

ANALYSIS OF MODULAR CONSTRUCTION TECHNIQUES ADVANTAGES AND DISADVANTAGES

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The absence of alternatives clears the mind marvelously.
Henry Kissinger

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Ao final deste ciclo, impossível olhar para trás e não me emocionar com todas as recordações que trago comigo, cada uma das experiências vividas ao longo destes anos, hoje fazem parte de quem sou, como profissional e como humano.

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落合磨先生 と 恭子先生 – どうもありがとうございます。

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ABSTRACT

Modular construction is a modern method of construction that involves assembling prefabricated modules off-site and integrating them into the overall structure at the building site. This highly industrialized process is largely performed in a factory environment, where approximately 80% of the total construction process can be completed. The promotion of off-site manufacturing and on-site assembly, improves construction efficiency, safety, and productivity.

Prefabricated structures became popular as a means of supplying the high demand for affordable housing after the war. However, the rapid expansion of "systemized" building exceeded the technical understanding and collective experience at that time. Customers perceived it as inferior in terms of quality and durability, impeding its growth. Today, modern modular construction has seen a resurgence due to technological advances and increased demand for sustainable and cost-effective construction options.

Climate change, increasing urbanization, and galloping demographics are forcing us to rethink old and antiquated building methods. Costs have risen and shortages in materials and labor are becoming more frequent, demanding new and sophisticated methodologies to advance our sector toward industrialization. In this sense, software compatibility and modeling technologies have brought forth numerous possibilities in the field of architecture, offering levels of precision and detail richness previously unattainable. Digitally assisted projects have the potential to deliver exclusive architectural solutions that were hindered by barriers, preventing their full development.

This investigation aims to introduce volumetric construction and its main characteristics. Starting from the historical contextualization of the use of prefabricated structures, a comprehensive analysis of the available literature for this type of construction will be assessed to evaluate the alternative potential for improving productivity throughout the sector. The objective is to elucidate contexts in which this methodology could be preferred for project execution, evaluating ways to maximize its potential benefits and mitigate possible obstacles and interferences.

Different materials for the layouts of structural components and the envelope were considered, as well as their implications for the complexity and development of this type of project. Through the simulation of its use for a range of applications, the study argues that the advantages could be more significant when used for the construction of multiple, medium-sized, and repetitive or cellular buildings. In addition, technique advancements are presented as mitigation instruments for the stages identified as critical for the unrolling of activities, namely, the design conception and the further transportation of fully finished units to the place where they will be installed and connected.

KEYWORDS: industrialized construction, prefabrication, modular, volumetric

RESUMO

A construção modular é um método moderno de construção que consiste na montagem de módulos pré-fabricados fora do local, seguida de sua instalação no sítio da construção. Este processo altamente industrializado é majoritariamente realizado em um ambiente fabril, onde cerca de 80% do processo total poderá ser concluído. Isso estimula a produção rentável, segura e eficiente.

As estruturas pré-fabricadas tornaram-se populares como um meio de fornecer habitação acessível no pós-guerra. No entanto, a rápida expansão da construção "sistematizada" excedeu a compreensão técnica e a capacidade coletiva naquele momento, assim os clientes muitas vezes as percebiam como inferior em termos de qualidade e durabilidade, o que impediu o seu crescimento. Hoje, a construção modular moderna tem visto um ressurgimento devido aos avanços tecnológicos e à crescente demanda por opções de construção sustentáveis e economicamente eficazes.

As mudanças climáticas, a crescente urbanização e rápida evolução demográfica obrigam-nos a repensar métodos de construção antigos e antiquados. O aumento dos custos e a escassez de materiais e mão de obra são cada vez mais frequentes e exigem novas metodologias sofisticadas para viabilizar o imensurável avanço do nosso setor em direção à industrialização. Nesse sentido, a compatibilização via software e tecnologias de modelagem trouxeram inúmeras possibilidades no campo da arquitetura, oferecendo níveis de precisão e riqueza de detalhes antes considerados inatingíveis. Esses projetos assistidos digitalmente têm o potencial para fornecer novas soluções arquitetônicas que antes impediram o pleno desenvolvimento da metodologia no mercado.

Esta investigação tem como objetivo introduzir a construção volumétrica e as suas principais características. A partir da contextualização histórica do uso de estruturas pré-fabricadas, será realizada uma análise abrangente da literatura disponível para este tipo de construção para avaliar o potencial alternativo de melhorar a produtividade em todo o setor. O objetivo é, então, elucidar contextos nos quais esta metodologia poderia ser preferida para a execução do projeto, avaliando maneiras de maximizar os seus potenciais benefícios e mitigar possíveis obstáculos e interferências.

Foram considerados diferentes materiais para os layouts dos componentes estruturais e do invólucro, bem como as suas implicações para a complexidade e desenvolvimento deste tipo de projeto. Através da simulação do seu uso para uma variedade de aplicações, o estudo argumenta que as vantagens poderiam ser mais significativas quando usadas para a construção de empreendimentos múltiplos, de tamanho médio e repetitivos, ou celulares. Além disso, avanços tecnológicos são apresentados como instrumentos de mitigação para as etapas identificadas como críticas para o desenvolvimento das atividades, nomeadamente, a concepção ou design e o transporte adicional de unidades completamente acabadas para o local onde serão instaladas e conectadas.

PALAVRAS-CHAVE: construção industrializada, prefabricação, modular, volumétrica

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SYMBOLS, ACRONYMS AND ABBREVIATIONS

AEC Architectural, Engineering and Construction projects.

BIM Building Information Modelling

BTB Beam to Beam (connection)

CAGR Compound Annual Growth Rate

CE Conformité Européene

CLT Cross Laminated Timber

CTC Column-to-Column (connection)

Dfma Design for Manufacturing and Assembly.

DfR Design for Reuse

DSF Double Skin Façade

EPS Expanded polystyrene

FTF Fitting-to-fitting Connection

HVAC Heating, Ventilation and Air Conditioning

IBC International Building Code

ISO Polyisocyanurate

JIT Just in Time

KPI Key Performance Indicator

LOB Line of Balance

MIS Modular Integrating System

MMC Modern Method of Construction

OSB Oriented Strand Board

OSC Off-site Construction

OSM Off-site Manufacturing

PCSC Prefabricated Component Supply Chain

P-DfMA Platform Design Approach for Manufacture and Assembly

PVC Polyvinyl Chloride

RA Recycled Aggregate

RFID Radio Frequency Identification

SIP Structural Insulated Panel

XPS Extruded Polystyrene

1

INTRODUCTION

1.1 CONTEXT

The advancement of broadband technologies and information technology has brought about a revolution in communication processes, resulting in significant performance improvements across various sectors of the economy. However, despite being a significant contributor to the world's total economic production, the construction sector has been slow to adopt these innovations, possibly due to its unique characteristics.

In terms of site production, construction is not a fixed-base industry, unlike production in areas such as automotive, airplane or ship manufacturing. On contrary, construction is a one-of-a-kind production. This means exclusive and unique building products are designed in order to comply with the different requests of clients and, its successful restructuring requires changing traditional relationships to a shared culture without regard to organizational boundaries [1].

With that in mind, the industrialization of construction aims to improve productivity through increased mechanization and automation and **modularity** is one of the commonly involved processes. Indeed, the manufacturing industry considers modularity as a crucial concept that has played a significant role in facilitating widespread industrialization by integrating standardized and prefabricated products [2].

By carrying most of the works off-site, higher levels of quality and precision can be reached, and approximately 80% of the activities can be transferred to a covered and safe environment, reducing accidents and improving general working conditions. A great asset for the construction sector industry which uses more than half of the natural resources extracted from the planet in the production and maintenance of the built environment [3]. Through this standardization, mass production can be conducted off-site, in a controlled factory environment, leading to several benefits that will be the center of this investigation.

The primary challenge is to establish a standardized model unit or module that can be fully designed and replicated in a factory. While there may be a greater upfront design phase for early projects, the duration of subsequent design phases will decrease as designs are repeated (and improved), resulting in potential time savings of up to 28% [4]. The solutions can be temporary or permanent and allow for a wide range of techniques to be implemented to

define the best layout for these modules, as well as a functional and aesthetically appealing way to arrange them.

Once manufactured, those units need to be transported from the factory to the site where they will be assembled. Striking a balance between robustness, to ensure adequate resistance strength, and lightness, which impacts transportation logistics, is another key concern that requires intensive planning and coordination among those involved [5].

In this context, we can highlight modular as a traditional building method, which has been documented and studied for years and that introduces us to a highly productive and sustainable way of building. On the other hand, such a rapid building methodology may require a skilled labor force and additional collaboration among stakeholders during the early phase of the project [6].

1.2 MOTIVATION AND OBJECTIVE

The industrialization of construction is currently recognized as an efficient way to increase productivity and competitiveness in the construction sector. Factory environments allow the staging of the assembly line into smaller areas, reducing displacements and accidents. Additionally, such a restricted environment allows for the implementation of monitoring and continuous improvement measures, reducing costs and waste.

While there is a growing amount of research that addresses the applicability of modular construction and its advantages, few studies aim to examine the contexts in which this type of construction is truly a preferred alternative. Moreover, there is still a gap in terms of mitigating the main complications arising from its use.

The objective of this investigation is to present volumetric construction and its main peculiarities. Through a thorough analysis of its implementation, it aims to evaluate it as an alternative for improving overall performance in the construction sector. Moreover, the study aims to assess contexts in which its use is more frequent and explore measures that can be utilized to mitigate its main constraints.

1.3 METHODOLOGY

The literature review was conducted by searching for articles, publications, and studies on platforms such as Google Scholar, Capes-BR (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior), ScienceDirect, Sudoc (Système Universitaire de Documentation), digital and physical collection of the Library of the Faculty of Engineering at the University of Porto and related platforms. The initial period filtered comprised 2003 to 2023, however, references prior to this period may also have been included. Articles on websites, reports,

videos, and other digital media were also used, all properly referenced in accordance with the NP405 guidelines.

1.4 DISSERTATION STRUCTURE

This dissertation is divided into six chapters:

Chapter 1 introduces the context of the study, the motivation behind it, and the methodology employed to achieve the research objectives.

Chapter 2 defines the context in which modular construction is situated, emphasizing its relevance for the industrialization and digitalization of the construction industry. Additionally, it lists modern construction methods and their applications, and provides an overview of the prefabricated market and trends.

Chapter 3 aims to establish the main strengths and weaknesses of modular construction by analyzing its key characteristics, highlighting the main themes and possible applications for this research.

Chapter 4 elucidates the main alternatives found to mitigate and improve activities related to volumetric construction, ultimately suggesting guidelines for improving the implementation of this type of construction.

Chapter 5 introduces techniques found for improving volumetric construction. Through an analysis of the main obstacles encountered, the chapter describes the application of these techniques, allowing for a detailed analysis of possible results and effects of their implementation.

Chapter 6 analyzes the results obtained from the study, providing final considerations and suggestions for future research in the field.

2

STATE OF THE ART

The construction industry reflects the society, therefore, its development proceeds relatively accordingly to the growth pace of cities. The process of urbanization leads to increased demand for real state and intense (and usually disorderly) densification of urban centres. As immediate consequence of that, fast expansion of the means of production and overall increase in costs, pollution indexes and waste generation. On the other hand, the heating of economy and technology, innovative materials usage, and development of new building techniques.

Early humans manipulated their environment to protect themselves from adverse weather conditions and attacks, from both animals and invaders. Those structures were usually temporary like lean-tos or windbreaks, their building materials included sticks, branches, tree fiber, leaves, mud, animal skins and fur. For the handling, tools made from bones and stone.

As more people settled in cities, the scale and scope of construction grew. Humans built increasingly sophisticated permanent structures where they could live, work, and gather together, as well as the infrastructure to support their sedentary living. Implementing these projects required engineers and architects, coordination of materials, as well as rules to guide construction, and then, the industry as we know it began to take shape in the 16th century [7].

For such establishment, humans had to develop new techniques and materials, the living standard demands aimed more sophisticated solutions and concerned with comfort and aesthetics, revolutionizing the way edifications are conceived. Nonetheless, many elements of construction industry are known to yield high carbon footprint. Cement, for example, has one of the largest shares in generating carbon footprint with a production of 8% of world total CO₂ emission, to give us a better idea of this dimension, If the cement industry were a country, it would be the third largest emitter in the world - behind China and the US [8].

In addition, aggregate plays a very crucial role in concrete occupying around 60%–75% of its total volume, with the increase in rate of consumption. It is expected that its demand will be doubled in the next two to three decades. Even so, the use of concrete as the most non-sustainable material, which consumes the maximum amount of natural resources, does not seem to cease [9].

As a matter of fact, human beings are still learning how to properly develop whilst considering the natural capacity of the planet to regenerate and the finiteness of its resources. A good example of this is the new guidelines set by the French government in 2020, mandating all government-funded structures to be built with at least 50% bio-sourced materials [10].

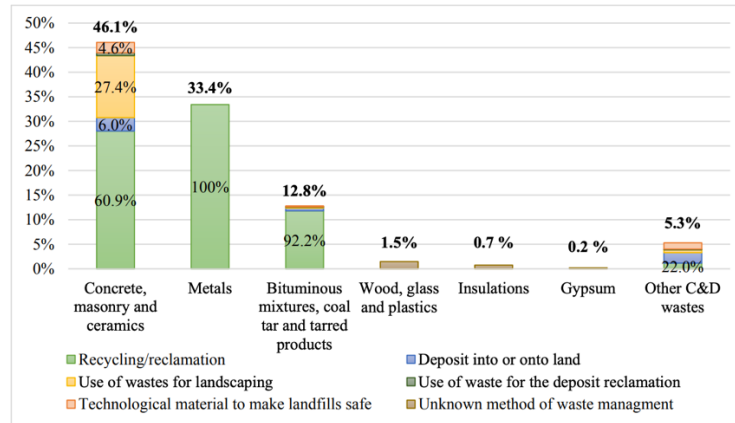


Figure 2.1 The weight percentage of material categories in construction and demolition waste and their further use [9].

As a matter of fact, human beings are still learning how to properly develop whilst considering the natural capacity of the planet to regenerate and the finiteness of its resources. A good example of this is the new guidelines set by the French government in 2020, mandating all government-funded structures to be built with at least 50% bio-sourced materials [10]. Although diverse and complex, the path for such conscient-grow mostly rely on the implementation of technological advancements and massively industrialization, an inevitable correlation between those concepts that will be exhaustively explored throughout this study.

Indeed, sustainability has renewed its place as one of the major focuses of new building practices; the introduction of less harmful, alternative materials finally seems to consolidate its acceptability and the total amount of waste disposal is gradually decreasing, moreover, society as a whole has grown more aware of climate change, the depletion of natural resources, and the human impact on natural habitats.

So that we pursue a more parallel development, efforts are being made for this industrialization of the construction sector. Rational building procedures, prefabrication and digitally assisted construction are trending terms that reflects the current effort for its traction. Digital transformation in construction is picking up and will play a critical role in solving sustainability and other persistent challenges in the industry. Rethinking old-fashioned methodologies may resemble precautionary, however, real state is already considerably late in regard to this digital revolution.

In this context, the Fourth Industrial Revolution, also called Industry 4.0, takes place. IBM defines it as the manufacturers adoption of new technologies, highlighting the Internet of Things (IoT), cloud computing and analytics, AI and machine learning. Those tools, when incorporated into production facilities and throughout the operations, accrete valuable optimization, control, improvement on the production line and easy detection and repair of flaws that could plenty interfere in the final result.

Building systems are getting each time more diverse and the urge of new solutions is directly affecting the way we build. Modern Methods of Construction (MMC) meet the main criteria for such digital implementation, adding up a lot to the earnings brought from off-site production and proposing alternative building solutions that could help alleviate such lagging.

Modular system is one among the key processes for this transformation, its main benefits include (1) Dimensional coordination, simplification, and diaphaneity, (2) Limitation of variants, (3) Standardization, (4) Prefabrication and (5) Industrialization of the processes. All of them leading to the main goal: increase production in the building sector through increased productivity [11]. Those factors ensure that all the building components are correctly designed, built and assembled considering the proposed functionality, techniques and aesthetics, furthermore, factories grant quality, precision and, consequently, minimum waste of raw materials.

