this area which can be used by

designers. When you select that code, the dimensions are set." (Participant 6)

As one of the participants noted, the cost of standard work is always much lower. Prevention of labor waste, reduction in stock costs, and reduction in waste are some of the aspects that contribute to the economy enabled by standardization in modular construction. In addition, streamlined design and manufacturing processes are indirect savings items.

> *"Then the manufacturers could make safer investments knowing that they would always produce the same door, regardless of the client. If the manufacturers knew that the doors would always be 90-2.00 meters or 90-2.10 meters with such filling materials in a medical facility, then the production process could be automized, increasing productivity, and the manufacturers could make investments accordingly. ... This would increase productivity and reduce costs." (Participant 2)*

The example given above is related to a simple door design. If more components could be standardized, then the scale would grow, productivity would increase, and the costs would be minimized.

The other significant contribution of standardization would be sustainability, because it enables minimization of waste as mentioned above. As one of the participants noted, modular construction has a tremendous ability in waste management, and this will shift to another level with standardization. Incredible results could be achieved with standardization, but the most important barrier is the mindset. We need to engage an industrial mind and move from manpower to a more automated and robotic order. Removing the human factor in this way would significantly increase productivity, and this has already begun.

"When the architect sees it as a requirement for waste prevention instead of a constraint this will significantly increase productivity. This is something beyond monetary loss. It is about sustainability, and it hurts to see such a big waste of resources." (Participant 6)

Quality

All participants agreed that factory production increased quality, but there were different opinions about whether standardization contributed to it. Some participants strongly expressed that standardization of work increased the measurability and quality of workmanship, but some others thought that the quality was always there, and you could achieve the quality regardless of standardization.

The participants who thought that standardization increased quality based their opinions on the aspects like automation and repeatability enabled by standardization. Automation meant that production would no longer depend solely on human capabilities. Also, the focus could be easily placed on quality when the types of elements were standardized.

"Maybe five per thousand buildings around the world are constructed as modular buildings, but when this ratio reaches maybe 20%, standardization will prevail… Firstly, it will reduce unit costs. The cost of standard work is always much lower. Secondly, the quality of workmanship. Achieving the quality of workmanship and then maintaining the quality of workmanship. As I have mentioned, when you shift to industrial construction from conventional construction, the product must have a standard quality. You need to be able to produce the same product with the same quality." (Participant 1)

According to the contrary opinion, standardization just simplifies things for human beings, and it is not necessary to have a standardized approach to achieve quality.

However, finding an efficient way, or the most efficient way, of doing something and making it a standard could be beneficial.

4.1.7 Question 7: Standardization vs. Creativity

How do you think standardization affects freedom of design and creativity, or how can a balance be achieved between the two?

The participants gave a wide variety of answers to this question. However, these answers could be categorized under the four main propositions listed in the table below. These are not exclusive, and they may be intertwined.

Table 4.7 Propositions related to Standardization vs. Creativity

Propositions related to Standardization vs. Creativity	
Standardization opens new venues of creativity	9
Standardization and design freedom are inversely proportional	7
There are standards and restrictions in conventional construction as well	5
The aim of modular construction is not to create unique buildings anyway	3

According to the participants, standardization definitely restricts freedom of design to some degree, but it also opens new venues of creativity. Modular buildings do not have to look like military barracks, and an endless number of combinations can be created using a few types of modules. In addition, working with standardized modules increases demountability and reusability in different set ups for different user groups, and it improves circularity.

One of the participants gave an example of the houses built in Eastern European countries in the 1970s and 1980s with prefabricated elements. He argued that the cubature and the shapes of these houses were very sophisticated, and architects still had a lot of space for creativity if they knew the tools and the limits they had. Another participant acknowledged that standardization naturally drew a framework, but this could either be considered as a constraint or a necessity. It only required a change of mindset.

> *"We can move a 12-meter-long module from Point A to Point B across the world. This module enables an infinite space in one direction. Volumetrically, you can design an infinitely long space with 12-meter width. This is not a constraint but designing within boundaries." (Participant 6)*

One participant, who is an architect designing high-end custom homes, stated that standards allowed them to put together a full set of documents and detail it, dimension it, and communicate it to the factory making sure they were talking the same language. They found inspiration in those limitations and found opportunities to design something using those standards. Similarly, another participant talked about the design flexibility enabled by standardization and gave the examples of Germany and Japan who are specialized in panelized construction. These countries achieved standardization in their product platforms through mass customization. They also achieved design freedom within parameters, standards, and constraints. Without standards, each home would have to be reinvented. In addition, standardizing engineering solutions could liberate architects from tedious detailing works.

> *"Some architects are fearful that they'll lose control of the design when they have to use standard components. ... On a fundamental level, a brick is a prefabricated component, but that doesn't stifle design creativity. ... You can use Lego to create lots of different things. And you can be very creative with Lego. And all you have to do is to understand the constraints of the system that you're working with, whether it's modules or panels." (Participant 10)*

Some participants declared that standardization and freedom of design were inversely proportional and there was no way these two could go together. Some of these participants expressed concern that too much standardization could restrict the design and bring monotonicity. One participant argued that design shouldn't be very restrictive, because restricting the architect restricts the end-user as well. Another opinion is that it is not possible to standardize module dimensions because each architect designs according to the requirements of the building. Standardization could perhaps be achieved in mass housing, but it is not possible in other projects, because each plot of land is different. Standardization is a barrier against arranging pieces freely. One could play with the facade, add canopies, or add divider panels to the balconies but other than that, the building form is pretty much clear, and even the locations of the doors come from the form of the modules. The more you broaden your horizons, the more difficult it is to standardize. However, one participant also argued that modularity gave the opportunity to change components of buildings without damaging them, just like a car, and this is the direction the industry needs to go, creating standard buildings.

The third proposition argues that there are many standards, or limitations, within conventional construction as well. The level of these limitations is rather caused by the building function and not so much by the construction methodology.

Apparently, not all buildings are fit for modularity. Buildings with repetitions such as hotels, dormitories, hospitals, and schools are more suitable for modularity. This is also true for certain parts of housing such as bathrooms, kitchens, balconies, etc. In fact, modularity has been successfully used in social housing for decades. However, it would not be the first choice for more monumental buildings such as concert halls or temples which require large spans. However, even in these buildings, there could be hybrid solutions.

> *"Maybe you cannot build something like Frank Gehry's Guggenheim Museum with these standards or something like Zaha Hadid's buildings*

but when you look at the inside of the building, you can use standard products for 80% of the building and special design for the remaining 20%." (Participant 1)

One participant referred to a study which argued that in building groups such as medical facilities, educational buildings, mass housing to a certain extent, and hotels, creativity prevailed in 30%, whereas in the remaining 70%, there was repetition. Designers are already quite restricted in certain building groups such as day care centers, which are subject to strict regulations.

Another participant pointed at the fact that in building types like hotels, where dimensions are defined, conventional construction has standardized as well. Or there are typologies in site-built houses. There are restrictions caused by the structural grid, but these are established standards, and they are not seen as constraints.

"Look at all the hotels in the world, the room of an affordable hotel is 18 m^2. It is 24 m^2 when it is somewhat bigger. These are things that are already standardized. ... The structural designer will design a column layout. Can you call it a constraint? ... I call it an order." (Participant 6)

The last proposition in this question argues that the aim of modular construction is not creating architecturally unique buildings anyway. The main purpose of modularity is to achieve standardization, mass production, and repeatable production. The logic of standardization is making something more economical, faster, more robust, and more efficient. On the other hand, the design processes in modular construction can be quite satisfactory for an architect, especially if it includes designing a whole system instead of a single building. This is a problem-solving process that requires creativity. After all, architectural design is not just about aesthetics.

4.1.8 Question 8: Impact of Legal Regulations

How do legal regulations affect standardization processes in modular construction?

In this question, the impact of legal regulations on the standardization processes in modular construction was explored. However, the answers given by the participants mostly addressed the relationship between legal regulations and modular construction. It was observed that there were similarities between the answers of participants from the same country or the same region, which was not surprising. These will be examined below, but a general inference would be that the lack of compatibility between regulations is a barrier against standardization in modular buildings.

As this study is conducted in Turkey, the highest number of participants are from Turkey. The main concern of the participants from Turkey is that there are no standards set at the moment in terms of legal regulations. Turkey is lagging behind in this area, but it is also a new topic in the world. Especially the participants from modular building companies who exported their products to foreign countries noted that regulations were more established and stricter in the countries like the UK, the USA, or Germany compared to Turkey, but this kind of construction did not have any worldwide definition or established standards yet. There are different regulations with respect to different load bearing systems, but modular buildings are still not bound by formal regulations issued by public institutions in the world. For instance, there is still no standard for the structural analysis of modular buildings, and structural designers work with assumptions. There is nothing universal for connection of dynamic systems, and special solutions are produced by different companies. Standardization in terms of structural design is necessary for legal standardization. The only reference used in Turkey is TS498 for steel buildings, and even that is based on reinforced concrete anyway. One participant complained that they could not find engineers to design light gauge steel buildings maximum 5 years ago, let alone modular buildings. Another participant complained that their product did not even comply with the legislation because there is no proper legislation on modular structures in Turkey. As a matter of fact, there is no separate heading or regulation related to modular buildings in the world yet.