Finally, the industry has started to re-think its methods, implementing new technologies and modern buildability concepts. On top of that, the National Innovation Agency (ANI), in collaboration with the European Association of Research & Technology Organizations (EARTO) articulate the twin transition in Portugal, promoting debates in regard to the green and digital transition in the context of recovery plans, particularly addressing the role of technology and innovation in the development and promotion of regional, national and European technological capabilities.

2.1 THE INDUSTRIALIZATION OF CONSTRUCTION

The construction industry is among the least digitized sectors around, with almost all its processes being repetitive and labor-intensive. Industrialization can be seen as structural means for eliminating, or at least drastically reducing, on-site activities in construction through increased mechanization and automation, for example. It improves the overall quality of the construction site, reducing the average time spent on-site and unnecessary displacements. Additionally, activities performance is improved, corroborating for materials and labour shortages – another major concern of the sector [12].

A study by McKinsey showed that large projects typically extend 20 percent beyond the initial project completion date, usually up to 80 percent over budget [4]. Industrialization is a

significant trend of scientific and technical advancement in construction as technology is changing how we design, manufacture, and assemble. High precision elements can be designed with the aid of a modeling program, machines can be programmed to perform repetitive tasks and then, all of this progress can be monitored and improved by software.

In the manufacturing industry, modularity has been shown to reduce the number of suppliers from thousands to a few hundred, becoming a key issue in the engineering management literature applicable to such manufacturing industry [2].

2.1.1 BACKGROUND

The first documented use of prefabrication is dated back to 3800 BCE, an ancient causeway assembled in England, the Sweet Track. That is what we consider as the birth of “off-site manufacturing” concept. The unfolding of such industrialization began with the widespread use of prefabricated elements, since then, several improvements have been developed and supported by technological amenities.

Years later, during the Roman Empire, the army used to carry the forts in prefabricated sections, this way, as soon as they arrived at their destination or new territory, the structures would be ready to be assembled. In the 1600s, fishing houses were built in England and shipped to Massachusetts, United States. About two centuries later, Henry Manning built parts for prefabricated houses and sold them to their - at the time colony - Australia. The concept was arrestingly received there and hundreds more were sent [13].

During the inter-war period, postwar housing takes place and *Sears, Roebuck and Co.*, Chicago based, sells about 70,000 - 75,000 prefabricated homes, revolutionizing the market with several size and arrangement houses, promising cost savings from 25 to 50% compared to traditional construction methods [13][14].

At the height of its popularity, in the 1990s, renowned names in the architecture endorsed the methodology, pointing it out as an economic and sustainable alternative. During those years, Frank Lloyd Wright designed ‘Falling Water’, modernist modular model which has been called "the best all-time work of American architecture [15].

Back to Europe, Charles Édouard Jeanneret-Gris, Le Corbusier, conceived the concept of ‘Machine for living’: a modern house designed to work like a machine, efficiently and without extraneous parts [16]. Not only, Walter Gropius developed prefabricated houses to solve housing access problems during post-war Germany and founded Bauhaus, art school that became famous by its approach to unify the principles of mass production with individual artistic vision and strove to combine aesthetics with everyday function. Few years later, in 1968, a 22-storey prefabricated building collapsed in London-UK, the durability and structural integrity of such system began to be questioned by experts and a negative perception was left amongst the market [17].

In recent years, the government's commitment to improve resources efficiency and innovation in construction sector, alongside efforts to alleviate the materials and labor shortages, has re-introduced the concept of modular construction. In Sweden, panelized single dwelling residences already represent over 80 per cent of the country's overall housing market [18].

Digitally assisted projects and 'Modular Architecture' concepts seems to develop and grown again. A brand-new range of possibilities takes place, in the 2020s.

2.2 MODERN METHODS OF CONSTRUCTION (MMC)

Modern Methods of Construction are methods which provide an efficient product management process to provide more products of better quality in less time by using parts manufactured and assembled off-site or components manufactured off-site and brought together on-site for assembly prioritizing an efficient, profitable, diverse building method where customer requirements are the focus [19-20].

Some of the methods currently considered are (1) 3D-volumetric constructions (in which Modular is comprised), (2) Lightweight structures, (3) Prefabrication, (4) Tunnel forms and (5) Flat-slabs.

The main conditions that together points toward Modern Methods of Construction (MMC), are still to be in-depth presented here, however, the industrial environment is responsible for considerable portion of the advantages. Summarizing, the purpose here is to treat the construction product just like any other, design and work with a model that enables its reproduction in a role – and concurrently assures higher levels of quality and yield. The insertion of these MMC still crawls and the market and whether the players or the customers perceptions are still under development in reference to the acceptance of such methodologies [19].

This phenomenon is not unusual and 'public perception of innovation' has been exhaustively studied. Also known as the "Innovation adoption curve" or "Diffusion of innovation", these theories seek to explain how, why, and at what rate new ideas and technology spread. The figure 2.2, presented below, was formerly proposed by Everett Rogers, a professor of communication studies, who later popularized the theory in his book *Diffusion of Innovations* [21].

A relevant interpretation applied to our MMC context can be took from it and, regards the long process by which an innovative idea must go through till it heaps enough market share and become competitive. Modular industry, after almost fifty years, is found at the 'Early Majority' stage, denoting that much effort still needs to be held for it to become genuinely established and widespread embraced as an alternative to the traditional methods.

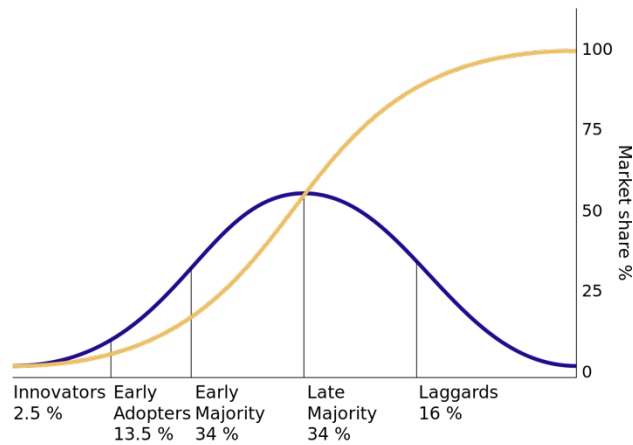


Figure 2.2 Diffusion of Innovations, Rogers [21].

There is still demand for new contractors, and as the market warm up, it eases the access for the specific supply of materials and connection structures, for example.

Regarding the carbon footprint, fuel consumption and emissions, a significative reduction of 51% on total carbon incorporated and 34,87% reduction of primary sources fuel consumption when a MMC is employed [22]. Those rates vary and mostly rely on the building level of prefabrication, described below.

Various outputs are being developed, one of which is a new categorised definition framework for different forms of innovative construction methodologies. This framework was established by a specialist sub-group led by Mark Farmer of Cast Consultancy, the chair of the wider MMC working group, supported by representatives of Buildoffsite, Homes England, National Home Building Council (NHBC) and Royal Institute of Chartered Surveyors [19].

The definition framework identifies the following seven MMC categories [23]:

- **Category 1** – Pre-Manufacturing - 3D primary structural systems
- **Category 2** – Pre-Manufacturing - 2D primary structural systems
- **Category 3** – Pre-Manufacturing - Non systemised structural components
- **Category 4** – Pre-Manufacturing - Additive Manufacturing
- **Category 5** – Pre-Manufacturing – Non-structural assemblies and sub-assemblies
- **Category 6** – Traditional building product led site labour reduction/productivity improvements
- **Category 7** – Site process led labour reduction/productivity improvements

The intention is for this framework to regularise and refine the term ‘MMC’ by defining the broad spectrum of innovative construction techniques being applied in the residential market, both now and in the future. The UK Government also defended the framework as an opportunity to create more structured datasets capturing use of MMC and its performance, so

enabling clients, advisors, lenders and investors, warranty providers, building insurers and valuers to all build a common understanding of the different forms of MMC use [23].

However, the adoption of these modern forms of construction still appears to be subtle. The costs of implementing a functional factory are high when compared to the initial investments required by the traditional manner. Other main obstacles are namely the poor interface and inadequate coordination, lack of skills and tools, high costs suspicion regarding performance and barriers within the system, which also include the need for skilled labor [19]. The benefits arising from this transition may take time to materialize and are often not sufficiently stimulating to encourage such an evolution and niche transfer. Therefore, the first step needs to be awareness regarding the long-term achievements that will result from increased productivity and waste reduction, for instance.

2.2.1 PREFABRICATION

As opposed to "cast in-situ" construction, prefabrication is the practice of assembling components of a structure in a factory or other manufacturing site and transporting complete assemblies or sub-assemblies to the construction site where the structure is located. Some prefer to use "offsite construction", which refers to sub-structures or components of a structure built at an offsite place, other than the location of final erection [24].

With the union of architecture and industry since the beginning of the industrial revolution, the architectural culture of prefabrication was born, intrinsically linked to the development of modular construction [25].

Prefabrication can also be classified as *non-volumetric* or *volumetric*. Non-volumetric prefabrication includes single elements or sections that are transported to project site for installation and assembly, such as precast concrete, cold-steel panels/structures, Structured Insulated Panels (SIPs), panelized walls, and prefabricated trusses. Non-volumetric prefabrication methods eliminate the assembly of different elements in the factory and prevent waste of spaces in transportation, however, the process to connect the elements in the construction site increases the complexity of the construction. Volumetric prefabrication includes manufacturing and assembly of free-standing building units in a protected factory environment. In the residential sector, volumetric prefabrication is classified as **modular**, manufactured, and park homes [26].

In addition to the benefits previously mentioned, prefabricated elements are also recognized for their superior environmental and social benefits. In today's world, where climate change and natural disasters are becoming more frequent and severe, prefabrication has emerged as an alternative construction method and a prime example of resilient design [26]. Prefabrication helps reduce waste and carbon emissions by allowing for more efficient use of materials and reducing on-site construction time. Additionally, prefabrication offers social benefits by

promoting worker safety and improving working conditions. The controlled environment of the factory setting reduces the risk of accidents, while the standardization of processes ensures consistent quality and safety standards.

As we can see bellow in table 1, prefab is actually a concept, which comprises different levels of complexity and indexation, from single elements to fully preassembled volumetric units. In a summarized form, prefab is actually a category of construction methods rather than one specific construction method [24-26]. Different approaches and arranges can be employed; studies sustain that the higher is the level of off-site indexation, the higher is the attained reduction in construction time, for instance, varying from 15% to 60% for levels of indexation (from level 0) that fluctuate from 10% to 70%, respectively [28].

In the world of construction, people tend to use the terms prefabricated and modular buildings interchangeably, however, they are not the same. All modular buildings are prefabricated buildings, but prefabricated buildings may or may not be modular structures.

Level	Description	Examples
0	Cast in-situ	Conventional construction technologies, using formwork and falsework, rebar and cast in premixed concrete
1	Component and sub-assembly	Components like doorsteps, lintels, and so on, to be formed as functional components such as doors and windows
2	Non-volumetric assembly	2-dimensional precast concrete wall panels, precast components with no usage space enclosed, e.g., precast concrete partition wall, precast lost form, semi-precast slab, non-structural prefabricated external wall
3	Volumetric assembly	Encompassing all 3D preassembled units enclosing usable space but do not constitute part of the building structure, e.g., volumetric precast bathroom, precast kitchen, precast water tank, precast refuse chute
4	Modular building	3D preassembled volumetric units forming part of or the complete building structure, like motel

Table 1 Taxonomy of different levels of prefabrication [24].

While Modular construction specifically consists of the building of repeated sections called modules being built in the factory and then assembled on site, prefabrication refers to any construction process that does not take place on-site, the term encompasses modular houses, as well as those built using panel construction and steel frame construction [29].

Hence, volumetric construction has higher level of industrialization and its eased design conditions grants better compatibility and assembly conditions, however, prefab panels are easier to accommodate and transport, factors which interfere on final costs as well. In this sense, a combination of both could decrease freights average number, however, it could result in an increase in the on-site time required for the execution of more complex projects.

To address this challenge, a framework can be developed to consider both technical and non-technical factors in determining such an optimal level of prefabrication. It could include a multi-criteria decision-making model that takes into account project complexity, resource availability, stakeholder preferences and other relevant factors to the project development [27].

2.2.1.1 APPLICATIONS

Some of the commonly employed prefabrication products include:

- i. Pre-cast panels – also referred to as Panel systems or panelised construction, this process offers increased flexibility when compared to the volumetric units, the components can be flat-packed, which facilitates their transportation. The panels can integrate insulations, mechanical and electrical systems as well.
- ii. Pre-cast foundations - the foundation units are pre-engineered and manufactured off-site, prefabricated units are leak-resistant, less susceptible to cracking, stronger and lighter when compared to other competing materials.
- iii. Staircases and other structural elements, such as beams, columns or RC walls.

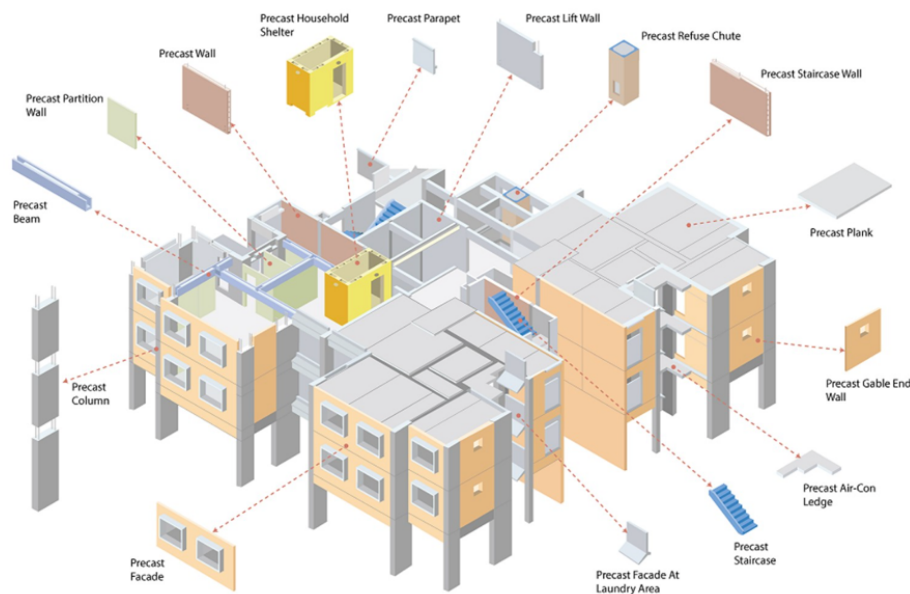


Figure 2.3 Types of precast components in a Building (House and Development Board, 2022)

2.2.2 3D- VOLUMETRIC STRUCTURES

Main target of this investigation, volumetric structures are a type of prefabrication method based on the use of panelized members or full volumetric units, produced off-site in factories, and transported to the intended site for assembly this method of construction uses factory-

produced building units called modules that are delivered as components, parts or whole buildings to be erected on site [30].

The Modular concept aims to create a standard dimension, which makes rationalization possible from the conception to the construction of buildings, thus increasing the level of industrialization with all the inherent advantages, while still maintaining an acceptable level of design freedom from an architectural point of view [31].

Most are characterized by rectangular blocks combined side by side, and/or stacked, without displacements between the blocks, generating larger prismatic shapes. The lack of variation can lead to architecturally similar compositions, a factor that has been inhibiting the widespread use of this type of construction. Few have other shapes, such as trapezoidal prisms demonstrated in the Modular Construction patent [26].

In the literature, measured quantitative effects of modularity in construction are rare. Indeed, many of modularity's effects are difficult to measure in quantitative terms e.g. variety and complexity as well as process related effects in development, manufacturing, and production. However, it was shown to create buildability by promoting a high productivity and aid in a lean process, enabling easier management and improvement of its main processes [2].

2.2.2.1 MANUFACTURING PROCESS

Modular construction involves prefabricating building components in a controlled factory environment, eliminating weather delays and allowing parallel manufacturing of multiple components. Another consideration in regard to those environments concerns the implementation of quality and control principles, which usually demand time and depend on how well-defined standards are, indeed, such enclosed environments restricts displacements and favors zoning by specialty or activity, where safety and surveillance practices can be implemented with ease and contribute to considerably reduce accidents and delays [32].

The simplified assembly process of each volumetric unit can be divided in eight stages, summarized as the following. Once the layouts and arrangements are defined, the manufacturing of the base module can proceed in series, enabling the establishment of a productive, lean, assembly line [32].

Phase 0 Gathering and preparing materials for assembly

Phase 1 Building the floor, installing decking, putting up interior and exterior walls, attaching the structure to the chassis

Phase 2: Constructing the roof and installing the ceiling, putting in interior partitions, and plumbing

Phase 3: Hanging sheetrock on walls and roughing in electrical

Phase 4: Finishing sheetrock on the ceiling, insulating, and finishing rough electrical.

Phase 5: Applying exterior plywood sheathing, tidying up rough openings, and cleaning up the interior

Phase 6: Wrapping exterior with plastic sheathing, completing interior finishing work

Phase 7: Installing finish plumbing and electrical, laying flooring

Phase 8: Installing windows, siding and weather-proofing the exterior

The most relevant assemblies are structural components and exterior cladding [33]. At first, structural elements comprise corner pillars and beams, however, resistance to horizontal loads is provided either by the walls through bracing or diaphragm action and, for buildings taller than 6 stories, an additional bracing system is usually necessary around the access core [34].

Two forms of framing are usually considered (1) Continuously supported or 4-sided modules, where the walls transfer vertical loads, and (2) Open-sided or point-supported modules, where vertical loads are transmitted through corner and intermediate posts. The choice of assembly method will depend on the specific requirements of the project, such as the size and intended use of the structure, and the availability of resources [35].

For the placing stage, lifting equipment such as cranes or hoists are required and once the assembly is completed. Finishes are needed to ensure the watertightness of the entire edification.

2.2.2.2 APPLICATIONS

Sweden provides a notable example of how changes in legislation and master plans in the 1990s have led to improved utilization of constructions. Amendments allowed for the construction of new light wooden structures on top of century-old buildings and eased regulations for up to four-story buildings. Consequently, the country has achieved an impressive 85% of new contracts involving volumetric or prefabricated units [36].

Due to materials shortages and ensuing delivery delay, 221 modular units of toilet facilities were assembled for a student housing building in Porto – Portugal, the assigned company emphasized the attained benefits and alleged that otherwise, the deadline would be impossible to be reached. Other nine similar buildings were sold to Round Hill Capital for an estimated amount of 200 million euros, considered to be 2022's highest investment in this sort [37]. That is an example of **mixed use** of prefabricated modular components.

Among others on the list, the 2E Expansion Terminal, at Charles de Gaulle **Airport** - Paris is probably the biggest construction in which modular technology has been employed: "Instead of being traditional cubic ones, the arched pieces allow for the curved aesthetics to be maintained while remaining open to future additions. The elaborate shape of the structure could only be resolved by utilizing BIM", as declared by *Atom Consultants*, British company in charge of the works execution [38]. Still in this category, the east wing of Geneva Airport, in

Switzerland, was performed by *Rogers Stirk Harbour & Partners* using four modular parts, 20 meters long each [39].

In **Housing/real state sector**, an increasing number of companies are staking in cataloged sustainable houses. With lower energy consumption levels, they offer the same comfort and performance conditions of the traditional method, whilst reducing construction costs by 25 to 30% [4][33]. A common feature between most of these companies is the expansion possibility, connection tools foresee the assembly of additional modular units such as visitor rooms, offices, parking lot, steam room and other typologies. It is also important to highlight those additional services analogous to the construction namely: licensing documentation, land acquisition and preparation, foundations, module transportation and technical installations, extra costs that usually are excluded from the final price. A house can be installed and finished in only 6 days, and therefore is attractive in suburban areas where land prices are very high and is usually used there for 2- or 3-storey housing. However, it is important to keep in mind that obtaining credit for this type of licensing must be harder, the documentation required, yet similar, is distinct and leads to a lengthy process. Compelling to difficulties and impositions, a third-part company is often required in the process and the increasing sense of complexity is usually responsible for the quitting of regular customers.

The tallest prefab modular building according to The Guinness World Records is a residential tower located Croydon, UK. The 44-storey building was topped out in 2019, with 1,526 modules built to accommodate 546 apartments and facilities. However, a pair of 56-storey skyscrapers in Singapore will be complete and after its release, on May 2023, they shall be nominated as the tallest prefabricated buildings in the world.

Another sector with increasing demand is **Hospitality**, in which hotel buildings, holiday tents, summer houses/airbnbs, student housing and other related are comprised. In this context, buyers – usually investors, wants to minimize costs of construction and on the other side, costumers – usually tourists, when looking for temporary accommodation, seek for comfort, but in the end, the best cost-benefit they can spot, in the closest place to what they consider to be the desired location is the deciding factor. In other words, here, functionality is what really matters.

Thus, for larger projects, the use of multiple modular units – and the consequent earnings - seems to justify the bureaucracy. By way of example, the Courtyard at the Domain, in Austin, was built by the assembling of 540 modular units, considered to be the biggest modular structure in the United States and in Europe, the Latvian builder *Forta Pro* has completed an 88-room hotel in Copenhagen seven days after its component parts were shipped from Latvia. [39]. The tallest modular building hotel in the world, Tower B2 - NY, has 32 floors and 363 apartments built with modular technology, this residential building is part of the massive urban rehabilitation project in Brooklyn, Atlantic Yards, and a US\$ 5 billion venture [40].

In Japan, modular housing has been widely used since the early 1970s and around 15% of new housing construction is related to prefabricated construction. The marketing of modular housing there is based on a high degree of user choice in the layout and fitments in the modules, and a fast design, manufacture, and installation turnaround [28][41].

The regional impact of COVID-19 has been unprecedented and staggering, with modular construction witnessing positive demand across all regions amid the pandemic, perfect context for **temporary** giant **Hospitals**, built in matter of days and delivering beds with an agility never observed before. In China, Huoshenshan and Leishenshan Hospitals, built in 10 and 12 days respectively, delivered together more than 3000 beds [42-43]. In Europe, Birmigham Hospital – England, just two weeks after work began, delivered 800 beds and commissioned a second phase with another 400 beds, delivered two weeks later [44].

Finally, **Commercial** use, from little shops to pavilions, small sized modules, assembled inside permanent installations serves as complement and easy solution for new offices or meeting rooms without the inconvenience of going into renovation. The Asia-Pacific region has been leading, massively employing and promoting the concept. Mini Sky City, a mixed use 57-story and 204,0 m high building in China, was built in 19 days and now the company has ambitions to assemble the world's tallest skyscraper: 220 floors, in only three months. However, it is fundamentally a conventional steel-framed building, albeit one made in a highly organized and systematic way [45].

In Sweden, Sara Cultural Centre, housing venues for arts performance and as well as a hotel. One of the world's tallest timber buildings using modularity to date. For the incorporation, two different construction systems have been developed: one for the cultural centre and one for its sibling structure, the hotel. The high rise, which houses the hotel, is constructed of premanufactured modules in cross-laminated timber (CLT), and the low rise consists of a timber frame with pillars and beams made of glue lam and cores and shear walls in cross laminated timber [46].

To cut a long story short, the possibilities for arrange and materials are innumerable, the usage of innovative solutions seems to increase design options and progressively attract new aspirants. In process of consolidation, such method leads to several advantages and, knowledge regarding its techniques and applicability are major requisites to maximize those benefits.

2.2.3 TUNNEL FORM

The method consists in a formwork system, which main component is the half tunnel. Recognized by the Department of Trade and Industry as a Modern Method of Construction [47], the box-sided framework is manufactured entirely from steel, each half is made of a

horizontal and a vertical panel braced by two struts, forming a crutch that provides support and stability to the future slab. When two halves are put together, the tunnel form is completed.

Wheeled strut system with levelling jack ease displacement and further removals, jacks complete the configuration possibilities. Accessories ensure the link and surfacing between the panels and alignment stoppers help position the tunnels together.

Once fixed, the tunnel is tailored to the room to produce a length that suits either the building dimensions or the craneage. The single and monolithic pouring allows load bearing concrete walls and floors to be casted in a single operation, the wall-to-wall and wall-to-slab interactions has proven to positively impact torsion and wall-openings on loads transfer mechanism. The monthly production capacity is around 12,000m² to 25,000m² [49].

Operation can be performed on a 24-hour cycle, however, the average cycle time of the system lies between 1 to 3 days, production line automation confers agility and efficiency to the process. Its effectiveness is better perceived in cellular-type constructions with 100 rooms or more [49].

Casting process:

- i. Machinery is positioned.
 - Prefabricated wall reinforcement is placed by crane along the entire wing prior to casting the kickers (used to position wall formwork).
 - Two and a half tunnel are craned into place, bolted together
 - Ties are added.
 - Wall concrete is poured.
- ii. Slab reinforcements are fixed.
 - Slab concrete is poured.
- iii. The tunnel-forms are removed.

The process is then repeated for the next two bays.

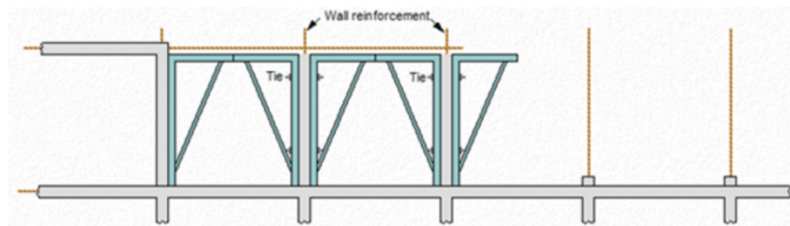


Figure 2.4 The Casting Process of Tunnel Formwork [49].

After the curing, the structures proceed for dismantling. Formwork itself costs around 20-25% of total cost of project. Once removed, such forms can be reused over 600 times [49], consolidating it as a highly economical and sustainable alternative which replaces traditional single-use wooden forms and cooperates to the reduction of waste and raw-material consumption.

The main attained benefits [47-50]

- i. Optimal quality steel-faced finish
- ii. Inventive architectural design.
- iii. High dimensional accuracy.
- iv. Reduced need of skilled labor
- v. Allows addition or subtraction of panels to vary bay span.
- vi. Eliminates the use of any subsequent wet trades (Plastering etc)
- vii. Construction costs reduced by 15-25%
- viii. Reduction in crane time by almost 50%
- ix. Time savings by 25%

2.2.3.1 APPLICATIONS

Particularly suited for cellular reinforced concrete type construction i.e., at the occasion of repeating patterns, namely mass housing, hotels, student accommodations, prisons and others. The formwork system provides pour to be wrapped in tarpaulins and, the use of butane heaters maintains sufficiently high temperatures for the concrete to reach its striking strength overnight [47-48], conferring agility in the production line and enabling its feasibility in adverse weather conditions, in which those curing conditions would be unsatisfactory.

Technical installations must provide adequate space to accommodate and move the forms and, although wide long spaces present innate advantage to such usage, the mould can be installed in a variety of dimensions, as aforementioned. Furthermore, in regions prone to high seismic risk, it presents enhanced performance due to the additional strength that reinforce concrete redeems [50]. Nevertheless, the continuous nature of its components may result in increased sound transmission, posing potential drawbacks in terms of acoustic and thermal comfort, particularly with regards to reverberant sounds. Alternatively, mitigating measures such as using thermally enhanced insulators or plastic balls can be employed to address this issue [164-165].

2.2.4 LIGHT-WEIGHT STRUCTURES

The increasingly concern with sustainability propel the search for lighter alternative materials which minimize levels of raw-material consumption and originate less heavier structures (tf.

Lower dead weight values associated), while maintaining safety and performance. To enable such feat, the use of natural less dense materials and the advantageous effect of curvature are major considerations. As the activity data is directly related to the mass of the product, the lightweight of product is a valid approach to low-carbon footprint [51].

Under operational or extreme load, the behavior of this types of structures depends on the interaction of structural geometry and material properties, in light wood-frame buildings, the gravitational and lateral force-resisting systems are composed of floor diaphragms and shear walls. Thus, by controlling the geometry of these type of structures one can develop very economic and efficient structural elements for practical applications. Structural optimization with failure analysis can be used to investigate the structural efficiency of lightweight structural geometries [51].

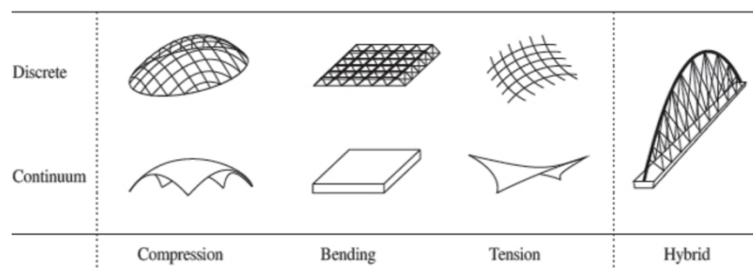


Figure 2.5 Classification of typologies of lightweight structures according to the actual stress state and the type of structural components [52].

Currently, lightweight design methods are basically classified into the two following types: (1) achieved by means of structure optimization and (2) by material selection. With the advent of the 20th century, improved lightweight materials such as aluminum, magnesium, graphene, beryllium, titanium, titanium aluminides, engineering plastics, structural ceramics, and composites with polymer, metal, and ceramic matrices began to appear. The high specific compressive strength is a determining property for such slenderness, whose densities range from as low as 0.80 g/cm³ and for unfilled polymers to as high as 4.5 g/cm³ for titanium [51-53].

2.2.4.1 APPLICATIONS

In this category, the following by-products can be comprised:

a. Wood frame

The high ecological value and construction performance of wood makes it widely employed as building material. Timber buildings have shown to be suitable and feasible in a wide range of boundary condition. Moreover, when it comes to timber structures in

seismic zones, the wood-frame system has proved to be an efficient solution to resist the lateral and overturning loads developed by earthquakes on mid-rise structure [54].

This system employs a range of prefabricated structural frames, such as external and internal walls, floors and roofs to help form a combined structure which can be clad in another material on-site.

b. Thin-walled structures

With the development of advanced deterministic methods and the introduction of such materials, the slenderness of masonry structures could be progressively readjusted to smaller values. They are capable of carrying substantial loads for deflections far beyond those corresponding to ultimate or buckling loads; plastic deformations magnitude exceeds by far those corresponding to the buckling or ultimate loads and are indeed confined to relatively small areas [52-53].

The use of thin-walled structures is a natural optimization strategy to reduce dead load and minimize construction material. In addition to their slenderness and specific strength, thin-walled structures also leverage the advantageous effect of curvature in shell structures, which allows for the optimal distribution of transverse loads [53]. By using this approach, the material consumption can be reduced without compromising structural stability or load-bearing capacity. Additionally, thin-walled structures offer other benefits such as improved thermal insulation and acoustic performance. They are also well-suited for creating complex shapes and forms, allowing for greater design flexibility and creativity.

As such, thin-walled structures are increasingly being employed in a wide range of construction projects, from residential homes to large-scale commercial developments, in order to optimize efficiency, minimize environmental impact, and achieve a more sustainable built environment.

The type of light-weight structure depends on the load-resisting mechanism; the most commonly observed are (1) thin-shell, (2) 3D-lattice, (3) cable-net, (4) tensile membranes and (5) flat plates.

c. Light steel framing (LSF)

The light steel framing is usually made of galvanized steel profiles that work together to support the structure. This structure is complemented by OSB plates or cement slabs, bolted directly to the profiles of the structure [56].

Light steel framing comprises galvanized cold-formed C sections of 70mm to 100mm depth in the wall panels, and 150mm to 300mm deep C sections or lattice joists in the

floors. Spans of up to 6m can be achieved, which can eliminate internal load-bearing walls and therefore leads to flexibility in internal space planning [57].

The light-gauge steel framed wall is fabricated with light-gauge steel stud, interior and exterior wallboards and insulation material. There are many advantages for this type of wall, such as excellent heat insulation, light weight, ease of prefabrication and energy efficiency [57].

d. Thin-joint masonry

Thin Joint is a masonry wall construction technique which replaces conventional 10mm cement layer; As these mortars are getting expensive, from the consideration of reducing costs, the thickness of the mortar layers is reduced to approximately 1–4 mm and is referred to as thin mortar layered masonry [58].