The participants stated that there is no aspect in the legal regulations to either prevent or support standardization, but the main restriction is about the inspections. In modular projects, part of the inspection needs to be done in the factory. However, the building inspection companies are used to conducting on-site inspections and they are not experienced in inspecting modular buildings. In the USA, Germany or the Netherlands, inspection is done by third parties who check whether factory production is made according to the drawings.

> *"The problem now is that there are no legal regulations. In other words, the process can be prolonged because no one knows what to do. The process can take longer because the officer does not know what to do. When there are legal regulations and everything is in place and there is no gray area, it will be beneficial compared to the current situation." (Participant 7)*

Participants from Europe also considered the inspection as a major problem and complained about the lack of standardization among different countries in terms of inspection processes. The modular building manufacturers produce the modules in one country and then send them to another country. It would be convenient to have the same regulations in each country and be allowed to use the same materials. Especially the different standards and requirements related to electric installations are very tiresome, so they would like to have the same standards at least within Europe. Other than that, the legal processes in every country are very slow, and the safety standards for modular buildings are tighter compared to conventional buildings.

In the UK, higher safety standards are required for modular buildings compared to traditional construction, especially after the Grenfell Tower fire. Off-site and MMC delivery are mandated and encouraged in the UK, but there are discrepancies in the regulations. For instance, in the UK, to sell a new house you need to be able to get a mortgage, and in order to get a mortgage you need a warranty. However, the building regulations, the fire testing and the warranty requirements are not compatible. In addition, the way that modules are dealt with from a regulatory point of view varies in the UK such that England and Wales are different from Scotland and Northern Ireland.

The USA has more regulations for modular buildings as well. They need to obtain a state permit in addition to the local permits, thus it takes more time. However, the participant from the USA declared that they were not affected by the intensity of the legal regulations they were subject to. When someone understood what those regulations were and how they should be worked with, it could actually be a more efficient system. Although it took them a long time to learn those various aspects, they would not get any surprises now because they did their homework. Also, it was a better idea to learn, understand, and embrace the constraints instead of fighting them.

Safety regulations seem to be troublesome in Canada as well. For instance, the participant from Canada complained that they could not find fire resistance tests because they were usually designed for conventional construction methods. The biggest problem related to modular buildings in terms of regulations was the lack of regulations. Processes were prolonged because no one knew what to do, and bureaucracy hindered high-rise modular buildings in Canada. The increase in bureaucracy could discourage many investors from building modular buildings in Canada.

Similarly, the participant from South Korea argued that legal regulations did not reflect modular building construction because they were developed according to conventional construction methods. Therefore, it took a lot of time and money to deal with them. Legal systems and standards had to be changed to suit modular buildings, but this was not an easy process.

“I think the authorities and the legal process should somehow face the fact that people started to build buildings in factories, where there are no requirements or laws due to regulations, and just connecting them on site. I see a lot of space here for standardization.” (Participant 9)

4.1.9 Question 9: Successful Examples of Standardization

Are there any successful attempts at standardization in modular construction you have observed or been involved in? If so, what do you attribute this success to?

Many of the participants were unable to give an example in response to this question. Some participants talked about standards developed by individual companies. For instance, one participant from Turkey talked about a company that pioneered in light prefabrication in Turkey introducing significant standardization. He argued that the standardization brought by this company was still used in the prefabrication industry in Turkey. They brought in container dimensions, and this resolved certain aspects in that industry. Major companies adopted these standards, and it provided market freedom for the consumers.

There are some companies around the world which create their own building blocks with fixed dimensional standards. They don’t change these dimensions according to the client’s needs or the requirements of the project. However, a company should have a certain stand and power to dictate its own standards. These companies create their own ecosystem and sometimes work in vertical integration. For instance, the participant from Canada talked about the company he was working in. The company was also a steel producer, and they used their own products. The whole structure was a standard system with its assemblers and so on. There are also companies which produce bathroom pods for their own projects.

One participant noted that Germany was very good at standardization whereas Japan and Korea were very successful on the engineering side. On the other hand, some Chinese companies developed AI to such a point that the American, British, and German companies were lagging five years behind. The UK seems to be very active in this area and there are many attempts there including government-initiated projects. Observing the lack of standardization, the UK government divided government-commissioned works among smaller manufacturers instead of expecting a big factory to produce everything. In this way, they intended to unify smaller manufacturers by establishing standards to form a greater force. They also established a platform called Construction Innovation Hub supported by the government, aim of which is to establish standards. Making BIM mandatory in public projects has also created a catalytic effect in the industry.

The UK government funded or supported three major projects. The first is the "Advanced Industrialized Methods for the Construction of Homes" (AIMCH) project which addresses the challenges of the housing sector. The second one is the "Seismic Platform" which promotes standardized design practices and interoperability in offsite manufactured solutions. The third, and probably the most well-known is the "Kit of Parts" project. Multiple manufacturers can deliver a planning permission and a house within the kit of parts concept, so that the contractor can be changed without going through the planning process each time. In this concept, it is possible to design a project that can be delivered by any manufacturer.

> *"There is no success story from there yet. What we could call a success story there is the fact that the government has started an initiative like that. There is ongoing work, and both the academia and the private sector are included in the process. Time will show whether this project will succeed or not. But even initiating something like this shows the level of awareness about the topic. I would call this a success story." (Participant 2)*

There is an endeavor in the UK to standardize the performance specifications, rather than trying to standardize the construction method. British Standards Institute in the UK is developing a publicly available specification for residential modern methods of construction. In addition, some of the module manufacturers in the UK collaborated to design connection points and components. The success of this initiative was based on collaboration. Another success story is the prison construction program in the UK, using concrete panels, where the top-level contractors collaborated, and brought together a design team and a delivery team.

Another example is the Education Department of the British Government. Many schools are delivered in modular, enabled by the standardized designs they have. The size of the school, the number of classrooms, the number of bathrooms, and the size of the canteen are all standardized without much variance in a formulaic way. They are simple and replicable designs, which have enabled the modular manufacturing industry in non-residential to grow and be successful. The only challenge here is to keep the program running.

> *"So, you need that program to keep running. And unfortunately, the way government works is usually there's a program that's over a number of years, and then there's an end, and then there's a gap, and then maybe there's a new program." (Participant 11)*

An example in France took the opposite approach. A design company, who is in the position of a client, designed modular student accommodation and started subcontracting the construction. They hand their module design to the manufacturers and make sure that they can control the size and layout of the modules and standardize the products.

> *"So instead of leaving the design with the module manufacturer, the client takes ownership of the design and then basically said this is what*

I would like rather than the supplier actually saying this is what I can give you." (Participant 10)

One participant gave the example of a town in Czechia called Staré Město. He talked about the standardization achieved in this town where all the producers in the town work in a way complementing each other. These producers, which are actually tiny workshops and not big factories, have a great capacity together. These tiny workshops have become strong businesses because they are standardized.

"Sharing is very important here. We must be willing to share. If we learn to share, if we learn to share, we will be able to meet the needs of everybody, because conventional builders cannot meet the need. ... We are not sharing what we have in our pocket. We share what we don't even have in our pocket, something we don't even see." (Participant 8)

One participant from Poland talked about what success meant for him. According to him, success meant more people being able to buy some goods, and standardization allowed manufacturing of products that were available for more people, just like standardized cars or DIY goods. He argued that it had to be the same with buildings and that modular technology was the answer for it. He stated that the thousands of people suffering due to war or other crises could be helped more effectively if we standardized everything, including dimensions and finishing materials.

There were no participants from Japan, but a participant from the UK mentioned a Japanese company, which has very advanced manufacturing capabilities. This company, which delivers 50,000 houses a year employs a thousand seven hundred architects in-house who work within their manufacturing platform, design platform, and product platform to design these houses. Each house is unique within the standardization of the product platform which means they do not design anything the manufacturer cannot produce. The permitting system in Japan facilitates this because the regulating bodies do not ask for any modification in the design that is unavailable for the manufacturing process. They have a fully automated, robotized manufacturing process. This company is a good example of mass customization. However, as the participant stressed, not everybody has this type of manufacturing capability, so it would be a good idea to reduce variability and accept more standardization, at least for the moment.