It offers a solution to builders wishing to maximize the thermal performance of a building, minimize CO₂ emissions over the building's lifetime and yet maintain the familiarity, comfort, stability, and long-term solidity of a masonry building.

2.2.5 FLAT SLAB

Flat slab is a reinforced concrete slab supported directly on columns without the use of beams. Is defined as one sided or two-sided support system with shear load of the slab being concentrated on the supporting columns and a square slab called 'drop panels', those structures play a significant role here as they augment the overall capacity and sturdiness of the flooring system beneath the vertical loads thereby boosting cost effectiveness of the construction [59].

Strengthening methods such as using carbon fibre reinforced polymer (CFRP) sheets as external reinforcements in the tension area have proven to be useful in increasing the punching shear capacity and ductility of RC members. The slabs reinforced in shear exhibited ductile behaviour having achieved their full flexural potential; thus, proving the effectiveness of the new reinforcement [60].

2.2.5.1 APPLICATIONS

Reinforced concrete (RC) flat slab floors lead to architecturally pleasing buildings and bridges as well as simplify and accelerate site operation.

Suitable for most type of constructions and for asymmetrical column layouts like floors with curved shapes and ramps, the solution provides clearer space, higher architectural flexibility and shorter construction time. However, slabs supported directly on columns may face a brittle

failure mode due to punching shear failure, which is the main disadvantage of such systems, particularly when used in seismic zones [59-60].

2.3 BIM AND DIGITALIZATION

In Portugal, productivity in the construction sector accounts for 13% of world GDP and has grown at an average annual rate of just 1% over the last 20 years, compared to 3% globally [61]. Technology is undoubtedly one of the factors that most contributes to the competitiveness of companies, as AEC projects are each time more complex, such advances are helping industry professionals work more efficiently and effectively. In the meantime, digitalization in the civil sector is still below the average and plenty mystification haunts innovative tools implementation.

Of equal essentiality, information sharing in construction projects remains as other of its major obstacles to overcome. One explanation for that rely on the large amount of companies and players involved, which results in fragmentated information, both vertically and horizontally, real barriers to productivity enhancement. Moreover, huge amounts of time and data are wasted between site and head office workflow with detailed and reliable transfer, such waste is expected to be significantly reduced [62]. That is the first accomplishment of BIM integration, the systematical organization and storage of information in real time. No loss in transfers, no loss of information, no time wasting.

Building Information Modelling- BIM, is an intelligent model-based process that integrates through series of software all information regarding the components of certain project, including their dimensions and scales, materials, fabricators, predicted lifespan and others. In addition, the interface between structural elements, technical and sanitary installations can be previously considered and incorporated since the beginning of the designing phase. This way, contractors can efficiently design, budget, build and operate constructions and infrastructures ensuring improved conditions of communication, enhanced transfer of information and reduced omissions, which before used to lead to misreading and eventual delay.

The 3D visualization grants better accuracy of information, productivity, and global vision of the building process. The applicability of BIM principles to Modular construction is summarized, but not constrained, to (1) Model creation – an accurate virtual prototype of prefabricated components of the buildings can be designed and furtherly replicated for all other elements of the assemblage. Once in scale, those can be reused in future projects for which minimum modifications will be required – mostly effective for large undertakings with remarkable potential for time saving; or (2) Modularity technique – can be held after the design phase, in already existing 2D-plants. Resorting to clustering tools, software evaluates spatial dimensions and reveal possible locations for volumetric units' implantation, sorted by room typology, size etc. Even if not fully manufactured, some of the building components can be prefabricated, giving rise to mixed constructions, and attaining (partial) advantage of off-site production [63].

It is about time to spread innovative concepts and take advantage of all the digital literacy that the pandemic has brought. Companies need to perceive BIM as any other methodology, which requires extra effort in favor of its consolation within the market. For that to happen, the first step is to embrace the cause, modify the organizational structure and provide appropriate training to employees in the face of those advances. Such process may be gradual and sometimes requires simple adaptations of existing processes. For that, the use of multidisciplinary teams seems to promote greater agility when defining a new technical-economic solution in conformance with deadlines; Performance earnings are most felt during the execution stage and accordingly to its rooting, other dimensions can be furtherly incorporated.

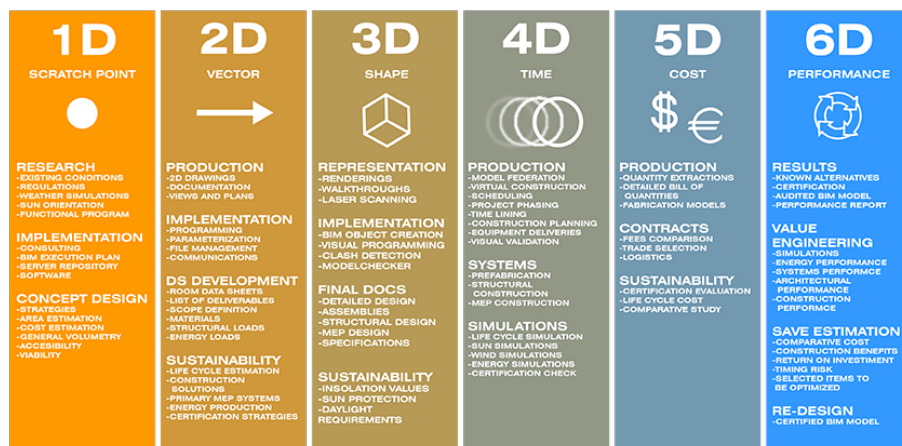


Figure 2.6 BIM dimensions and applicability [64].

The United States have long been a global leader in BIM development and implementation in the construction industry [63]. Perhaps the biggest impact in the UK Building Regulations, considered by many to be the most ambitious and advanced centrally driven implementation program in the world, the government now mandates use of BIM for new residential buildings 18 meters or more. In Portugal, the translation of norms and directives is held by Built-COLAB in partnership with CT-197 and it's expected to be soon available. Although it could boost companies that already have enough implementation capacity, other possibility is the creation of imbalances with entities that do not have such strength and investment capacity. First, public entities need to create bases for such change, which must be phased, progressive and adapted to each company context.

The development towards a fourth industrial revolution requires a transformation of industries and integration of technologies not least, it requires capabilities in terms of people, processes, and technologies. The digitization of the sector has transformed the way agents collaborate. Innovative construction processes, the use of new technologies and the implementation of sensors on site enhance advances in the field of productivity, safety, and quality, while increasing the complexity of information management.

Construction 4.0, also known as the Fourth Industrial Revolution in Construction, refers to the integration of emerging technologies and digitalization in the construction industry and aims to automate the various stages of the construction process, from design and planning to building and maintenance. Based on a confluence of trends and technologies that promise to reshape the way built environment assets are designed, constructed and operated. Knowledge of a set of tools and techniques applicable to it is essential to guide and shove the successful development and implementation of innovative actions [65].

2.4 MODULAR AS DfMA

Vital component of Modern Construction Methods (MMC), new construction techniques that are gradually being promoted include: design for deconstruction (DfD), design for reuse (DfR), design for manufacture and assembly (DfMA). As one of the most prominent MMC methodologies, a platform design approach to manufacture and assembly (P-DfMA) is fast becoming a ubiquitous construction term [66].

P-DfMA (Product-Platform Design for Manufacture and Assembly) is a digital approach that aims to advance off-site construction methods by building upon the successes achieved by various industries that use off-site manufacturing. The approach involves designing a set of standardized components digitally that can be utilized across multiple types of built assets, thereby reducing the need to create bespoke components for each type of structure. For instance, the same component could be used for constructing a school, hospital, or prison, enabling greater efficiency and reducing costs. The P-DfMA approach not only enhances construction quality and speed but also offers significant sustainability benefits by reducing waste and carbon emissions [66-67].

The government is pursuing a strategy to foster a new market for manufacturing in construction by adopting a consistent approach and utilizing standardized, inter-operable components across various building projects. By doing so, they aim to leverage economies of scale and streamline processes to achieve greater efficiency. This approach not only benefits the government but also encourages innovation in the industry and promotes sustainability by reducing waste and energy consumption.

2.5 PREFABRICATION MARKET - OVERVIEW

Modular industry is experiencing a new wave of attention and investments; several factors suggest its renewed staying power through software compatibilization, which offers unparalleled conditions to the performance of works. The maturing of digital tools has radically changed the modular-construction proposition—for instance, by facilitating the design of modules and optimizing delivery logistics. The concept of digitally modelling a whole house and building its parts in a factory is culturally settling and consumer perceptions of prefab

housing are beginning to change, particularly as new, more varied material choices improve the visual appeal modular buildings.

The demand for residential and commercial real estates is expected to increase significantly through 2030. For instance, recent modular projects have a proven track record of reducing project timeframes by 20% to 50%. This saves a huge sum of money approximately 20% of the project's cost as well as man hours that can be put to better use [4]. The foreground of such achievement occurs prematurely, at the beginning of the works, when land preparation and foundation activities take place. While the former is being performed, the execution of the volumetric units is already happening, off-site, with superior quality achieved by the factory-based construction process and predelivery checks. The earnings on scheduling varies and are correlated to the levels of off-site manufacturing, notably increasing from elemental or planar parts to fully modular buildings. This time saving subject will be crucial for our study and will be discussed in detail further.

According to the UN, metropolitan areas will house approximately 68% of the world's population by 2050. Furthermore, the World Bank projects that approximately 300 million new housing units will be required to house approximately three billion people by 2030. The increasing penetration of modular and prefabricated building systems in single-family and multifamily homes is predicted to boost the market growth.

Modular and prefabricated construction market size valued at USD 140 billion in 2021 and is estimated to grow at over 6.8% CAGR (Compound Annual Growth Rate) from 2022 to 2030. Temporary facilities were highlighted during the pandemics and the brisk solutions offered for health facilities were responsible for attending and saving millions of patients. However, permanent construction segment is leading the industry [68]. Regarding the barriers imposed to the uniqueness, its geometrical shape might be clustered to other complementary structures, such as façades, can be supported directly on the building and offer customizations options.

Financial institutions and investors usually back commercial and residential construction projects. According to the European Investment Bank, in 2018, approximately USD 13.300 million was invested in Europe for infrastructure, environmental projects, SMEs and mindcaps financing [68].

2.6 TRENDS FOR MODULAR BUILDING

The market structure is fragmented, and the industry is highly competitive with the presence of several small, medium, and global manufacturers, catering to a wide range of construction activities. Mergers and acquisitions, strategic partnerships, joint ventures, expansion of dealers, and production facilities, among others are key strategies adopted by manufacturers [68].

The modular and prefabricated construction market from Hospitality application is set to reach over USD 56 billion by 2030, followed by Educational and Institutional sectors. Already mentioned before, this sector presents essential features that enable its fully implementation using modular technology and the architectonic solutions seems to adequately result.

The market overall is positive, the growing adoption of lean manufacturing practices and digitally assisted projects are some of the latest trends. At the Autumn Budget 2017, in the UK, the government announced an investment of £170 million to support innovation and skills in the industry via a platform approach to design for manufacture and assembly, P-DfMA, mentioned before in 2.2.1 – Modern Methods of Construction (MMC).

In addition to population growth in general, another trend is the increasingly intense urbanization of the population. By 2050, the urban population is expected almost to double. This urbanization process, with populations and their economic activities increasingly concentrated in cities, brings enormous challenges in terms of sustainability, housing and infrastructure. Further, BPIE (Building Performance Institute Europe) estimates that deep renovation of buildings by 2030 will cut 36% of their energy consumption, reducing European energy imports dependency. Modular offers a solution for urban densification, consonant to heritage preservation.

One of Japan's largest companies in the modular sector, Sekisui Heim CO., not only sells houses but also provide management, renovations, guarantees of apartments/condominiums and other services in order to meet real estate needs and keep its competitiveness and positioning in the market [69].

In addition to various other factors, such as greater efficiency and cost savings, the declining number of skilled construction craftsmen is accelerating the adoption of modular construction techniques. As the industry struggles to find skilled labor, modular construction provides a viable alternative with the potential for automation, 3D printing, and other advanced technologies. From single-family units to towering skyscrapers, modular techniques offer enhanced precision and speed, resulting in reduced construction time and costs. By leveraging the benefits of advanced technology, the industry can produce higher quality buildings while meeting the growing demand for sustainable construction practices.

3

STRENGTHS AND LIMITATIONS

3.1 BRIEF: THE “MODULE” UNIT

The term “modular” has become widely used across many industries, from construction to educational fields. It’s commonly understood to refer to symmetrical, volumetric objects that can be easily stacked, such as LEGO™ blocks. While this definition may seem simplistic, it plays a key role in establishing an understanding of the benefits and origins of modularity.

In ancient Greece, the beauty and harmony of buildings were expressed mainly by proportionality between elements. The diameter of the column was used as the basic parameter, and all the dimensions of the elements, including the shaft, the capital, and the characteristic architectural distances, were determined by multiplying or dividing by this. Some authors claim that the modular concept was already implemented at that time in Egypt, where there was a modular relationship between the stone blocks used in the construction of the pyramids.

Further, in 1971, Ernst Neufert established and spread with great precision the German modular system which had one module $OM = 125 \text{ mm} = 1/8 \text{ m}$, as starting point for a base unit entitled “octameter” used for dimensional coordination of the structural framework. In the United Kingdom, such a normalization was based on the value of $M=100 \text{ mm}$ and $3M=300\text{mm}$ [11]. This detail may seem irrelevant to today’s buildings, but it is the cradle of modular dimensional coordination and multimodal design and still influences the way prefabricated building processes are thought.

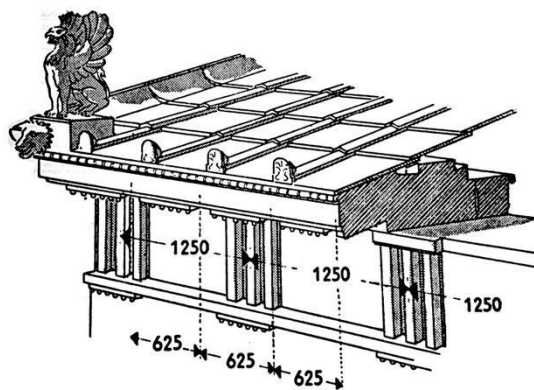


Figure 3.1 “Bauordnungslehre”, E. Neuffer (1971) [11].

Modern industries transformed and expanded the traditional definition of “modules.” It is now viewed as a design system rather than just a measurement system. While the idea of a unit remains, products are no longer designed simply as multiples of module dimensions. Instead, they are structured into modules, based on functional constraints and requirements.

In architecture, the method of modular construction with volumetric modules generally refers to a system where prefabricated or prefabricated volumetric units are used as the basic building elements to create a structure. These volumetric modules are usually constructed off-site from the main construction location and then transported and assembled on-site.

On the other hand, the method that uses the principle, but not necessarily volumetric units may refer to a system where the principle of modularity is applied, but the units are not necessarily volumetric. Instead, other elements or components can be used and later assembled on-site to conceive the desired structure.

Basis of this investigation, a module here is defined as a prefabricated cuboid volumetric unit of variable dimension, partially or fully enclosed. Those structures can be designed to serve as individual dwellings, in which isolated units ideally work alone or, as part of mass cellular undertakings. In the second case, repetitiveness grants serial assembly, maximizing both construction overall performance and off-site production advantages [31].

With regard to the integrity of the main structure, accessories, and connectors are needed and are used to unite the building’s components and ensure adequate behaviour and response to external loads [34]. The type of connections vary and can be classified according to their main function, it is, therefore, necessary to study case by case so that the correct dimensioning of such elements is properly carried out.

Similarities and patterns in modular design are beneficial for production efficiency as they ensure the system’s feasibility and maximize compatibility between units, allowing standardized assembly procedures and modularization of electrical, mechanical, and plumbing components. Beyond that, software assistance and 3-D printing are progressively eliminating former barriers that used to slow the development of industrialized alternatives, offering optimization opportunities to the whole production chain, improving processes and eliminating both material and time waste. In addition, producing (or even printing) tailored connectors to ensure perfect compatibility and assembly conditions, as well as the design of one single universal locking system are ideas that are becoming more and more probable.