Another example of mass customization is from the United States. It is the design company of one of the participants which uses standard methods of production to create unique one-off products. This company developed a typology using certain base elements and schemes, responding specifically to each client and each site. The company developed a series of private modules, bedrooms and bathrooms, and communal modules, kitchen, dining, and living. They also developed a way to work these from inside out, based on the dimensions that were needed. The designers sought to create an aesthetic based on a scheme that reflected how their buildings were built and why they were built the way they were.

> *"If we can come up with a design methodology that works within the limits of the factory's method of production, then we could, in theory, design very high-end custom home built by regular factory. ... As long as you can work within that system, you can almost design anything." (Participant 15)*

The last example is a modular house produced by a Turkish company where one of the participants works. This is a fully folding system, which was designed to be used mostly in African countries. When closed, it looks like a 20 ft container, but it can be installed in 8 minutes transforming into a two-bedroom house. The company presented this product to be used as a disaster house in Turkey, but they had difficulty competing in terms of price. They designed another product, which is also a modular system container that folds in the shape of an accordion. 10 of these can be loaded onto a truck, and they can be installed in half an hour.

4.1.10 Question 10: Promoting the Adoption of Standardization

How do you think the adoption of standardization in the field of modular construction can be promoted?

In this question, the participants were asked to declare their opinions about how standardization could be promoted in the modular construction industry. Was it something to be created within the industry or did it have to be top down?

Some participants argued that this was useless anyway because you could not standardize needs. Expectations beyond very basic needs could not be standardized. Furthermore, it was not necessary to establish global standards. Most participants, however, had more positive thoughts on the subject.

Table 4.8 Promoting standardization

How can we promote standardization?	
Within the industry itself	8
natural progress	
collaboration across stakeholders	
led by architects	
Top down/government	7
incentives	
regulations	
It won’t work	2

The participants who thought that standardization could be created within the industry and those who thought it had to be top-down, whether by government incentives or regulations, had their own reasons. Some of the participants who argued that this was something that the industry would create within itself envisioned a collaboration across stakeholders including contractors, manufacturers, factories, designers, customers, the government, insurance companies, etc. All of these stakeholders needed to be part of the conversation, and they needed to be listened to. It is needed to define clearly what it is that needs to be standardized and then develop that within the industry as an industry standard.

> *"There are many customers that won't use a modular manufacturer because of the risk. And the risk is if the factory fails, what's your plan B? Who else can deliver that product or that project? Often enough, there is no plan B, and therefore the customer doesn't come, the customer says no. So, it's about bringing the stakeholders together, the factories, the customers, the government, the warranties, the market structures, to go what do you want, what do we want, how do we do that?" (Participant 11)*

One of the participants argued that a top-down approach would not work because although standards could be set by the government, especially in government programs, these standards became useless when these programs ended. Thus, engaging various stakeholders, including architects, engineers, and suppliers, in the development of standards could lead to more practical and widely accepted solutions, as another participant stressed.

One participant in this group thought that it was definitely the architects who had to lead the way. He argued that first of all, the architects needed to understand that standardization was not a constraint but an order.

> *"Take Corbusier, he started from that tiny house and produced his famous block. Is it a constraint? No, it is an order. He broke new ground there. ... It is a tremendous thing to express how well the order of prime numbers in nature works there. Of course, he has a set of measures. There is a ratio, and that ratio is a beautiful thing, not an ugly thing.*

It's both useful and beautiful. ... So, if that mind transforms, the rest will transform very easily." (Participant 6)

The attitude of the architects was the most important barrier against standardization, and it was the architects who needed to say that this was not a restriction. Then the structural designers, mechanical and electrical engineers would follow. Even in public institutions, it was the architects and engineers there who had to promote these changes.

"They can't improve because they stopped learning. If you ask me which profession group should lead the way, it is definitely the architects. ... The designer will first accept that this is not a constraint, but an order, and that this is the right thing to do, and will explain it well to the client. Then it will penetrate the whole society." (Participant 6)

Several other participants argued that the modular industry would eventually standardize within the natural flow of things. However, the number of modular construction companies, related demand, and the use of products had to increase because there cannot be standardization in something that doesn't exist, as one participant stressed. This participant thought that standardization was mostly needed by the main contractors. When the main contractors had challenges combining different products from different companies, they would start standardizing them. This participant noted that modular construction was most effective where on-site labor was expensive, and when we could prevail quality and time over cost, then people would turn to modular.

"Especially in the Middle East, when it was impossible to find tilers to work on the 40th floor at 40°C—this is exactly what happened—things changed. If you can have the same job done in an air-conditioned facility in places where it is 40°C or 50°C with just assembly work on site, then you start becoming preferable." (Participant 1)

Other participants argued that modular companies had to promote themselves better, and a shift of awareness in the clients was crucial for the improvement of the modular industry. One participant stated that encouraging top-down standardization could lead companies to create a common standard, but free enterprise driven by the entrepreneurs in the market would be more successful because they had a greater motivation in the end. He gave the example of BIM software which has standardized architectural drawings to a certain extent. With the increase of people using BIM software, a similar language is seen in the drawings, and it is something that people look for. For instance, seeing this common language, the municipalities skip without much scrutiny when approving a project. Another participant gave the example of phones with touchscreens. When everybody understood it was a better option, all phones started having touchscreens.

The participants on the other side were of the opinion that establishment of standards in modular construction had to be led by the government, from top down. Left to the players of the industry, it could end up in company-based specifications instead of standardization, as one participant put it, because companies would like to eliminate competition. Of course, this process had to be carried out in collaboration with the stakeholders and not by force. The experiences of the companies had to be examined, and their opinions had to be heard. For instance, the platforms established in the UK, in which data from various stakeholders would be blended together and distributed to the industry, were good examples of this collaboration. Government incentives were also a good idea to promote the establishment of standards, and customer demand for a standard product could be created by the government.

> *"These companies need to come together and unite and form a power in the eyes of the state and have a say, and then at the management level, at the government level, they need to change the regulations and then trickle down. Otherwise, if we go alone, that is a Quixotic attempt." (Participant 8)*

4.1.11 Question 11: Comparing the Modular Construction Industry to the Shipping Industry

Considering standardization attempts in other industries, such as the station or platform approaches in the automotive industry or the standard freight containers in the shipping industry, do you think that there can be a similar standardization process in modular construction? If so, what elements do you think need to be standardized?

At this point of the interview, a couple of slides were shown to the participants, comparing the shipping industry and the modular construction industry. The participants were informed that the ISO container was chosen as an exemplary material because of the standardization process it went through. It was also a unit that was used from time to time in the construction industry. From manpower intense ports with incompatible bales, boxes and piecemeal cargoes, we have now come to a completely different port appearance where we see hundreds of colorful boxes all produced by different manufacturers. However, types, dimensions, materials, connection details, load bearing capacities, cranes are all standardized. This simple unit has transformed the ships and the ports likewise after decades of struggles. Thus, the participants were asked whether they could envision a process like this in the modular construction industry, and if so, what its parameters would be.

Many participants declared that it was impossible to directly compare the shipping industry and the modular construction industry. Some participants even found this question disturbing. It was explained to them that this example was chosen partly because it was a very extreme example, so that it would challenge the interviewees and lead them to examine the subject in a little more detail. Five participants rejected the idea. Four of the participants, however, liked the idea and articulated it. The others argued that this kind of standardization could be possible in certain building types like mass housing, hospitals, clinics, hotels, student housing, classrooms, or prisons. Or there could be regional standards or standards for different building functions. Another option would be to develop adaptive systems instead of fixed systems, which would also be more interesting from a financial point of view.

"Containers have no souls!" (Participant 12)

The participants who argued that it was impossible to achieve a perfect standardization in modules that we achieved in containers gave various reasons to justify their case. For instance, a building has more variables compared to the shipping industry, and the challenge in achieving the same level of standardization as the shipping industry is more related to the briefing requirements of the buildings rather than the construction of the modules. There are cases where design concerns prevail, and design offices do not want to be restricted to certain standards.

Transportation of goods is much simpler than assembling a building. Standards for shipping containers address the requirements related to shipping goods over the ocean. So, they need to be efficient and protected in a utilitarian design method and response. However, buildings are for people to live in. Domestic space needs to be nurturing and engendering. Homes are designed from the inside out.

Drivers of the change in the shipping industry may not apply to the construction industry. The situation of the ISO container is very different because the whole industry is making a deal there. They made an international agreement because these products need to travel around the world. However, a building is something permanent and immovable. So, there is no need for multiple manufacturers to deliver the same module. In addition, any system would optimize in 100 years.

Cultural differences are critical. For instance, Europe, which is an old continent where land is scarce, has no problem living minimally, but some cultures do not give up on their spatial needs. People demand larger spaces in some countries. And people don't want to have standard houses. Different people have different mindsets.

> *"Think about this, in a country like Sweden where average personal income is $60,000, people may live happily in a 3-meter room. But in our country where the average personal income is 8-10 thousand dollars, a 3-meter room is called a pigeonhole. This is a cultural matter. Cultural aspects are very limiting for modular construction." (Participant 6)*

Each country has different technical conditions. For example, there are different building regulations in each country, which make standardization impossible. Even different parts of countries have different rules. Also, every geography has its own problems such as seismic risk. Lastly, there are different transportation conditions, varying from country to country.

Participants proposed different standardization parameters. Electrical, mechanical, and structural specifications are essential. That means that dimensions, cable and pipe transitions, and the load bearing capacities should be compatible. Materials should be standardized as well. However, the most critical aspect is solving the transportation, which was mentioned in the earlier questions as a barrier.

> *"What you will do in terms of standardization will be standardizing the connections to the system of the main building. Other than that, you must be free in terms of coating, materials, colors, textures, etc. No one has a problem with it, as long as it fits into the system, but you have to keep the building functioning." (Participant 1)*

As said, the main issue is to solve transportation, because the modules are not produced in the construction site. The commonality between shipping containers and modular buildings is mostly related to transportation and logistics. There are many restrictions. For instance, a module needs to fit on the back of a lorry. It cannot be too tall either, because it must fit under a bridge. Thus, the width of a lorry and the height of a bridge become the maximum dimensions. A police escort is needed when these limits have to be exceeded. And every time these limits are exceeded, additional costs will be incurred. So, there is not much to do unless transportation is solved.

What complicates the problem furthermore is that each country, sometimes each province, has its own size limitations and traffic rules in road transport. Therefore, it is crucial to set common standards for road transport.

> *"Depending on the area, different parts of the country require different rules. So, one of the problems for factories is they are traveling through different municipalities and local authorities. And for one, they need a police escort. For the next one, they don't need a police escort. The one afterwards, they need another police escort. And they're constantly parking and waiting for another police escort to come and collect them so that they can carry on with their journey. So, there's a huge dysfunction there." (Participant 11)*

Some participants were quite optimistic about setting standards in the modular building industry and some even declared that this was already happening. According to these participants, one needed to conform to established standards and embrace them as their own to reduce both time and cost. First, cultural habits needed to be changed, but then these restrictions would prompt designers to design aesthetic products within these standards.

In this process, some aspects like supervision and certification must be addressed. There must be an equivalent of the DNV (Det Norske Veritas) and CSC (International Convention for Safe Containers) standards for containers in the building industry. But soon, there will be modular construction standards similar to ISO standards used in freight containers. Just as the intercontinental trade in the world transformed into something else with the invention of the container, modular construction industry could change with a tiny change of mindset.

Some participants talked about some examples showing that this change could already be on the way. For instance, one participant noted that some world-class modular manufacturers and contractors were already trying to standardize. Another one talked about some factories who have been working on details to stack modules on top of each other, just like the standard corners of the shipping containers. These factories worked on developing connections on the standard knuckle, but it was over-engineered at the moment. These attempts could especially be important for high-rise buildings.

4.1.12 Question 12: Impact on the Entire Construction Industry

What would be the effects and consequences of this on the construction industry?

This was an open-ended question. Nevertheless, there were some common themes. The table below shows the common themes mentioned by the participants. These will be explained below together with some cause-and-effect relationships.

Table 4.9 Consequences of standardization

Consequences of Standardization in Modular Construction	
Speed	5
Cost efficiency	3
Solution for labor shortage	3
Automation	2
Increase in modular buildings	2
Simplification	2
Mobility	1

As a result of standardization in modular construction, we may end up producing buildings like automobiles. In essence, automobile factories are assembly lines all around the world. All components are manufactured outside. The construction industry is going in the same direction. Those components should be standardized so that they can be assembled in the factory. Thus, the building materials industry would go for an incredible standardization in terms of sizes. This is a chain reaction with many consequences. As automation became more prevalent in the industry, productivity would increase. Investment decisions could be made more easily.

> *"Modular factories must operate like assembly factories, just like the automotive industry. Thus, this transforms the building materials industry as well. Just like the container transforming the ship, and then the port. Those container dimensions even defined the limits of the product sizes. The internal dimensions of containers set the limits for optimum transportation of produced goods. The same will be true for us. Technology, cultural aspects, and logistics will be the three main factors affecting this transformation." (Participant 6)*

Standardization would make construction processes much simpler and enable predictability. It would be easier to compare buildings, especially in tenders. It would speed up processes as well. Design would speed up, because the need for new details or new decisions would decrease. Construction would speed up, and this would be especially critical in disaster recovery.

> *"By making modular systems and standardizing them, you can build buildings that you could not build otherwise in places where you could not deliver buildings otherwise." (Participant 13)*

Standardization would increase the number of manufacturers and modular buildings. There would be different styles, different exterior cladding, different interior walls, etc., which would facilitate stock control, prevention of waste, and proper use of resources. As costs would be fixed, cost efficiency would increase. The increase in volume would have a positive impact on pricing. Housing shortage could be addressed more efficiently.

> *"An investor may swiftly decide to build 5000 houses in two years, as such fast production, standardization, and achievement of continuous quality will make many inspections unnecessary. Demand is falling, it can immediately reduce it to 3000, it can increase it to 8000. The investor can make such decisions very quickly." (Participant 7)*

Automation facilitated by standardization would solve the problem of the lack of blue-collar workers. It is a big problem to find craftsmen in Europe, and the manufacturers in the UK are de-skilling with the help of automation equipment and assembly processes to solve the problem of construction labor shortage. Reducing the labor intensity would also reduce the number of accidents. Liberating some of the skilled construction workers from new home construction could allow the existing workforce to work in other areas like retrofitting old homes or producing bespoke craft houses. Thus, they could deliver something that a factory cannot and does not want to deliver. If the modular manufacturers could deliver higher quality products at a competitive or even a lower price, then this would restructure the market in terms of labor and scale in a disruptive way.

Other than these common themes, the participants made some interesting future predictions as well. One participant argued that standardization similar to that of the shipping industry would allow putting together different units—regardless of the manufacturer—that would fit different architectural styles or urban fabrics. This could be likened to houses travelling in the ocean. Thus, mobile houses could emerge consisting of a module that can be moved and connected to main stations in different places through connections similar to those of the freight containers. But the main stations must be standardized for this, otherwise it would be useless. This participant gave the example of the International Space Station, which has standard main connections for space shuttles of different countries. Each country has a different shuttle, but they all connect to the same connection.

> *"To have prefinished building modules just like plug-in Lego pieces which can be installed in a—how should I put it—main unit. Imagine*

such houses you can move and plug in any main unit, independent of location. This would also open new frontiers in architectural design. You can plug your house into a place on the 56th floor. Then you get bored and move the house to another main station in another city. We think that the system will evolve into this. It will be mobile.” (Participant 1)

4.1.13 Question 13: New Technologies and Innovations

What would be the new technologies and innovations to support standardization in modular construction?

Excluding a few participants who argued that modular construction industry did not need anything in terms of technology, but had other problems like financial, social, and bureaucratic problems, the answers of the participants can be examined under three main categories. These are improvements in production technologies, developments in software, especially AI, and advanced construction materials.

Apparently, any technology that would cut down costs without affecting the product would be beneficial. The same is true for new tools expediting production processes. According to the participants, the leading technologies in this regard are automation and robotizing. For instance, one participant noted that there were now companies using station logic in their production methodologies at the most advanced stage, and the company of this participant was also trying to move to that phase. This company was trying to perform site work in the factory environment within a station logic. This means that instead of sending different work teams to the modules, the modules would travel in the factory visiting all the 17 stations like framing, cladding, electrical works, mechanical works, painting, furniture, windows, facade, etc. In addition, these stations were evolving to a point where there will be robot arms, just like in the automotive industry, where the module will arrive at the station and the robots will operate on that module. The same participant also argued that robotizing meant liberation from manpower, therefore we had to robotize to achieve standardization and maintenance of quality. He likened this to the automotive industry, in which cars were handmade a hundred years ago, and gave the example of the Tesla Factory.

> *"As technology comes into play, order and standardization become a necessity. Just like in automotive. For example, today a code needs to be sent to the robot on the production side, it needs to enter a code for production. That robot needs to work CAD-CAM. In the background, you need a design precision of a millimeter. It seems that standardization will be pushed by technology, with the driving force of technology, even if we do not want it." (Participant 6)*

The Tesla example was given by some other participants as well. One participant talked about a fully automated company in China producing incredible numbers of containers each day. Participants talked about dark factories, where machines work all day without lights. Automation and robotizing expedited production with a minimized manpower. This is especially important in Europe where manpower is very expensive. The investment cost is high at the beginning, but then the system pays for itself.