As an answer to the antiquated principles of traditional methods of construction, people are starting to rethink their relation to the environment. Industrialized sustainable solutions are growing, fostering lower levels of energy consumption, and promoting behavioural modifications. Much beyond, costs are getting higher, and lack of materials and labour are each time more recurrent. In order to follow such incessant evolution of the way we think of

building, the industry has to maintain (or increase) its development and constantly reinvent its methods.

This chapter intends to assess and analyze the main advantages found in concern to modular alternatives, mainly those that attain, directly or indirectly, possible gains in execution time. Through the study of its main specificities, types, materials, and components, the execution of such structures will be elucidated, emphasizing relevant techniques that maximize time and costs savings and how (and where) they can be implemented in the chain in order to contribute to the dynamization of several processes and improve the productivity and overall performance of the activities.

3.2 BUILDING PROCESS

As previously mentioned, the repetition of uniform intervals and dimensions simplifies both design and building process as identical edifications of identical functionalities tend to repeat many of its dimensions. Besides that, many of the structural details will perform identically, demanding similar supporting structures. The harmonization of those dimensions, repetitions, and uniform sizing paves the way for factory production [11].

Modular units are perfect fit for cellular constructions, and several are the possibilities for arrangements and dimensions, from low to high-rise, temporary or permanent and, although in-site activities demand reduced operational space, the off-site manufacturing activities demand considerable easement area to be properly carried out. Most part of the production lines are rather covered to originate enclosed spaces, which will resemble just like a regular factory, for building production.

As illustrated bellow, in Figure 3.2, the modular building process has similar stages to those observed in the traditional method of construction. The first stage involves designing and engineering a structure using prefabricated components or volumetric modules, which are fabricated off-site and transported to the construction site. The modules are then assembled and installed on-site, followed by finishing and fitting.

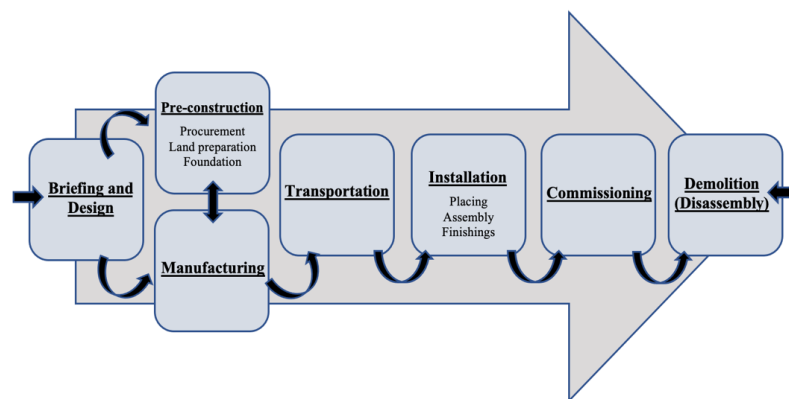


Figure 3.2 Modular Building Process. By the Autor; adapted [70]

Such a process offers benefits such as faster construction, reduced labor and material waste, and increased precision and quality control. In that sense, the first time-related benefit can be noticed right after the end of the tendering, when, concurrently with site preparation activities, the manufacturing of the modules also befalls. This overlap is responsible for the first 30-50% reduction in execution time [4].

3.2.1 LEGISLATION

With regard to regulations, modular construction is legally framed like any other. As such, in most parts of the countries, it must follow standards substantially identical to traditional methods of construction [71].

Ambiguities in contract documents are among the major causes of conflicts, disputes, and claims in the construction industry. When it comes to modular construction, the issue of ambiguity and the undesired consequences becomes even more critical. A study by the Canadian Office of Legislative Oversight in 2015, indicates that ‘change orders’ in modular buildings increased 30.3% of the time and 8% in contract overall costs, a fact which illustrates the urge for development in that matter [72].

However, in Pacific-Asia, region which presents the higher growth rates, China Engineering Construction Standardization has already issued the Technical Specification for Modular Freight Container Building (CECS334:2013) [73], which contains relevant executable regulations for the design, construction and supervision of prefabricated container buildings, comprising relevant particularities regarding the modular design, exterior structure construction, interior decoration, building protection, structural design, foundation, construction and acceptance as well.

As a matter of fact, the country has been promoting the development of sustainable alternatives, an important move to stimulate new contractors and alleviate bureaucracies related to licensing processes [71]. As it develops, the trend points for more countries issuing their own modular guidelines, leading to positive consequences in regard to legal framework, ambiguities and overall requirements.

It is therefore concluded that, although modular building and prefabricated houses attain faster execution and yield benefits, legal procedures go against the grain, meaning that licensing bureaucracies may be greater and demand longer response time when compared to traditional building methodologies [71]. Still, the remaining benefits – especially the ones related to time-saving – endorses off-site added value and with the correct planning, the process presents the same feasibility of the traditional ones.

3.2.2 DESIGN

3.2.2.1 TYPES

The options for prefabricated modular units are vast, and the intended use and lifespan of a building greatly influence the design, components, and quality. These decisions may be influenced by various factors, such as tradition, climatic conditions, the need for compatibility between volumetric units, budget, and applicable deadlines. It's important to consider these factors when selecting the appropriate prefabricated modular unit, as each decision can significantly impact the final outcome. Additionally, the use of prefabricated modular units provides a wide range of benefits, including greater efficiency, reduced construction time and costs, enhanced quality control, and increased sustainability. These benefits make prefabricated modular units an attractive option for a variety of building types and applications [31-32].

The following categories are commonly distinguished [35]:

1. Portable – Those structures ideally ease assembly and relocation conditions. For commercial use, it provides an economical alternative for short-period installations, such as offices, storages, toilets and outbuilding facilities. When used for housing, they are also referred to as ‘mobile homes’ and are classified as multi-axle vehicles for taxing and zoning purposes. To enable hook and transportation, they commonly have an attached steel chassis and to improve aesthetics, pier and beam foundations with skirting can be used.
2. Temporary – Offers economical solutions for traditional buildings when pondering their further dismantling, it is also a good option to meet extra space demand caused by sudden increases in personnel or activities. The highlight here goes to the Campaign Hospitals built during the pandemics, which cooperated to deliver thousands of beds and health facilities in record periods of time.
3. Permanent – Depending on the structure’s main material and the way the assembly was conceived, they can still be dismountable, however, it is no longer their central feature. The category comprises all the edifications designed to remain and carry out the lifespan of regular buildings, from single houses to high-rise buildings.

A frequent misconception concerns the term “panelized homes”. In that case, only structural components of the house (walls, roof and slab systems) are built inside a factory, meaning that, once delivered, on-site activities take place and are concluded similarly to those observed in traditional constructions, demanding additional labour force to perform the assembling and increasing the time spent in the construction site.

This study will focus on long-term/permanent edifications. This type of construction, on contrary to the small-sized relocatable ones, do not dispense previous assessment regarding the soil strength, which means that pertinent land treatment and foundations shall be provided. Indeed, considering the parallelism of such activities with the manufacturing, the longer the ground preparation takes to elapse, the longer will be the period available for the volumetric units assembling. In this sense, we could argue that Modular is also a good alternative for scenarios in which the soil geomorphology is loose, weak or rugged.

3.2.2.2 COMPONENTS

The second important consideration when using prefabricated modular units is the combination of 3D-volumetric units with 2D-prefabricated parts. This integration requires careful planning and design to ensure compatibility and proper installation. In this sense, modular components can be sort as (1) 2D panels, (2) 3D modules or (3) Mixed/Hybrid [4].

Combining 2D and 3D prefabricated elements in modular construction can save time by allowing for more efficient and precise fabrication and assembly on site. The use of 2D elements, such as prefabricated walls and floor panels, can speed up the construction process as they can be manufactured off-site and stacked in piles, facilitating their transportation. On the other hand, the use of 3D elements, such as prefabricated bathroom pods and stairs, can increase the level of customization, allow more complex building designs and shorten execution times [4].

The combination can also be used to expedite regular constructions, incorporating modular elements to those stages where construction processes were overdue. Therefore, it is arguable that Hybrid usage offers a solution to supply prefabricated elements when in periods of high demand and shortages, as well as when agility is required to improve the activities' development. In addition, it could help us to increase the speed, efficiency, and quality of modular construction whilst reducing the assembly time and costs with full volumetric unit transportation.

3.2.2.3 SHAPE

In regard to their shape, modular structures are commonly classified as:

- a. Closed Systems (4-sided modules)

The first shape to be thought of when it comes to prefabricated buildings. Fully enclosed, with no open edges or faces, its shape resembles shipping containers; simple stacking is permitted and frequently limited to three floors [81].

In order to build higher structures, additional bracing to gables or a stabilizing central core are required [94]. Closed units are generally easier and faster to assemble as they do not require additional finishing work such as adding roofing or cladding.

Their handling can be eased by using cranes or other lifting equipment, making them faster to install and reducing the time spent on on-site assembly activities.

Another concern concerns the insulation, which can be performed with ease and provides better thermal efficiency and energy/costs savings.

b. Partially Open Systems (Partially Open-sided modules)

Similar to previous, it has open sides and allows the creation of new spaces through the combination with others. These units can be more complex to assemble than closed systems and may take longer to install. However, the added flexibility of partially closed systems allows more customization and design options.

c. Fully Open Systems (Open-sided modules)

Composed by four pillars and beams which are responsible for supporting the ceiling and the possible extra loads caused by stacking. They are typically used for outdoor spaces such as balconies or terraces and usually require additional bracing and can be furtherly enveloped. These units can be the fastest to assemble, as they require no additional finishing work, but may require more advanced equipment and extra effort during the design phase to ensure structural stability.

The shape of a volumetric unit can greatly impact the time spent on assembling activities. Closed systems are the easiest and quickest to design and assemble, walls and façades may present strength to help with the transmission of loads. In that matter, openings usually decrease structural response capacity and restrict the simple stackings, demanding extra time during the designing phase and higher assembly precision. Ultimately, open systems are the fastest to assemble, but they require more time during their design and demand more complex solutions when pondering taller buildings [74-75].

A possible distinguishing for the structure framework could be (1) Open-sided or column-supported and (2) 4-sided or continuously supported. Column-supported modules have beams that run along the edges of the module and are supported by columns at the corners or at intermediate points. In that regard, the author elucidates that although column-supported solutions result in faster assembly, 4-sided modules present higher strength, and act as a structural component of the edification [76]. The most common typologies, as well as their impact to the performance of works, will be investigated in detail in the next chapters.

3.2.2.4 INTERFACE

And finally, modular products, which can be defined by the interface between modules [75]:

- a. Slot modularity - Different interface between components; The components cannot be interchanged with ease.
- b. Sectional modularity - Components are connected through identical interfaces.
- c. Bus modularity - A single component, the bus, is responsible for the interface between all the components.

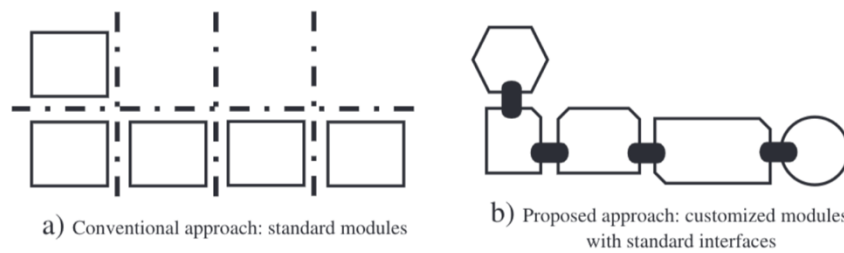


Figure 3.3 Proposed approach for standardization of interfaces between modules [75]

The interface between volumetric units in modular construction can have a significant impact on time savings in building construction and is crucial to maximize the benefits of modular construction. Precise interfaces between units can greatly speed up the assembly process, as the units can be quickly and easily connected and aligned [75-76].

Sectional modularity is currently suggested as the least condition to ensure proper compatibility between the modules of the structure, as well as the need of using advanced manufacturing and fabrication techniques to ensure the correct dimensioning and interface, reducing the time spent on site, as well as the need for additional support and bracing [76-77].

3.2.2.4.1 CONNECTORS AND JOINTS

It is important to foresee compatibility questions since the beginning of project development, an efficient standardization of the module base dimensions ensure proper fitting conditions and rigidity. Interconnections need to be designed in a way that provides alternative load paths in the event of accidental damage to structural members therefore, creating a detailed design and plan for the prefabricated units, including all necessary technical drawings and connecting elements specification, is a crucial and time-consuming aspect of the process [76].

To achieve the desired composition and structural response, various connectors and interface systems can be used, providing stability and support to modular buildings. These elements are also responsible for handling horizontal and uplift forces generated by natural events like wind or earthquakes, as well as extreme forces resulting from accidental events such as blasts and loss of support [77].

In the conventional design of modular buildings, units are typically connected using mechanical fasteners in their corners, which ensures both lateral and vertical stability of the structure. However, advancements in technology have led to the development of new and improved connectors and interface systems, which provide enhanced strength, flexibility, and ease of use [77-78].

Researchers and engineers are still striving to develop universally high-performing connection systems, which are currently categorized into three types: (1) intra-module connections, (2) inter-module connections, and (3) module-foundation connections. Among these, the inter-module connections are particularly crucial for determining the overall structural behavior of the system [78].

By improving the quality and reliability of these connection systems, it is possible to enhance the safety, durability, and efficiency of various products and structures. Advancements in connection technology have led to the development of stronger, more flexible, and more adaptable products, thereby paving the way for innovative new designs and applications.

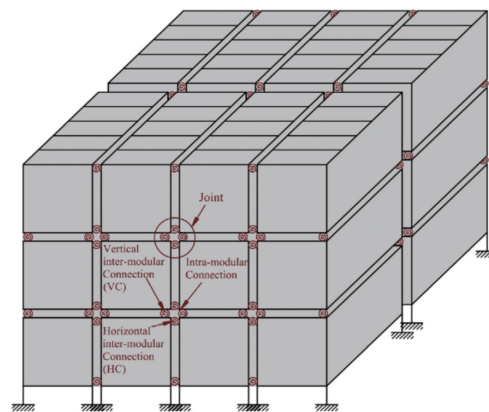


Figure 3.4 – Corner support moment frame modular building [78]

A systematic classification for IMC (inter-module connections) based on the method of joining provides a harmonized overview of the most employed systems [78].

1. IMC with locking devices
2. Post-tensioned IMCs
3. Bolted IMCs
 - 3.1 Column-to-column (CTC) connections
 - 3.2 Beam-to-beam (BTB) connections
 - 3.3 Fitting-to-fitting (FTF) connections

Furthermore, a multi-attribute scoring system was proposed based on three core criteria, namely structural, manufacturing and constructional performance attributes. This study revealed that the use of corner fittings, bolted joints, self-aligning/locating parts, and damage control devices were all must-have features for IMCs with all-round performance and therefore, their usage shall be prioritized [77].

In comparison to traditional construction, interlocking based structures present several potential advantages. It is basically a rigid integral mechanical attachment that provides consistent join between the parts by using geometric features that causes mechanical interference and interlocking among the parts. Moreover, interlocking connections are easier to accomplish than most fastening systems, a factor that may contribute to the efficiency of the assembly [76][78].

Another relevance of interconnecting systems concerns tolerance control. During the fabrication, expansions, shrinkages and overall deformations caused by the transportation may occur. Due to that, some degree of dimensional variation is possible and might influence the correct placement and as well the assembly accuracy [77].

Moreover, this tolerance is responsible for maintaining the building stability when relevant eccentricities and consequential additional inter-module stress are observed. To solve this issue, the design of rather adjustable connectors allows dimensional adjusts between modules [77].

The complexity of the design, the size and scope of the project are some of the particularities that may influence the complexity of the design and interface requirements, however, once well defined, one modular unit can be used as model, replicated and reproduced to countless other projects, meaning that, even with punctual modifications, the time spent from the preliminary design to the project's final acceptance can be significantly shortened when compared to traditional constructions. Furthermore, the development of new technologies allows accurate dimensioning of elements and a variety of arrangements possibilities that could be used to customize constructions and prevent them from over standardization, a frequent complaint among the sector's customers and architectural critics.

This design-related aspects have a significant impact on project execution. Complex designs require more time, as well as more complex engineering solutions, additional structural elements and better connecting systems. In the next chapter we will delve into how these design parameters and even the factory layout can affect productivity, in attempt to quantify possible time savings during the project conception.

3.2.2.5 ASSEMBLING

3.2.3.1 MATERIALS

In attempt to reduce losses caused by shortages and fight the overall increase in costs, new materials with enhanced properties are being constantly developed and introduced in the market, revealing an uninterrupted process where, new, improved solutions come to replace outmoded others, contributing to rapid development of the sector and emphasizing the need for such an alternative.

Modular building materials commonly employed include timber, steel, concrete and composites, another possibility is the combination of them, availing their major features to different parts of the structure. Such choice varies according to climate, geomorphological and economic conditions and may exert considerable influence over the manufacturing complexity.

The production of prefabricated units, including cutting and forming the components, is a time-intensive task that requires specialized equipment and skilled labor and around 20% to 50% of the total operating expenses in modular manufacturing are related to material handling and layout [74].

The purpose of this subchapter is to present the main components and their respective materials, elucidating the main advantages related to each of them and how they can influence the execution and performance of the assembling activities.

3.2.3.2 WOOD

Traditionally known for its high ecological value, wood is considered a versatile and useful building material with a negative carbon balance, meaning it absorbs carbon from the atmosphere while providing much lighter solutions. It has been used in countless applications for more than 10,000 years and is usually the first choice for home framing. In addition, its aesthetically pleasing appearance promotes harmonious and comfortable integration into the environment, from structural components to cladding [54].

Among the strongest building materials, wood presents good fire resistance, relatively light-weight and one of the best materials in terms of supporting its own loads. In addition, it is easy to use and cut down to size, allowing details, doors, windows and other openings to be easily made at any time during the construction works.

Mid-rise light wood-frame structures are widely considered to be cost effective, due to relatively low material costs, reduced construction time, availability of resources and labour. However, the industrialized prefabrication of engineered wood products – e.g., glue laminated timber, laminated veneer lumber (LVL), cross laminated timber (CLT) – has allowed the increased use of wood in large scale construction, wood-frame multi-storey construction (WMC) is enjoying a period of increasing popularity within the public and the execution of ‘Timber towers’ and ‘wooden skyscrapers’ are gaining traction as software and digitally assisted constructions grow [54-55] [79].

There are two types of framing configurations for wood construction: the platform-frame, and the balloon-frame [80], some authors would also consider Semi-balloon framing, which requires hangers and is often used as an alternative to platform framing in structures where fire requirements or shrinkage may be a challenge.

In Scandinavia, panelized single dwelling residences represent over 80 percent of the country's overall housing market, being recognized as the world's highest percentage of factory built wooden houses in the world, mainly by using partially finished closed panel timber frames [18]. The advantage is most related to the ease of transport, on the contrary of volumetric units, 2-D panelized panels are easier to accommodate and attains the possibility of stacking, which optimizes the use of space and reduces freight costs. On the other hand, it requires skilled labour and increases the hours necessary to perform assembly activities.

As preventive measure, the wooden panels are covered with OSB board, a type of durable engineered wood made from oriented panes with crossed layers, which provides protection to the studwork and high mechanical and moisture resistance, not only, it also protects the build stopping damp from occurring, preventing any weather damage [81]. Other treatments can be foreseen and to ensure its integrity, maintenance and retouchings must occur for the whole building's life.

Even with the possibility of designing all the structures in wood, by the end of the 20th century, it still faces obstacles regarding its limited height and durability. Concrete and steel became the subject of the construction revolution and most of the companies rather work with 'sandwich' panels made out of galvanized **steel**.

3.2.3.3 STEEL

Among the subjects of building revolution, some of steel's properties elucidate the reason for such preference. Classified as metallic alloy, the reduced percentage of carbon on its composition distinguishes it from regular iron, providing higher values for mechanical strength and ductility, at lower costs. Moreover, recent studies found out that steel savings runs around 35% to 45% when a DfMA technique is used, also designated "eco-friendly", the ease of assembly and further disassembly corroborates the reduction of ecological footprint whilst secures recycling and new employ for used components [74].

To connect the panels, cold-galvanized steel profiles and special molded joints may be used, which are joined together with robust, easy-to-install connectors. These connectors are essential to maintaining the structural integrity of the entire assembly [77].

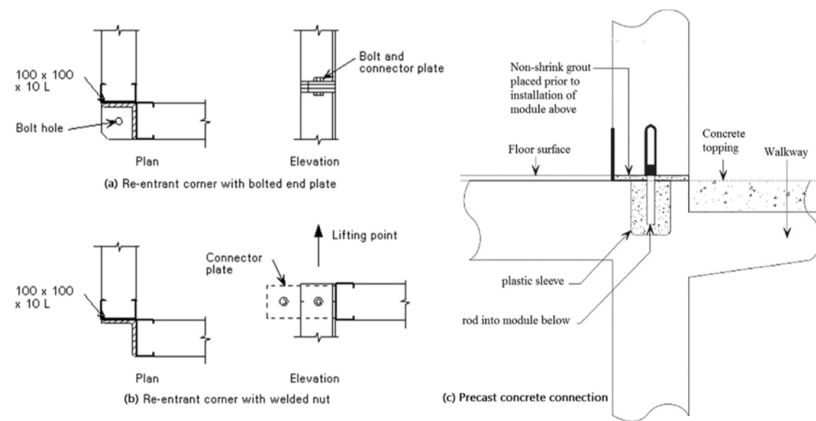


Figure 3.5 The most common connecting systems in concrete and steel modular construction[77]

Compared to other materials, steel offers favorable conditions for both assembly and disassembly, making it easy to reuse parts in other constructions or melt them down for recycling. It is a traditional material still prevailing in Asia-Pacific countries like Japan and China due to its cost-effectiveness, durability, and speed of construction. Even when it is not the primary material used in a building, it can still be a cost-effective option for structural elements, mounts, and connections. In addition, reinforced concrete slabs and partition walls are often integrated into steel modules to provide excellent acoustic and thermal insulation, resulting in a complete building system for modular steel construction [82].

3.2.3.4 CONCRETE

Approximately 11 billion tons of concrete are consumed annually, representing an impressive amount of 1,9 tons per inhabitant, a value which is only surpassed by water consumption. Once cured, it becomes a homogeneous, rigid mass, conceived to perform just like an artificial rock; before that, its plasticity grants adequate fluidity for the pouring, allowing the modelling to be performed in varied shapes and sizes. Moreover, the average consumption of raw materials, such as gravel and cement, is biased high and concrete production is often associated with considerable environmental impact [83]

The main components and their respective proportions vary and are measured accordingly to the expected performance and strength required by the project design. Once demolished, concrete waste is hard to recycle, and the average employment of RAs is still derisory when compared to its overall consumption [9]. Therefore, in order to prevent the generation of even more waste, its use in modular edifications is strictly recommended for permanent edifications.

The fabrication of concrete units requires extensive planning by the supplier to prepare the units in a timely manner and is crucial to the success of this type of project, in order to take advantage of the time savings that precast concrete offers [9]. Concrete is easily produced and

can be incorporated in different parts of the project, from walls to structural frame, it provides high stiffness and is a cost-effective substitute for steel or wood, contributing to work around the generalized shortages of materials.

The components can be either cast in place or precast in a factory. Advantages of precast concrete over site cast concrete include a drastic reduction of shoring and formwork costs, and better quality control over strength and surface finish. On the contrary, precast members require more highly skilled workers, more complex techniques, and a more complex design [84].

Other materials such as light weight concrete and light weight steel-concrete composite are becoming progressively used and prove to be good alternatives for filling and sealing walls, partitions and panels. Further, they considerably reduce the structure weight without compromising its strength and stiffness, presenting good applicability for high-rise buildings while inheriting concrete benefits, namely durability, fire-resistance, water and sound-proof qualities [57].

3.2.3.5 GLASS

Modern architecture is increasingly employing glass façades or curtain walls as substitutes of regular masonry and concrete elements, attaining its aesthetic visual whilst meeting safety, comfort and functionality requirements. The second mentioned is still in process of establishment, promising to reduce building sway, increase thermal efficiency and act as both a buffer and an insulator for air and moisture [85-86].

Glass and translucent façades may be a good opportunity to compensate for the lack of natural daylight, providing better use of such natural resources. In terms of that, translucent bricks possess additional load bearing and thermal insulating properties when compared to other translucent solutions and can be used as design substitution for regular opaque walls [87]. Moreover, it is a traditional ally to improve aesthetics, customize and decorate spaces.

However, investigations after earthquakes worldwide have conclusively demonstrated that the glass façade systems are very vulnerable to various failure mechanisms, therefore, to ensure the structure's stability and proper functioning, mirror elements must follow specific fixation mechanisms and appropriate design and response to seismic and strong ground motions [85].

Concluding, materials' market share may also vary according to the business sector. In this sense, steel construction has established a 'track record' in the commercial building sector, where the benefits of speed of construction and long spans with service integration are well understood, however, when it comes to the housing sector, two- or three-story buildings market share is currently 3%. Moreover, time savings of 30-50% in total construction time can be achieved by using light-steel in larger undertakings [34].

Studies in the field investigated the sustainability and environmental effects of concrete and steel modular building systems in the context of urban development. To ensure comprehensive evaluation and accessibility of data, eleven Key Performance Indicators and twenty sub-indicators through an extensive review of literature on modular construction performance were defined. As a result, he reported that the duration of on-site superstructure work in concrete and steel cases saw a decrease of 32% and 50% respectively.

Engineering construction uses modular composite building finished products to the greatest extent, which reduces the workload of field operations and saves a considerable amount of time [161]. In that regard, the performance of steel modular construction considerably deviates from concrete, offering a faster pace of 40% and making it an ideal solution for urgent building projects [88].

Category	Applications	Advantages	Disadvantages
Steel – MSB module	Hotel, residential apartments	Suited to high rise buildings, high strength	Corrosion, lack of design guidance
Steel – Light steel framed module	Max. 10-storey, 25-storey with additional core	Lightweight	Suited to low rise buildings
Steel – Container module	Post-disaster housing, military operations, and residential developments	Recycle shipping containers, easy transport	Additional reinforcing required to strengthen container when openings are cut in wall
Precast concrete module	Hotel, prison, secure accommodation	Fire resistance, acoustic insulation, thermal performance, high mass helps meet vibration criteria, high capacity	Heavy, potential cracking at corners
Timber frame module	1- to 2-storey, education buildings, housing	Sustainable material, easy to fabricate	Poor fire resistance, durability

Table 3.1 Module classification by type of material [78]

3.3 MAINTENANCE AND DURABILITY

The quality of all building components is sooner or later going to be tested by the users of long-term edifications. At first, the performance of those elements rely on accurate dimensioning, specification of materials and detail richness of plants and projects, when adequate, misreading tends to be less recurrent, and the execution of works is properly developed [4]. Other parameters that may influence their functioning are the origin, storage conditions, as well as the further handling and transportation inside the factory. To prevent possible damages that may alter their quality, plan of actions shall be carefully studied and applied for each project, considering their own specificities.

Once inspected, handled, and preferably tested, the components are ready to be used and the owner may expect the proposed functioning for all the parts of the structure. The benefits of factory production go beyond the agility conferred to the process, it standardizes the production of all components, meaning that materials intrinsic properties will not be affected by climate conditions or human errors, maximizing their performance whilst considerably reducing

material waste generation. Moreover, with well-defined quality standards, the assembly of our structure is carried out with ease, ensuring stability and proper functioning for its whole lifespan.

The main structure of modular buildings is commonly composed of timber, steel or composites, each of them possess different fabric conditions which are responsible for inherently properties and unique maintenance demands. However, companies tend to work with standard versions for their units that require minimum modifications from one project to another. Similar projects may repeat good deeds and avoid repeated mistakes, meaning that modifications and improvements can be constantly applied to reduce execution and assembly mistakes, progressively ameliorate their base model and establish appropriate maintenance programs to their products.

Although often trivialized, this is one of the reasons why customers often used to judge modular construction as inferior in terms of quality and durability, which hindered its growth [4]. Modular units require periodic inspections just like the traditional edifications. Durability is strongly influenced by the layout and positioning of structural elements within the building frame and such an arrangement may facilitate or, make even more difficult, the establishment of a routine surveilling.

An outstanding example of that is the Nakagin Capsule tower, the 70's edification erected in 1972 with 13 floors and 140 capsules was disassembled in 2022 after years of neglect, which led to the abandonment of more than a half of the deteriorated capsules. In such case, the main proposal of modular alternatives does not materialize and the structure that should provide versatility and housing at low costs turns out to be one more to among the known cycle of traditional constructions, generating waste and polluting even more the planet. Such a divergence could hamper construction industry's efforts to reduce its environmental and economic impacts in the future, pointing towards the need of an integrated, holistic approach to improving the sustainability of the sector [88].

In an attempt to solve this matter, software compatibly and Corporate Performance management (CPM) programs may be used to catalog pieces and generate accurate assessment on their overall performance. Further on, those elements may be incorporated to maintenance scheduling or even be removed and reused. Moreover, several companies now offer periodic maintenance plans to customers included in their lot or home unit rental price. Such a strategy aims to preserve the modular heritage and change possible bad perceptions that people may still have about this building alternative. Alignment with this type of practice is fundamental for the modular option to continue to be stimulated and actually used as a building methodology.

3.4 SUSTAINABILITY

Three are the main benefits of modular construction: (1) higher quality, (2) shorter construction period, and (3) eco-friendly building methods [157]. The entire concept and design process involved in the methodology are sustainable or less harmful to the environment [90]. Prefabricated structures are bent, cut, and welded on-site, according to standardization and demand, and therefore have controlled waste, leftovers, and tolerances. Moreover, factory waste can be better regulated and policies for disposal and management can be implemented to reduce environmental impacts and emissions [91].

In the last stage of the building's cycle life, demolition is a disassembly. Many of the parts may be reused in future projects, reducing rates of raw-material consumption and waste. The process typically involves removing any fixtures and fittings, such as electrical and plumbing systems, and then carefully disassembling the structure itself. The pieces can then be transported to another location for reuse or recycled, depending on the condition of the materials. The complexity of the dismantling process can vary depending on the size, design, and location of the structure, as well as any environmental or safety considerations that need to be considered.

In addition to that, much effort is still devoted to improving prefabricated constructions sustainability; software compatibility supported by digitalization across the full lifecycle of built infrastructure enables modular components reuse and has the potential to optimize efficiency, maximize multidimensional value e.g., positive environmental, economic, social, and technical impacts, recovery and promote circularity in the sector. Indeed, a smart, modular construction regime can operationalize the collection and storage of components' lifecycle information, and help the sector build the capabilities needed to support the maintenance, recovery, and reuse of components [89-92].

Another relevant aspect of their implementation relates to carbon footprint. Modular systems generally have a lower carbon footprint compared to conventional construction, as factory manufacturing can be more energy-efficient and result in lower emissions of greenhouse gases. Additionally, many modular systems are designed to be energy-efficient, with thermal insulation and integrated renewable energy systems, which can reduce energy consumption over time.

In modular construction, the material production phase is reported to produce higher carbon emissions than the other phases, and compared with the carbon emission research in the operation and maintenance stage, the carbon emission research in the materialization phase presented a direct relationship with the construction mode [157-158].

As illustrated bellow in the Table 3.X, when considering the main construction materials used during the production phase, assessments of embodied carbon emissions showed that adopting a modular construction approach resulted in a reduction of approximately 36% in environmental impact compared to the conventional reinforced concrete method. However, it

should be noted that the modular construction was approximately 8% more expensive in terms of direct construction costs compared to the conventional reinforced concrete construction method [157].