> *"The factory is fully automated. Think of a conveyor band. Robots take modules from one place, weld it, and move it to another. The production scenario of the factory is defined. The end-product is fixed. Everything is predefined. When you define a standardized product and processes in the factory, then it looks like a science fiction movie." (Participant 2)*

One participant guessed that the number of their blue-collar workers would be reduced to one-third of the current number, because automation would come into play. Their new machines would be able to cut, bend, punch, and do everything by themselves. For this, architects and engineers needed to simplify the details in the products because the more complicated the design is, the more difficult it is for the robots to produce it. Or a more expensive robot would be needed. This participant argued that companies trying to avoid technology would perish in ten to fifteen years.

> *"Talking about technology, it is obvious that we will surrender the mental side of the process—not the emotional side yet, but the mental side—to AI in the very near future. But the AI does not want to communicate with human beings, it wants to communicate with machines. Those machines will be robots, instead of human workers. We are very close to those facilities we call dark factories. You cannot stand in the way of technology after this point." (Participant 6)*

The second category discussed by the participants was BIM software. The industry is increasingly using digital technologies including BIM and AI, and incorporation of these advanced technologies streamlines the design and construction processes, improving efficiency and accuracy. Parametric design tools and visual programming tools expedite design works. Standardization is not just the actual physical module now, as one participant put it, but the BIM model, so that anyone can use standardized drawings.

> *"The construction industry must quit producing hardcopy drawings and focus on digital twins produced in BIM. This would particularly increase productivity in modular construction. ... Standardization in this regard, a system in which BIM and modular design work together, like BIM software adapting to this, this can be an aspect of standardization." (Participant 7)*

One participant talked about the introduction of computer aided design in the late 1970s. The students, who had experienced using CAD at college, pushed their employers to start using CAD in the architectural companies when they graduated and were employed. The same thing happened with Revit and BIM. The students experiencing the 3D software at college wanted to use similar software and a similar approach to design when they graduated and then got a job. Thus, artificial intelligence could go the same way because students are actually experiencing it at college. When they graduate and get a job, they will be looking to use their experience of AI in design and construction.

Another participant compared industrialization with indoor construction and talked about the technical limitations in terms of the technology we have at the moment. He argued that these limitations would create no issues in indoor construction, because skilled construction workers working indoors could do whatever they are asked. However, when the manufacturing equipment had to deliver more variability, such as changing dimensions of a wall with greater ease on a manufacturing line, new technology and innovation would be required to create a common language between the BIM software and the automation equipment to smooth this process, creating flexibility and efficiency. Existing equipment can handle some design variation, but there are limitations to this. Ideally, the equipment should be able to automatically adjust itself between different project types. In addition, software used by different equipment specialists is mostly different and there may be interoperability issues.

The third and the last category mentioned by the participants is advanced construction materials. Innovations in the carbon steel that is used in the load bearing systems, or thinner materials superior to carbon steel, similar to those used in space technologies would be beneficial. There is research on concrete as well. For instance, one participant talked about a company in Germany which started producing modules from lightweight concrete. Normal concrete weighs 2250-2300 kg/m^3 but this company uses special additives to make it 650-700 kg/m^3. Timber is another material praised for its lightness as well as its renewability. One participant pointed out the industrial forests as sustainable resources and argued that they should be studied well.

Other than these three themes, one participant from the UK pointed at the need for regulatory flexibility in designs. According to him, innovation needed to be in creating regulatory flexibility that enabled material substitutions while maintaining regulatory integrity. At the moment, each manufacturer has to pay for fire tests and approvals for their building designs. If these could be shared between manufacturers, there would be no duplication among the manufacturers choosing to use similar materials. This participant argued that new technology and innovation was required to enable manufacturers to share pre-designed and tested construction details.

4.1.14 Question 14: Final Comments of the Participants

Would there be any suggestion or recommendation you would give to professionals or decision-makers working in the industry on this subject? Or is there anything you would like to add?

As this is the final and the most open-ended question of this interview, many different responses were given. Some were related to the problems of industry, some were country specific, and some were related to expectations or projections for the future.

A major problem of the industry was preference of cost over quality. When the consumers wanted cheap and low-quality products, the manufacturers just did that and supplied cheap and low-quality products. Especially in Turkey, even big companies preferred these cheap products, although they had the means to purchase better products. An increase in the awareness of the clients was needed in the industry. Companies could not push clients because they had to compromise to be competitive. However, unified opinions declared by the industry players were taken into consideration in the international arena, so companies needed to organize, first at the national level, and then internationally.

Another country specific problem was the lack of systematic approach in Turkey. One participant argued that standardization had to be based on systematic working, and in Turkey, even a standard CAD layering system could not be established in design offices. Therefore, a systematic approach had to be embraced as a country. Another participant argued that technical issues had to be liberated from politics.

An important aspect mentioned by the participants was the importance of being open-minded and never stopping learning. Hard work and research are very important in this regard, and transformation is only possible with professional efforts. NGO initiatives should be supported, the professionals should never stop learning, and especially the technical people in the public institutions should be in this mindset. The biggest problem in the construction industry is that the professional community has stopped learning.

> *"The building materials industry in Turkey is quite advanced, but our construction industry is still at the level of Industry 2.0, that's for sure. We are not even at Industry 3.0." (Participant 6)*

The participants contended that we could not solve the current housing problem with conventional construction methods. Especially architects have to be open minded about modular technology and the new way of building. The architects have a greater responsibility to lead the way, and all the other disciplines will follow. One participant argued that we could transform the industry with a simple pattern just like the pattern brought by the freight container. He stated that we would shortly see big automotive brands producing solutions for the housing industry, and the companies failing to transform would miss the chance to take a share of the international market.

> *"When you meet your existing needs with the conventional method, you trigger a much bigger problem because our industry makes 38% of carbon emissions. If you continue to meet your needs in the same way in your country, it will actually disrupt the environment we live in, and your economy will soon be shattered by those restrictions caused by carbon emissions." (Participant 6)*

Continuous research is very important to increase people's awareness and to raise demand. The best way to prove the effectiveness of modular construction is to present simple and summarized conclusions of experiments and research such as PhD studies and articles, because people look at the return of an investment to invest in it. The financial and social benefits of modular buildings and their benefits in terms of sustainability can be proven by these academic studies. Social benefits are especially important because modular construction means that workers work in a safe environment. There are fewer business problems, less disturbance to the local community, and less traffic obstruction. These social aspects must be discussed in scientific studies so that investors and the public will have a more positive opinion about modular construction. Eventually demand will increase and more investors will come. When the inferior image of modular construction is replaced with an image identified with innovation, this will create different results in the industry.

The factory produced buildings of the 21st century should be regulated by governments, and sustainability metrics should be integrated into design standards to promote the use of eco-friendly materials and construction practices. The standard contracts such as FIDIC, CC, or AIA should be adapted to modular, because there are a lot of different scopes in modular buildings. These must be very well defined in the drawings and the specifications, as well as the contracts.

Participants from the United States and Canada stated that new modular construction or design companies started each day, but many died as well. It is a big investment and there is a lot of coordination that needs to happen. Yet, a lot of people get into this industry without fully understanding the principles of design and implementation. In modular buildings, one should understand the limits of the methodology that is being used.

> *"Because a lot of times people starting factories just want to make a lot of money. And the reality before being able to make something that's worth a lot of money takes a lot of work and a lot of coordination." (Participant 15)*

CHAPTER 5

DISCUSSION

5.1 Summary of Findings

In this study, a 14-question interview was conducted with 15 industry professionals. Of the 15 participants, 7 were architects, 5 were engineers, and 3 were from economic sciences. Naturally, this is not a large enough population to draw any statistical conclusions, therefore the aim here was to find the common themes and discuss the topics that emerged.

First of all, there are differences among the participants with regard to the perception of modular construction. However, all participants are in agreement that it is about producing something in the factory, instead of the construction site. Most of the participants emphasized the mode of production rather than what is produced, whether it be 3D volumetric modules or 2D panels. Thus, modular construction is perceived as something that combines construction and manufacturing.

The participants mentioned several building groups for which modular construction can be a convenient method of construction. These include mass housing, hospitals, clinics, hotels, student housing, classrooms, or prisons. However, the most popular examples in this regard are the modular high-rise residential buildings and hotel buildings that were built in recent times.

The participants mentioned five major advantages of modular construction compared to conventional construction. These are time, quality, cost control, safety, and sustainability. The participants declared that the most important topic was shortened production time enabled by aspects like increased efficiency, distribution of production, parallel production on site and in factory, etc.

The participants perceived standardization as reducing the variability and bringing a certain order for the production facility to work in a flowing system, so that manufacturers will know what they will manufacture and how they will manufacture it. But this will be achieved by standardizing the design. In modular construction, the design stage causes the biggest loss of time and standardization can be a solution for this.