Materials	Modular (B-Wing)		Reinforced Concrete	
	Embodied Carbon Emissions (kg-CO ₂)	Proportion (%)	Embodied Carbon Emissions (kg-CO ₂)	Proportion (%)
Metal	47,961	35.32	24,793	11.66
RMC	37,967	27.96	146,506	68.92
Steel	29,719	21.89	-	-
Glass	6238	4.59	8047	3.79
Gypsum Board	5849	4.31	310	0.15
Cement	4236	3.12	19,886	9.36
Rebar	3191	2.35	10,757	5.06
Tile	474	0.35	1669	0.79
Block	121	0.09	408	0.19
Sand	31	0.02	112	0.05
Stone	-	-	71	0.03
Total	135,787	100	212,559	100
Per m ²	279.51	-	437.54	-

Table 3.2 Assessment of embodied carbon emissions [157].

Furthermore, in regard to the transportation of the prefabricated elements, the carbon emissions factor associated with the transportation of prefabricated components is heavily influenced by three parameters: (a) the full load ratio, (b) the average speed, and (c) the atmospheric temperature. The impact of atmospheric temperature, average speed, and full load ratio on the carbon emission factor increases significantly during turning. Therefore, when planning the transportation of prefabricated components, it is important to maximize the full load ratio of vehicles while adhering to the requirements of component transportation sequence. Additionally, choosing a smoother route for shorter distances and avoiding transportation during noon when temperatures are highest can help minimize carbon emissions during transportation [158].

3.5 TRANSPORT AND HANDLING

The transportation must consider the maximum dimensions of the volumetric units and their strength must be reinforced to furtherly to ensure stability and safe transport conditions. The transportation of prefabricated units from the manufacturing facility to the construction site can be time-consuming and complex, especially for larger or more complex structures [93]. In this sense, transportation logistics and coordination between the factory and the implementation site are mandatory and need to be carefully studied to ensure work's feasibility.

Not merely, another important particularity to be considered concerns the restrictions imposed on the maximum dimensions, which are limited by local traffic codes and must follow size

criteria. Therefore, the number of displacements and the respective cost increases accordingly to the size of the undertaking, which must be considered since the designing phase.

The transportation the main constraints encountered by offsite construction projects [6], however, it can be mitigated through the implementation of strategies and adequate coordination. This study will investigate this issue, as well as discuss possible resolutions.

3.6 SEISMIC RESPONSE

Extensive research works have been carried out to investigate the seismic behaviour of building structures, and displacement-base damage criteria such as the ductility ratio and inter-storey drift ratio widely used by the design guides to measure their seismic performances. Modular offsite construction technology has the potential to enhance the post-disaster housing reconstruction process due to its intrinsic characteristics of time-efficiency [94].

Studies concerning the prefeasibility of both multistorey wood-frame and steel building in high seismic zones have been developed [95-96]. The methodology was developed by analysing a comprehensive database of 201 wood-frame buildings designed with different seismic performance factors, architectural configurations, number of stories, soil conditions, and anchorage system.

The seismic performance of mid-to-high rise modular steel construction will be considered, the importance of the seismic performance of the lateral resisting system and introducing innovations on connecting system and other mechanisms [82].

3.7 COSTS

The issue of costs in this type of construction is highly complex and involves the analysis of various scenarios beyond the actual execution of construction activities.

The first consideration concerns the initial implementation cost. Although modular factories eliminate the need for temporary construction sites, they require the provision of a relatively large secondary space for the fabrication of modules. This space needs to be equipped with machinery, tools, storage space, and material handling facilities, as well as a site where finished units can be positioned until they are transported. For this reason, many factories choose to locate themselves away from major urban areas towards more remote zones where land with these characteristics is more abundant. On the other hand, the distance should be carefully considered to avoid transportation costs becoming prohibitive or significantly increasing freight costs later on.

Nevertheless, this enclosed environment allows for greater control and safety of activities, directly impacting productivity and quality of fabrication. Additionally, it eliminates dependency on weather conditions, which previously could have rendered activities unfeasible or delayed, resulting in losses for all project stakeholders. This factory can operate concurrently with site preparation and procurement, enabling significant time savings.

Regarding costs of materials and components for construction, both traditional and modular structures can be built using the same materials, including concrete, steel, wood, and composites. However, the arrangement of these materials is done differently, with concrete being commonly used in traditional buildings, while steel is abundant and tends to be the preferred choice for modular methodology. In addition to its unique strength properties, steel can be easily shaped, cut, and recycled. In combination with the highly controlled environment of factories, waste can be significantly reduced, gradually lowering the cost per cubic meter in the long term.

The quality of these materials also directly impacts maintenance and associated costs. In intra-module connections, for example, although welded connections may be cheaper than bolted connections, bolted connections allow for easier access and passage of technical installations and services, making them preferred for long-term installations. For temporary installations, components and connections can be reused multiple times for a variety of applications, so more robust and durable parts may be preferred, prioritizing the integrity and viability of reusability.

As illustrated bellow in Figure 3.x, when comparing the total direct construction costs of modular and reinforced concrete (RC) construction methods, it was found that the costs for modular construction were approximately 8.1% higher. However, when taking into account the potential for reusing individual modules, the cost savings from mass production of modules, and improved work productivity due to learning effects, this cost premium is partially offset by the significant economies that can be achieved. As a result, the unit cost of production over the entire life cycle of the module can be lowered [157].

Activities	Modular (B-Wing)		Reinforced Concrete	
	Cost (USD) *	Proportion (%)	Cost (USD) *	Proportion (%)
Metal work	186,202	39.01	88,020	19.93
Reinforced concrete work	-	-	129,968	29.43
Carpentry work	92,976	19.48	-	-
Miscellaneous	70,145	14.70	35,484	8.04
Windows	37,123	7.78	41,083	9.30
Interior finishing work	29,875	6.26	40,366	9.14
Temporary work	-	-	28,764	6.51
Roofing and gutter work	20,668	4.33	4700	1.06
Tile work	5750	1.20	19,398	4.39
Painting work	18,005	3.77	3124	0.71
Waterproof work	704	0.15	17,793	4.03
Glass	7487	1.57	16,831	3.81
Plastering	3124	0.65	6908	1.56
Stone work	5118	1.07	5969	1.35
Masonry work	155	0.03	546	0.12
Aggregate and Transportation	-	-	2626	0.59
Total	477,332	100	441,580	100
Per m ²	982.57	-	908.97	-

Table 3.3 Direct construction costs for the modular and RC construction methods [15]

VISION FOR IMPLEMENTATION

4.1 INTRODUCTION

Industrialized construction is closely linked to the factory environment and many of its advantages are related to such a controlled environment. Most of the work activities are executed there and their main product, volumetric units, are transported to the construction site almost ready to be lifted and placed. This means that temporary facilities, which are typically required in traditional construction, may be dispensable and need not be built on-site beforehand. Even though dedicated administrative offices or warehouses can be condensed to the main administration, logistics are crucial to ensure proper coordination between assembly activities and module transportation, leading to costly operations that vary according to the project's complexity.

Therefore, clear communication and planning are especially necessary in MMC undertakings and aim to ensure that the volumetric units are delivered and installed on time and to the required quality standards. Another important aspect concerns their integrity, volumetric units must be designed and fabricated to integrate seamlessly with other building elements, such as foundations, structural elements, and technical services. In this sense, connectors or fitting systems are dimensioned to meet rigidity and strength demands, enabling multi-modules arrangements to maximize occupancy and application options. In addition, volumetric units require additional resistance to grant their integrity during transportation and placement.

Plant's layout, machinery operation, alignments, fastening methods and many among modular's specificities are responsible for differing MMC methodologies from any other type of construction. In addition to that, the establishment of reliable parameters to assess quality control during the entire chain course will be indispensable to ensure appropriate coordination conditions, maximizing the overall performance during the entire conduction of all concerning activities and, after that, in the end-of the life cycle, when parts can be disassembled and reused in new projects.

In the previous chapters, the main characteristics of prefabricated constructions were assessed, and different types and materials were investigated in the optics of their assembling performance. In this chapter, the development of a regular modular undertaking will be simulated through an analysis of the main stages of the conception process, thus allowing to elucidate attained benefits and constraints faced by contractors that opt to use such methodology.

4.2 APPLICABLE TECHNIQUES

Modular techniques aim above all to dynamize processes and therefore, enable the establishment of a productive assembling line. Materials and techniques vary, thereby the construction process is always different depending on the location and environment of the building site, the economic situation of the country and the skills of contractors [97].

As a matter of fact, volumetric constructions employ several of the aforementioned MMC techniques, providing better control over manufacturing activities and reducing waste. Besides that, its high degree of standardization favors the establishment of a highly precise production chain, with detailed phasing and subject to the application of lean principles and other philosophies centered on its constant improvement.

4.2.1 LEAN CONSTRUCTION

Lean principles can be highly applicable in modular construction, as they can help reduce waste, improve efficiency, and enhance overall project quality. Value stream mapping can be used to analyze the entire construction process and identify areas where waste occurs. Modular construction can be considered as a hybrid of manufacturing and construction, and in many ways lends itself to lean production [2].

Continuous improvement involves continuously evaluating and optimizing the construction process, while standardization can help improve efficiency and quality. Visual management techniques can help enhance communication and reduce errors. By applying these lean principles, construction teams can optimize the modular construction process, reduce waste and defects, and enhance overall project quality [12].

4.2.2 DIGITAL COMPATIBLY

Digital compatibilization is especially relevant in modular construction, where the coordination and synchronization of information and data across different digital platforms and tools is critical to ensuring the success of the project. The use of digital technologies such as Building Information Modeling (BIM) and Computer-Aided Design (CAD) is essential to achieve the level of precision required for successful modular construction [63-64].

To complement, it helps to ensure that these technologies work seamlessly together, enabling efficient communication and data exchange between different software tools and platforms. This approach can help reduce errors and inconsistencies in the design and construction process, improve collaboration, and enhance project outcomes [98-99]. As modular construction continues to grow in popularity, digital compatibilization will become increasingly important to support the efficient and effective use of digital technologies throughout the project lifecycle.

Recent studies have demonstrated the possibility of incorporating RFID technology with BIM to streamline the management of prefabricated components. Radio Frequency Identification (RFID) is a tracking technology that has been widely applied in the different stages of the current construction industry. In the production planning process, RFID enables real-time production planning and scheduling. The advantage of BIM is the ability to integrate and store information, and the advantage of RFID is that it can accurately track the status of the target [100]. These tools can also aid in transportation logistics, as we will see in the next chapter.

New programs and software are being progressively introduced, allowing the execution of digitally assisted projects and cooperating for the conception of the aimed design, while in the meantime, preserving the benefits attained to this industrial concept. Furthermore, new proposed methods integrate linear scheduling method (LSM), critical chain project management (CCPM), and the last planner system (LPS) into a comprehensive BIM-based framework may be used as alternative to enhance scheduling, monitoring, tracking, and controlling of projects while considering uncertainty associated with activity durations [101].

4.2.3 MODULARIZATION

Currently, three are the main approaches considered to modularization [5]. The first, prefabrication, entails the manufacture of components in a workshop setting based on a prior design, often by a fabricator or supplier. The second, pre-assembly, requires constructing components to a pre-designed plan but assembling them at the construction site, typically with the help of on-site construction personnel. The third method, modularization, encompasses a variety of engineering and construction disciplines and can be performed wherever it yields the greatest benefit for the project.

In this regard, a graph-based methodology were proposed to decompose arrays into non-repetitive modules that can be assembled off-site, which also computes data concerning future replacement rates thru a clustering algorithm applied directly on BIM tools for an optimal definition of module type and its respective interface. It was concluded that Machine learning based methodologies could be employed after the Design phase in order to identify possible automatic modularization of non-modular projects, representing around 99,6% in time savings when compared to the traditional manual method [75].

If correctly applied, the program is able to generate maintenance and replacing plans according to the components concerning data, which will be responsible for relevant earnings during the assembly and as well during its use/operation phase, an important advance in sustainability and circular construction matters. However, this methodology mainly focused on interface systems and connectors.

4.2.4 CLUSTERING ALGORITHM

Posteriorly, Feist et al has developed a methodology that uses a semi-supervised clustering algorithm to group divisions with similar characteristics into clusters, using user feedback on the results to guide the algorithm and obtain more accurate results. From these results, it is possible to identify a base module to represent each set of similar divisions, an important procedure that aims to enable the introduction of prefabricated modules in traditional constructions [102].

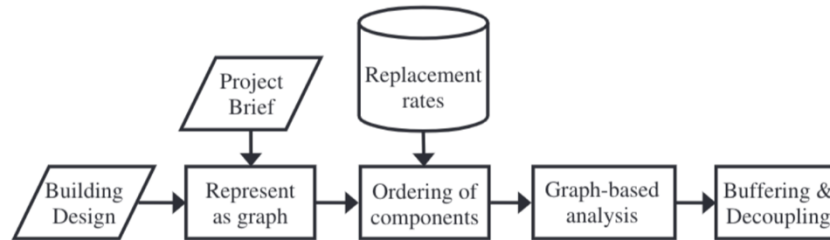


Figure 4.1 A methodology supporting the modularization of building design [102].

The introduction of such digitally assisted constructions also enables modularization to be studied and applied later, over formerly conventional design plants. In other words, hybrid projects get to preserve their originality, while imparting some modular benefits, considerably reducing the dependencies between construction activities that are carried out on site by different subcontractors and incorporating factory-production advantages.

4.3 DESIGN AND STRUCTURAL RESPONSE

Creating a detailed design and plan for the prefabricated units, including all necessary technical drawings, is a crucial and time-consuming aspect of the process. In that regard, the use of guaranteed-quality prefabricated elements may result in faster assemblies that will keep their shape over time and prevent it from bending over time. However, efficient distribution of loads is only possible when all the building components are properly dimensioned, meeting all their functionality purposes while attaining the factory's advantages.

Structural integrity against severe loading conditions and accidental loads is one of the primary concerns when designing multi-story modular buildings, therefore, connecting elements and interface systems play a central role in providing integrity and adequate performance to our edification. 3D imaging and analysis can be used to detect and assess structural defects in the building components, particularly during transportation and installation, when the structure is more susceptible to damage [103].

Moreover, the structural action of groups of modules is presented in terms of resistance to vertical loading, stability, and robustness [52]. One of the modular principles is the possibility of interchanges and further modifications in the original arrangement, therefore, each of these isolated volumetric units must be designed to work alone and carry out all the loads subjected

to it. Thus, the elements' robustness and connectors vary in function of the chosen layout and arrangement of the modules, which may be more or less conditioning.

Selecting the most efficient module configuration for modular construction projects may involve the development of a mathematical model that evaluates various factors, including site constraints, module dimensions, and construction methods. Such models use a generic

algorithm to search for the best configuration and help construction professionals to save time and resources by selecting the best optimal solution for each project, leading to faster and more efficient construction processes [104].

For the dimensioning, it is necessary to understand the behaviour and influence of the structure as a function of the spatial arrangement of the structural modules, forasmuch as such, defining the static and dynamic actions corresponding to the intended location. For each combination, a modelling program calculates the efforts applied to the bars, and for each control point of these bars it determines the ratio between the applied efforts and the resistance capacity of the section [105].

Three generic forms of modules are currently considered (1) open-sided or column-supported and (2) 4-sided or continuously supported and (3) non-load bearing modules. Column-supported modules have beams that run along the edges of the module and are supported by columns at the corners or at intermediate points. On the other hand, continuously supported side walls are responsible to provide such a support throughout the module's perimeter [96][105].

Both systems provide resistance to horizontal loads either by the walls through bracing or diaphragm action, however, for buildings taller than 6 stories, an additional bracing system is usually required around the access core [4]. Open-sided modules are commonly associated with their easy and aesthetically appealing assembly; however, continuously supported structures consume more time and material, resulting in denser and stronger frameworks that could help alleviate foundation requirements.

The distribution of loads on modular buildings can be summarized on two major mechanisms, (1) Gravity loads, which are basically originated by the stacking of other units on the top of the base module and, (2) Lateral loads transfer mechanisms. The first one relies on the individual structural performance of each module, without much interference of connectors. In the meantime, the quality of lateral load transfer and the overall diaphragm of actions depends above all on the adequate execution of these connecting systems. Further, the lateral-force transferring mechanism can be categorized into three types: the stacked module structure, module-moment frame hybrid structure, and module-concrete core hybrid structure [106].