Several responses given by the participants revealed three main aspects of standardization as sizes and dimensions, performance, and interfaces. The responses of the participants show that two factors are critical, or even decisive, in determining dimensions in modular construction. The first one is road and maritime transport standards. The second factor is the standard dimensions of the raw materials that are used in the production of modules. Length of steel profiles, drywall frames, pipes, gypsum panels, lumber dimensions, dimensions of cement boards and similar are included in this. The second aspect, standardization of performance, includes structural standards, composition of walls, thermal insulation, sound insulation, fire safety, and similar parameters. The third and the last aspect is standardization of the interfaces between modules and subcomponents. This includes connections between modules, connections between modules and a main building, and system connections such as ventilation, electricity, water, etc. In addition, there are two levels of standardization which are in-house standardization and compatibility between companies. For in-house standardization, a company must have sufficient economic strength and stand to be able to impose their own products instead of the client’s design. Regarding the compatibility of products of different companies, there are two aspects. These are interoperability, which means the possibility of using products of different manufacturers together, and interchangeability, which means swapping manufacturers.

Most participants are of the opinion that standardization can and should be achieved. It is beneficial and has many advantages in terms of cost and time. It speeds up production, reduces material and labor costs, and reduces the generation of construction waste. Even if global standards cannot be achieved, regional standards or standards on the basis of building type can be achieved in modular construction.

It is significant that the biggest obstacle to standardization in modular construction is declared to be the human factor, and not technical issues. The human factor mainly consists of two groups, the clients and the architects. Apparently, architects need to release their fear of losing control over design and change their mindset to adapt to modern methods of construction. On the other hand, as people's awareness increases, it will become easier to accept modular buildings.

The most basic feature of modular buildings is that they are manufactured somewhere and then erected in another place. Because of this, the discrepancies between the regulations of different countries, or different regions, is a major barrier against standardization. These differences create a significant problem, especially in terms of inspections. It is rather ambiguous where and how modular buildings will be inspected. The lack of an established inspection system and the heightened perception of risk create regulatory friction such that higher standards may be required for modular buildings in terms of safety, insulation, etc.

In order to achieve standardization in modular buildings, the market share must increase. It is still a niche market and when the number of modular manufacturers increases, the industry will inevitably standardize within itself. As a matter of fact, some participants argued that modular construction is starting to become a necessity, especially in Europe, and companies lagging behind are losing their market share.

Participants are of the opinion that standardization is beneficial for both the manufacturer and the end user in terms of speed, financial issues, and convenience. The design phase of modular buildings takes a lot of time, and standardization of design will significantly accelerate works. In addition, one of the biggest cost items in the construction industry is the design changes made during construction, for which standardization may be a solution. The cost of standard work is always much lower. Prevention of labor waste, reduction in stock costs, and reduction in waste are some of the aspects that contribute to the economy enabled by standardization in modular construction. In addition, streamlined design and manufacturing processes are indirect savings items. Also, modular construction has a tremendous ability in waste management, and this will shift to another level with standardization.

Some participants argue that standardization and freedom of design are inversely proportional and there is no way these two could go together. Yet others think that it also opens new venues of creativity. Conventional construction has its own standards and limitations, and the framework drawn by standardization can either be considered as a constraint or a necessity. It only requires a change of mindset. On the other hand, not all buildings are fit for modularity and the aim of modular construction is not to create architecturally unique buildings anyway. The main purpose of modularity is to achieve standardization, mass production, and repeatable production. The logic of standardization is to make something more economical, faster, more robust, and more efficient.

Standardization in modular buildings can be created within the industry by a collaboration of the stakeholders including contractors, manufacturers, factories, designers, customers, the government, insurance companies, etc. All of these stakeholders need to be part of the conversation, and they need to be listened to. Yet standardization should also be supported by the governments via regulations and incentives. The lack of a worldwide definition or established standards for modular buildings are causing confusion at the moment. It is argued that architects should lead the way in this regard. They should say that standardization is not a restriction, but an order within which new venues of creativity can be found. And technical people should not stop learning. This is a major problem in the industry.

In the second part of the questionnaire, the participants were required to compare the standardization process of modular construction to that of the freight container. Some participants quite liked this question, but some were apparently disturbed by it. It was explained to them that this example was chosen partly because it was a very extreme example, so that it would challenge the interviewees and lead them to examine the subject in a little more detail. Although most of them thought that it was impossible to directly compare the shipping industry and the modular construction industry at the beginning, this question made people think. Naturally, no one expects that level of standardization in the modular construction industry, but as people contemplated the issue, they started thinking about different aspects of it. For instance, standardization could be achieved in certain parameters or certain building groups. Certain components like doors and windows could be standardized or there could be regional standards. It was even discussed whether an agreement could be reached between the metric system and the imperial system, just like what Corbusier tried to achieve a hundred years ago.

One participant argued that the shipping industry had 100 years to optimize, and any system would optimize in 100 years. However, the modular industry also had 100 years but did not optimize. As a matter of fact, the shipping industry standardized in a couple of decades. Maybe the shipping industry had a greater need to optimize because it is very common in the world and had no choice but to be optimized. Modular construction is not as common. This brings us back to the previous argument that the market share must increase to achieve standardization in modular buildings. On the other hand, some participants thought that established standards would scale up modular construction. So, it works both ways. Market share and standardization feed each other.

Improvements in production technologies, developments in software, especially AI, and advanced construction materials are the three major categories of innovations that can support the standardization processes in modular construction, and also modular construction itself. The leading technologies in this regard are automation and robotizing. Automation and robotizing expedite production with a minimized manpower. This is especially important in Europe where manpower is very expensive, and craftsmen are scarce. There are in fact companies using station logic in their production methodologies at the most advanced stage. The number of dark factories is increasing. The investment cost is high at the beginning, but then the system pays for itself.

The industry is increasingly using digital technologies including BIM and AI, and incorporation of these advanced technologies streamlines the design and construction processes, improving efficiency and accuracy. Parametric design tools and visual programming tools expedite design works. Standardization is not just the actual physical module now, but the BIM model, so that anyone can use standardized drawings. The biggest need in this area is the development of tools that will provide flexibility of production to enable mass customization. In addition, the development of advanced construction materials and improvements in the current materials such as carbon steel, concrete, and timber would be very beneficial. Especially timber products are very important in this regard because it is a renewable resource with less carbon footprint, and industrial forests should be well studied across the world.

Some of the participants are more optimistic about setting standards in the modular building industry, and naturally, there are those against it. Although the population of the interviewees of this study is very small, it was observed that the average age of those who approached the matter positively is slightly lower than that of the negative thinkers. This could be an indicator of a generation gap. As a matter of fact, it seems that the industry is headed in this direction, and some participants even argued that this was already happening. Some argued that we could end up producing buildings like automobiles as a result of standardization in modular construction. Modularity enables manufacturing high-end products at factory precision, and standardization would make construction processes much simpler and allow predictability. Design would speed up, because the need for new details or new decisions would decrease. Construction would also speed up, and this would be especially critical in disaster recovery. Some participants expressed how important it is to standardize disaster buildings in order to provide rapid response.

The country that works most intensively in the area of standardization seems to be the UK with a collaboration of the state, the industry, and the academia. It is very important to collaborate and share in this business, and continuous research is very important to increase people's awareness and to raise demand. When the inferior image of modular construction is replaced with an image identified with innovation, this will create quite different results in the industry.

5.2 Summary of Standards

In the figure below, a summary of the areas of standardization that emerged in the questionnaire conducted within the scope of this research is presented. These areas are categorized under three main topics as design, production, and administration with further subtopics.

The findings of the questionnaire revealed a different profile than thought at the beginning of this study. While the participants were expected to propose standards related to module types, module dimensions or spatial dimensions, the most frequently mentioned issues in the interviews were regulations, transportation restrictions and performance standards, as can be seen in the figure below. The most basic principle of modular construction is that modules are produced and erected in different locations. For this reason, incompatibility in regulations, traffic rules and inspection procedures between countries or regions are particularly challenging in terms of modular construction practice. Accordingly, participants are of the opinion that these are first priority issues that need to be standardized. Structural design and electromechanical systems also stand out as other issues that need to be standardized for the same reasons.

As can be seen in the figure below, the areas that need to standardize are mainly located in design and administration categories. In the next section, a framework for action is given.

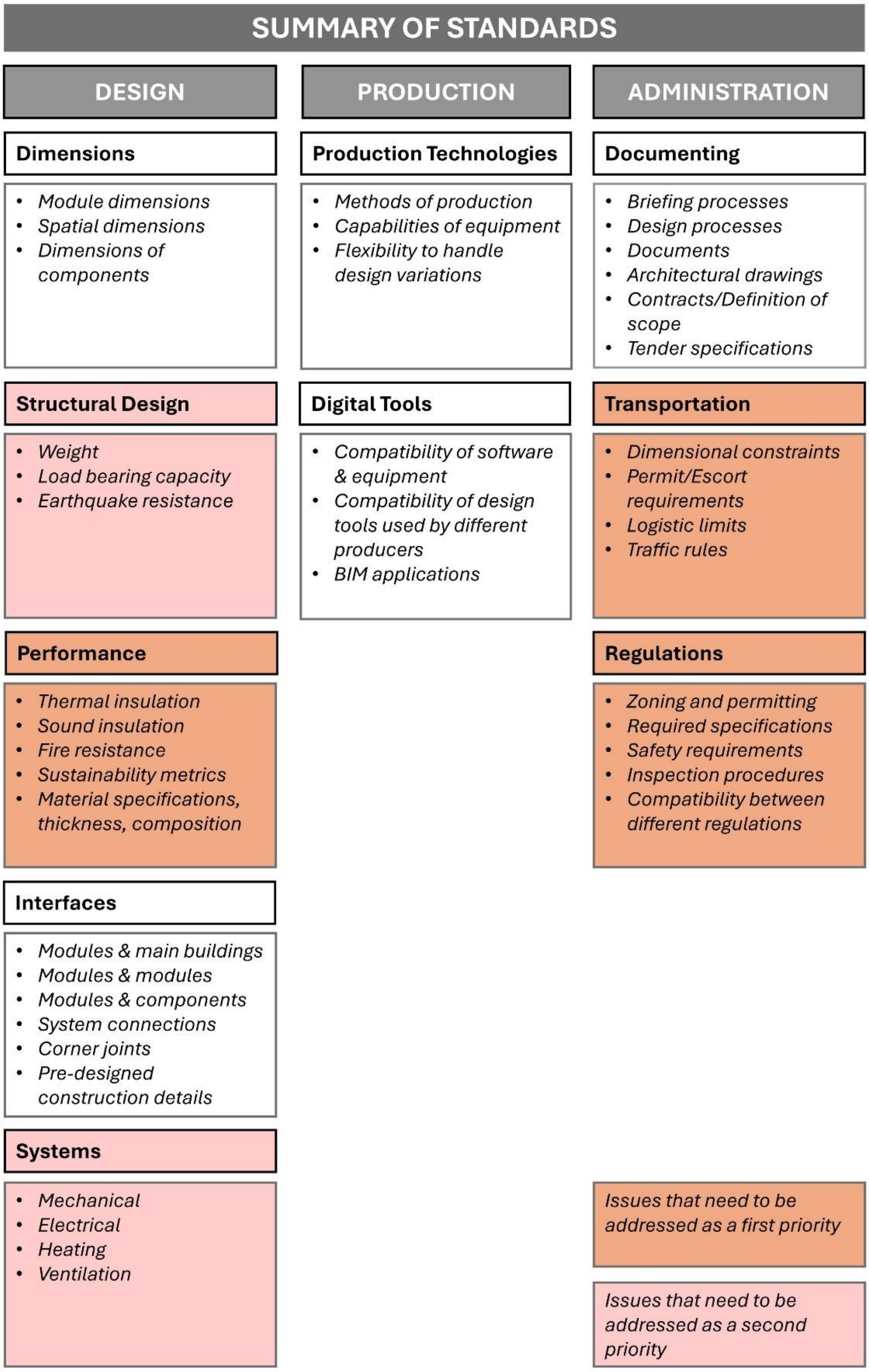


Figure 5.1. Summary of Standards

5.3 Recommended Framework for Action

The Framework for Action given below is the last part of this section. In the light of the insights obtained as a result of the interviews with industry professionals, the recommended steps to be taken by different stakeholders in order to achieve standardization in modular buildings are listed below. The subject is discussed under four main stakeholder groups: Architects/Designers, Manufacturers, Governments/Public Institutions, and Academia and NGOs.

5.3.1 Architects/Designers

The participants considered the attitude of architects as a critical barrier against not only standardization in modular buildings but modular buildings themselves. Architects are prejudiced against modular buildings whereas they should be the ones leading the way. The recommended actions for architects are as follows.

- Architects should be open-minded and keep learning.
- Architects should understand the benefits of modern methods of construction and promote them.
- Architects should understand that standardization is not a constraint, but it is a guideline in which a lot of space for creativity exists.
- Architects should take the responsibility to lead the way, so that the other disciplines may follow.

5.3.2 Manufacturers

Preference of cost over quality is a major problem for the industry. Manufacturers mostly have to comply with the clients' demands. They have to compromise to be competitive. Companies need to have a certain stand and power to dictate their own standards. When the consumers want cheap and low-quality products, the manufacturers mostly do that. The recommended actions for manufacturers are as follows.

- Unified opinions declared by the industry players are taken into consideration in the international arena. Therefore, companies need to organize, first at the national level, and then internationally.
- Companies should be willing to collaborate and share. The example of the town in Czechia is a good example of this where tiny workshops became strong businesses by standardizing among themselves. Small manufacturers may be a greater force by unifying.
- Companies should be willing to invest in research and development.

5.3.3 Governments/Public Institutions

There are basically two problems challenging modular construction in terms of rules and regulations. First, there are still no set of established rules and regulations for modular buildings, and there are inconsistencies between the existing ones. Second, regulations of different countries, even different provinces may be different, which is detrimental due to the mobile nature of modular buildings. As they are produced in one place and erected in another place, compliance between regulations is essential. The same is also true for transportation regulations. The recommended actions for public institutions are listed below.

- Public institutions should engage various stakeholders, including architects, engineers, and suppliers to develop regulations specific to modular buildings. They should promote and support research and development in the area.
- Structural design of modular buildings must be regulated.
- Safety standards should be developed for modular buildings including fire resistance, warranty, thermal performance, sound insulation, material specifications, etc.

- Standards should be developed for electromechanical systems to be used in modular buildings.
- An established inspection system should be created. In this way, the heightened perception of risk can be eliminated.
- Permitting procedures should be standardized for modular buildings.
- Public institutions should employ knowledgeable and experienced personnel in modular buildings. They should collaborate with third party consultants if needed.
- Traffic regulations should be standardized for transportation of modular buildings.

In the second stage, different countries should collaborate to develop common standards, especially on issues such as safety, performance, inspection, transportation, etc. because the lack of common standards among different countries is one of the major challenges in the industry.

5.3.4 Academia and NGOs

In the interviews conducted in this study, it was revealed that the human factor, especially cultural barriers, is a significant obstacle to the development and standardization of modular building industry. A shift of awareness among clients is crucial in this regard. Continuous research is very important to increase people's awareness and to raise demand.

- More academic studies related to modular buildings need to be done and various advantages of modular buildings need to be conveyed to people correctly such as technical, economic, and social advantages.
- It is necessary to change the image of inferior modular buildings in people's minds and to explain that modular buildings are high-end products. NGOs should promote modular buildings in this regard.

- It is a generally accepted issue that factory production and standardization in consumer products increase product quality. The work to be done by academic institutions and NGOs is of great importance in order to explain to people that the same is true in buildings.

CHAPTER 6

CONCLUSION

6.1 Summary of the Research

It is widely acknowledged that the construction industry has a productivity problem. Although the construction industry has a huge economic impact as one of the most important industry sectors in many countries, it is amongst the lowest R&D intensity sectors. There is an extensive gap regarding new technologies in the context of construction projects, and the value of digital processes, automation and industrialized construction are still essentially unexplored.

After defining the problem as the lack of productivity in the construction industry, modular construction was proposed as a solution to this problem. An extensive literature review was made on the subject. A brief history of modular construction, types, design processes, benefits and constraints, and realized modular projects were investigated. It was observed that there is usually a case-based approach in current research without any attempt at standardization. No definitive work could be found for the architects to build their projects on. In addition, there are certain drawbacks that slow down the adoption and implementation of modular construction.

The ISO freight container was studied as the selected exemplary material. Definition, history, structural properties, technical specifications, and related regulations were examined. The standardization story of the shipping industry was explored, and it was questioned how this could serve as a model for the modular construction industry. Another topic examined within the literature review was the growing housing problem in the world and how modular construction could be a remedy for this.

To compare the findings from the literature review to the actual situation in the industry, a number of interviews were conducted with industry professionals. For this, a semi-structured interview was designed, and the transcripts were used as the material of this study. Many industry professionals were contacted, and interviews were conducted with those who responded and accepted this invitation. 40 professionals were contacted in total. 14 agreed to give an interview, 1 gave written answers, and 2 declined. One of the companies declining the interview provided some short notes expressing their opinions on the subject. There was no response from the remaining invitees. The interviews were recorded and transcribed. The Turkish texts were translated into English. A qualitative analysis was performed on these texts.

6.2 Major Findings and Contribution

As shown in the first chapter of this study, research related to modular buildings is scarce. There is a gap between academic research and industry in this area, and academic research is lagging behind for the moment. There are hardly a few publications about standardization in modular buildings in the literature, and most of the information used in this study was directly sourced from industry. On the other hand, the increasing number of publications in recent years shows that the topic is gaining attraction.

More scientific research is needed to support the industry. All of the professionals interviewed, without exception, were of the opinion that more academic studies should be done on this subject leading the way. Academic studies will play a significant role in changing the inferior image of modular buildings and standardization in the eyes of people. When this inferior image is replaced with one identified with innovation, this will create quite different results in the industry. For instance, the regulatory friction caused by the heightened perception of risk related to modular buildings can be resolved in this way.

The originality of this study is based on the fact that it contains up-to-date information from professionals working in industry. Many valuable insights were revealed in the interviews with industry professionals related to the perception of standardization in modular buildings, its parameters, benefits and constraints, its relationship with architectural design, regulatory issues, consequences on the entire construction industry, and the technological improvements that are needed to facilitate standardization in modular construction. These insights are given in detail in Chapter 4 and Chapter 5. The findings of the questionnaire revealed a different profile than thought at the beginning of this study. While the participants were expected to propose standards related to module types, module dimensions or spatial dimensions, the most frequently mentioned issues in the interviews were regulations, transportation restrictions and performance standards.

Most professionals think that standardization can and should be achieved. It is beneficial and has many advantages in terms of cost and time. It speeds up production, reduces material and labor costs, and reduces the generation of construction waste. Even if global standards cannot be achieved, regional standards or standards on the basis of building type can be achieved in modular construction. On the other hand, it is significant that the biggest obstacle to standardization in modular construction is declared to be the human factor, and not technical issues.

In order to achieve standardization in modular buildings, the market share must increase. It is still a niche market and when the number of modular manufacturers increases, the industry will inevitably standardize within itself. As a matter of fact, some participants argued that modular construction is starting to become a necessity, especially in Europe, and companies lagging behind lose their market share.

Standardization in modular buildings can be created within the industry by a collaboration of the stakeholders including contractors, manufacturers, factories, designers, customers, the government, insurance companies, etc. All of these stakeholders need to be part of the conversation, and they need to be listened to. Yet standardization should also be supported by the governments via regulations and incentives. The lack of a worldwide definition or established standards for modular buildings are causing confusion at the moment. Architects should lead the way in this regard, acknowledging that standardization is not a restriction, but an order within which new venues of creativity can be found, and the first thing that needs to change in the industry is the mindset.

6.3 Limitations and Further Research

This study, which aimed to draw a framework for standardization in modular construction, is based on semi-structured interviews conducted with a limited number of industry professionals, and it reflects the opinions of these professionals. It was planned as a qualitative study, and the population is not large enough to draw any statistical conclusions. The aim was to find the common themes and discuss the topics emerging in the interviews.

In the future, this study can be revised according to the initial inferences here and expanded as a long-term study examining more topics with a higher number of participants from different countries. It can be conducted in a quantitative manner allowing statistical results as well. A comparative study can be made to make a more precise determination of different conditions and different approaches in different countries or regions.

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APPENDICES

A. Interview Questions in English

<u>Interview Questions – Modular Construction</u>

Introduction

1. Can you introduce yourself and give brief information about your experience in the construction industry, particularly in modular construction and prefabrication?

Perception of Modular Construction

2. How would you define modular construction? What are the main characteristics that differentiate modular construction from conventional construction?

3. What are some examples from the world that come to mind when you think of modular construction?

Standardization, Advantages and Disadvantages

4. What does standardization in modular construction mean to you? Do you think it is possible? What is the importance of standardization in the field of modular construction?

5. What are the main challenges associated with the standardization of modular construction processes and components, and in what areas do you think standardization is required?

6. In your opinion, how can standardization increase efficiency and quality in modular projects?

7. How do you think standardization affects freedom of design and creativity, or how can a balance be achieved between the two?

8. How do legal regulations affect the standardization processes in modular construction?

Execution

9. Are there any successful attempts at standardization in modular construction you have observed or been involved in? If so, what do you attribute this success to?

10. How do you think the adoption of standardization in the field of modular construction can be promoted?

Future Predictions

11. Considering standardization attempts in other industries, such as the station or platform approaches in the automotive industry or the standard freight containers in the shipping industry, do you think that there can be a similar standardization process in modular construction? If so, what elements do you think need to be standardized?

12. What would be the effects and consequences of this on the construction industry?

13. What would be the new technologies and innovations to support standardization in modular construction?

14. Would there be any suggestion or recommendation you would give to professionals or decision-makers working in the industry on this subject? Or is there anything you would like to add?

B. Interview Questions in Turkish

Mülakat Soruları – Modüler İnşaat

Giriş

1. Kendinizi kısaca tanıtır mısınız? İnşaat sektöründe, özellikle modüler inşaat alanındaki deneyiminizle ilgili bilgi verir misiniz?

Modüler İnşaat Algısı

2. Sizce modüler inşaatın tanımı nedir? Geleneksel inşaat yöntemlerinden ayıran temel özellikler nelerdir?
3. Modüler inşaat deyince aklınıza gelen belli başlı örnekler hangileridir?

Standartlaşma, Avantaj ve Dezavantajlar

4. Modüler inşaatta standartlaşma kavramından ne anlıyorsunuz? Sizce sağlanması mümkün mü? Standartlaşmanın modüler inşaat alanındaki önemi nedir?
5. Kendi deneyiminize dayanarak modüler inşaat süreç ve bileşenlerinin standartlaştırılmasıyla ilgili temel zorluklar nelerdir? Hangi alanlarda uyum sağlanması gerekir?
6. Sizce standartlaşma, modüler inşaat projelerinde verim ve kaliteyi nasıl yükseltebilir?
7. Sizce standartlaşma, tasarım özgürlüğünü ve yaratıcılığı nasıl etkiler? İkisi arasında nasıl bir denge sağlanabilir?
8. Yasal düzenlemeler modüler inşaatta standartlaşma süreçlerini nasıl etkiliyor?

Uygulama

9. Rastladığınız veya bünyesinde çalıştığınız, modüler inşaatta standartlaşmaya yönelik başarılı girişimler oldu mu? Olduysa bu başarıyı neye bağlıyorsunuz?
10. Sizce modüler inşaat alanında standartlaşmanın benimsenmesi nasıl teşvik edilebilir?

Geleceğe Yönelik Öngörüler

11. Otomotiv endüstrisindeki istasyon veya platform yaklaşımları veya denizcilik endüstrisindeki standart yük konteynerleri gibi diğer endüstrilerdeki standardizasyon girişimleri göz önüne alındığında, modüler inşaat alanında da İSO standartları gibi bir standartlaşma sağlanabileceğini düşünüyor musunuz? Bunun için hangi unsurlarda uyum sağlanması gerekir?
12. Bu mümkün olsaydı, tüm inşaat sektörü üzerindeki etkileri nasıl olurdu?
13. Sizce bu standartlaşmayı destekleyecek teknoloji ve yenilikler neler olabilir?
14. Endüstride çalışan profesyonellere veya karar alıcılara bu konuda vereceğiniz öneri veya tavsiyeler nelerdir? Son olarak eklemek istediğiniz şeyler var mıdır?

CURRICULUM VITAE

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EDUCATION

Degree	Institution	Year of Graduation
M. Sc.	METU Building Science	2001
B. Arch.	METU Architecture	1998
High School	TED Ankara College	1994

PROFESSIONAL EXPERIENCE

2024 – Present	Gazi University, Department of Architecture Part Time Instructor in Architectural Design Studio, “Studio Think Imagine”
2012 – Present	ALMILA İnşaat Mimarlık Mühendislik Müş. Tic. Ltd. Şti. (ALMILA Construction Design Engineering and Consulting) Owner/Architect
2009 – 2012	SİNPAŞ GYO / SİNPAŞ REIT Project Director, Project Development and Process Management Department
2001 – 2008	PRO^GE Proje Geliştirme ve Yönetim Merkezi A.Ş. (Project Development and Management Centre) Architect, Project Management Team
2001 – 2008	INNOCENT Teknoloji Tasarım Geliştirme Merkezi A.Ş. (Innovation Centre for Design and Technology) Architect, Research & Development Team in METU Technopolis
2000 – 2001	Mesa Mesken Architect
1999 – 2000	Türkiye Müteahhitler Birliği (Turkish Contractors Association)
1998 – 1999	Türkiye Ekonomik ve Toplumsal Tarih Vakfı (History Foundation of Turkey)

FOREIGN LANGUAGES

Advanced English, Intermediate German

PUBLICATIONS

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