In recent studies, there has been a significant emphasis on the stacked module structure for building constructions. This approach involves assembling individual module units on-site,

which are then connected to form the complete building. The design height of a modular building is generally governed by the bearing capacity of the columns at lower levels, which must be strong enough to support the load accumulated above [82]. This particularity will be addressed in detail in the next chapter.

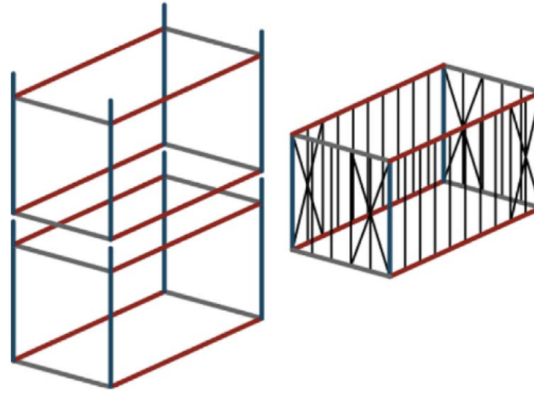


Fig 4.2 (L) Column supported modules and (R) Continuously supported modules [78]

Braced steel or concrete cores are often used in tall building designs to provide lateral stability, which is crucial in resisting wind and seismic forces. The core acts as a central spine around which the rest of the building is built, and it helps to distribute the load evenly throughout the structure. Moreover, bracing elements within the core can be designed to resist bending, twisting, and shear forces, ensuring that the building remains stable under even the most severe conditions [42].

Another module design, suitable for multi-story modular buildings, is the corner-supported steel-concrete composite module. To enable such a feat, the strength and stiffness of the individual modules are improved through the designs of concrete-filled steel tubular (CFST) columns, laminated double beams, and integrated concrete slabs [59]. This way, the structures attain enough resistance to support loads, whilst originating lightweight, easy-performing structures.

For structural response estimations, the shear, axial and moment-rotation behaviours of the inter-module connections are normally simplified and input into the overall numerical model [107]. Once determined, the modelling can be performed by resorting to finite elements programs for structural analysis and design, such as CSI-SAP, ETABS, STAAD, or similar.

Regarding modular housing developments, FEMA (Federal Emergency Management Agency) reported an overall relatively minimal structural damage. The module-to-module combination of the units appears to have provided an inherently rigid system that performed much better than conventional framing [108] and although there is more upfront design for early projects, the design phase will shorten as designs are repeated, with potential term cuts of up 28% [4].

In conclusion, the design of modular constructions is mostly influenced by the size, shape, and weight of the modules, as well as their transportation and assembly methods. While open-sided modules offer potential architectural benefits, decreasing the size and number of structural members and columns may demand increased robustness and overall resistance of building materials, which could lead to significant weight, and cost, implications.

4.4 LICENCING PROCCESS

Once determining the project's requirements, the contractor needs to provide all the necessary permits and approvals from local authorities before starting the construction process which may include building permits, transport licenses, and environmental approvals. In relation to the construction site, provisioning adequate land treatment, site access and utilities may consume a reasonable amount of time and must be carefully studied since the initial stages of the project's conception.

Many European countries have regulations that require certain minimum standards for housing space. Indeed, it is a measure of the acceptable intensity of dwelling occupation in the context of the prevailing cultural, social, climatic, economic and technological conditions in a particular society. In Portugal, space standards for new housing were established over 30 years ago. However, those standards do not apply to construction work on existing buildings or prefabricated buildings and should be used exceptionally as a supporting document during the design phase of the project [109].

The permanent occupation of the land and the use of spaces for urban purposes consist of urban operations subject to prior control under the terms of the RJUE - Legal Regime for Urbanization and Building, approved by Decree-Law no. 555/99, of 16 December, in the current wording [110]. In those terms, “ (...) any construction designed for human occupancy, which is affixed or linked to the ground and connected to infrastructural networks and amenities e.g., water supply, sanitation, electricity etc., is regarded as an urban operation”. Therefore, there is no evident distinction between traditional buildings and modular houses, which must be equally framed and subject to prior control by their legislation [110-112].

Although modular possesses favourable features for development in rugged and hard-to-reach terrains, compliance with legal regulations, public utility easements, and associated restrictions is a prerequisite for any land occupation, particularly in areas that are within the purview of the National Agricultural Reserve or the National Ecological Reserve, as well as in regions or counties of Portugal that are governed by Territorial Management Instruments [110-111].

Even in the case of mobile homes, caravans, or motorhomes that are not permanently stationed in one place, they are still subject to prior regulation in accordance with Article 18, No. 1 of Decree-Law No. 310/2002, as amended, and must meet the conditions specified in the Municipal Regulation for Licensing of Casual Camping and Caravanning Activities [111].

Once installed, the building will be subject to compliance with the Municipal Master plan, as well as any other applicable regulations. Regarding fees, the Municipal Tax on Real Estate (pt: IMI) is levied on the taxable value of rural and urban properties located in Portuguese territory and must be paid annually [112].

4.5 FOUNDATION WORKS

In contrast to traditional construction, which typically requires substantial foundations for perimeter and load-bearing walls, modular buildings distribute the foundation load across the entire footprint. Therefore, volumetric units may be a structural element of the building and as an immediate consequence of that, the groundworks approach for modular buildings differs significantly, usually requiring less excavation, which could result in less costly operations [113].

Another aspect concerns their lightness, since the units are later transported to the placement site, materials need to be strong enough to support loads as well as, lighter enough to relieve freight expenses. Therefore, depending on the final layout of the project, the final weight of the structure may be more or less conditioning in terms of foundation requirements [114].

Nonetheless, the starting point is the same as traditional constructions. A ground survey will provide an accurate assessment of land conditions and help to determine the appropriate soil treatment and the most suitable design for foundation systems. Furthermore, diverse ground improvement techniques, such as deep soil mixing and vibro-compaction, can be used to improve soil properties and increase the bearing capacity of the ground [115]. A well-performed study will aid in the identification of potential obstacles and mitigate risks before the beginning of the activities, meaning that any potential issues or irregularities can be corrected in advance, preventing unforeseen events that could originate additional expenses or delays in work.

When permanent, the foundations used to receive the modules can be block type or shallow, with isolated, combined or strip footing. Depending on the building requirements or critical soil conditions, deep foundations and piles may also be used [114]. For temporary buildings, usually pre-cast concrete blocks are the first option, concrete slabs with flat metal stock skirting are commonly used as well, the skirting confers aesthetic and ensures that it looks just like a permanent foundation, hence, the solution is both visually appealing and cost-effective [88].

Foundations in medium and high-rise construction are typically more substantial. In modular construction, base plates can be integrated into the modules and fixed to cast-in anchors or welded on site to accessible cast-in plates. As an alternative to traditional cast-in or post-fixed steel bearing plates, embedded column connection can be used to ensure optimal use of the full column strength and provide good ductility [78].

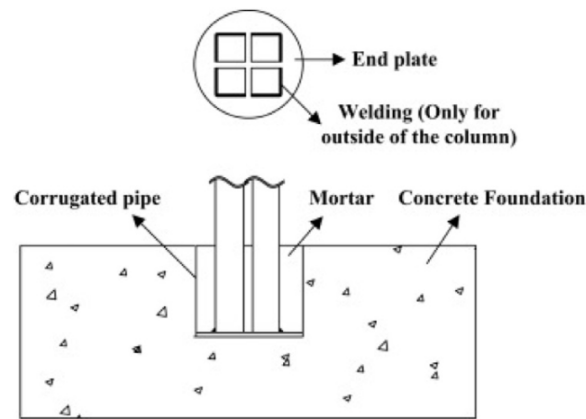


Figure 4.3 Embedded column connection [78].

Another type of foundation currently used is a concrete slab. Also known as “raft”, this type of shallow foundation consists of a slab that lays horizontally on the ground, covering the entire footprint of the house, providing a cost-effective, stable, and durable base for edification. However, such a rapid solution is not always viable, thus, proper coordination between the geotechnical engineer, the modular designer, and the manufacturer is extremely important and aims to ensure that the modular units’ requirements are compatible with the foundation system and the ground conditions [113-115].

Modular homes can also be a good option for scenarios in which the soil properties are unfavourable, presenting advantageous solutions for low bearing resistance of surface layers, shallow water tables, or high slope terrains. As a solution, modules can be placed over concrete-filled block walls and concrete piers to form the suspended floor. In addition, ground anchors, micro-piles, and screws can be used to aid the structure’s support [114].

4.6 MANUFACTURING

4.6.1 FACTORY LAYOUT

The layout of a modular construction factory is a critical factor to consider at the beginning of any project, impacting the speed and efficiency of the manufacturing process. Not restricted to the layout, dimensions, and capacity will dictate the expected volume of units to be delivered. Moreover, it can directly impact the space utilization within the factory, a well-designed layout should optimize the use of available space, maximize the number of modular units that can be produced, and minimize the need for additional storage space [116-117].

Ideally, the factory's infrastructure should be constructed first, followed by the manufacturing of the units. However, due to scheduling, budget constraints or space limitation, some contractors may opt to begin manufacturing before the entire factory structure is completed.

Regardless of where these precast production tasks are carried out, these tasks generally proceed on the basis of job-shop production, package production or flow-shop production [118].

However, incomplete factories that commence production will not benefit from working under adverse weather conditions, thus scheduling activities will be subject to traditional climatic restrictions. Moreover, enclosed spaces impose stricter control measures, and reducing displacements within the working site can significantly reduce the number of accidents, such as falls from heights.

Prefabrication plants commonly employ two types of component production systems: stationary and traveling. In the stationary system, all production activities occur in one location, typically using horizontal or battery molds. The traveling system involves moving molds on a rolling line or conveyor between workstations, with different tasks performed at each station [118-119]. While traveling systems can handle larger volumes of production, the stationary option could offer greater precision.

Recent studies tried to determine the most effective design for the facility layout in a modular construction factory by simulating improvements upon a practical scenario [31]. It was found that among the different layout options, the "cellular layout" had the highest output, while the "product layout" was the most cost-effective option for the case factory. Additionally, an effective Factory Layout Design (FLD) can reduce operating expenses related to material handling and layout by around 10% to 30%.

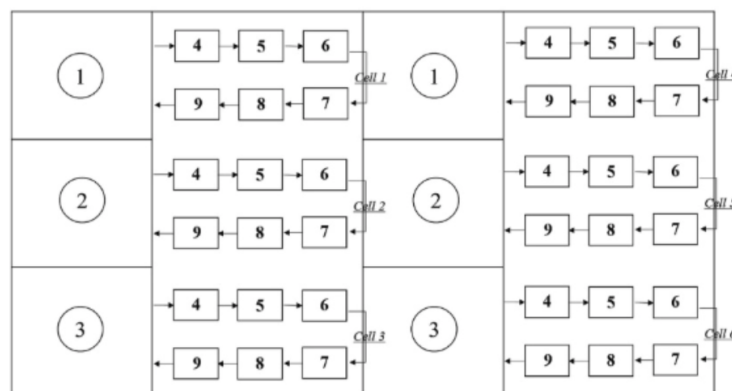


Figure 4.4 Cellular layout design [31].

However, the design of the factory is not the only factor that determines the success of manufacturing activities. Proper control measures and quality supervision must be implemented to realize the advantages of factory production. To be truly lean and increase productivity while reducing waste and defects, manufacturing must adhere to appropriate well-

defined standards, the chosen layout should allow for easy access to each modular unit, and provide space for inspectors to check for any defects or issues before the unit is shipped to the construction site [117].

In conclusion, while transferring a significant part of the project to a closed and safe space has proven advantageous, it is not a guarantee of success. The factory's composition, layout, expected volume of units, and machinery arrangement are factors that can influence the desirable arrangement of the factory and its overall performance. It is worth noting that the experiences of individuals who have attempted to open modular factories can provide valuable insights into the complexities of factory design [120].

Understanding the manufacturing process in modular constructions is essential to appreciate the advantages of the method. It involves the prefabrication of building components in a factory-controlled environment, which allows for greater precision and quality control than traditional construction methods. Nevertheless, prefabricated buildings require sophisticated construction techniques, thus, additional planning and coordination are necessary to ensure that the project operates efficiently and safely.

The manufacturing process in modular construction is typically an assembly line process, where each module is built in a sequential order and comprises a substantial component of the overall project scope. Indeed, approximately 70–80% of the work completed in the manufacturing plant. Moreover, offsite manufactures' enhanced productivity allows fast module build, promoting gains in time that revolve around 40-60% when compared to the traditional methodology [4].

On the contrary to traditional projects, in which each process would have to take place separately, off-site manufacture begins in parallel with foundations, concomitance responsible for approximately 20% of the schedule compression. In addition, construction over-run and redesign, which represents 25-50% of the projected construction duration, are very rare in off-site cases [4].

Modular construction manufacturing requires advanced technology, skilled labor, and strict quality control to ensure that each module meets the necessary standards. However, its repetitiveness allows workers to get familiar with the workspace and work because they perform similar tasks in manufacturing factories. Additionally, as the amount of onsite work decreases, there are fewer workers required, and it is comparatively easy to manage them.

The factory environment also reduces the impact of weather and other external factors that can cause delays or quality issues in traditional construction, high winds, and heavy rain can significantly increase the project duration of uncovered undertakings. Enclosed spaces promote the mastery of this obstacle and guarantee the continuation of activities under snow or extreme heat [121].

Another feat achieved by modular constructions is the execution of assemblies with high levels of precision, which can also count on the help of modeling software and high-tech machinery. Precision is critical in manufacturing, as each module must fit together perfectly to create a completely connected structure that provides adequate strength and stability. In that regard, cutting and forming the components is a time-intensive task that requires specialized equipment and skilled labour, in that regard CNC machines and other technologies can be used to ensure highly precise measurements and accurate cuts [122].

4.6.2 BUILDING MATERIALS

In terms of building materials, greater flexibility can be achieved by sourcing them from multiple locations, according to their abundance and the market's preference. Additionally, the performance of a modular building under seismic and wind loads will depend on the design and construction quality of the building, as well as the specific requirements of the building code for the location where it is built.

Materials must meet strict quality standards and also be able to withstand structural demands. In that regard, composites, and combinations are an option to reduce the overall weight of the structure and ease typical displacements inside and outside the factory. Materials commonly employed include timber, steel, concrete, and composites [79-83].

The benefits of wood-frame construction have been discussed for a long time and include low carbon footprint, renewability, and ease of construction. Another advantage concerns its high strength and reduced weight. Although commonly used for small-scale housing, several studies are currently testing its implementation for large-scale works and multistorey buildings.

Concrete constructions enable higher overall labour productivity, while steel provides faster construction [124]. Nonetheless, among the various module types for modular construction, the steel-based module is the ideal structural form, owing to its flexibility in architectural design, long span, lightweight, and convenience in connection as compared to concrete and timber framed modules.

In that regard, the sustainability and environmental effects of concrete and steel modular building systems in the context of urban development were also considered. As a result, it was

reported that the duration of on-site superstructure work in concrete and steel cases saw a decrease of 32% and 50% respectively. Moreover, the performance of steel modular construction considerably deviates from concrete, offering a faster pace of 40% and making it an ideal solution for urgent building projects [88].

Alternatively, to pure concrete, whose weight could make its use unfeasible, composite concrete incorporated with Polypropylene fiber and Chemosphere and steel-concrete composite systems are alternatives that could originate light-weight structures, with strength increased by up to 30% [125].

Determining the cost difference of materials for offsite manufacturing compared to onsite can be challenging due to multiple factors that can either increase or decrease costs. Despite this complexity, it is possible to achieve an overall cost reduction of 5 to 10% [4]. The appropriate handling of materials must follow their intrinsic demands for storage and transportation which should be carried individually, in accordance with the established quality standards.

One significant advantage of steel-based modular construction is that 90% of steel is recycled, making it a sustainable and environmentally friendly choice. In complement, steel modules are usually constructed with reinforced concrete slabs and partition walls to ensure good acoustic and thermal insulation, providing a complete building system for modular steel construction [126].

Steel construction is pre-fabricated to some degree, but the innovative use of this technology has arisen in response to market demand for higher levels of pre-fabrication, which can significantly shorten the amount of work that needs to be done on-site and provide rapid fitting and assembly. Studies show that the higher the level of off-site indexation, the more significant the reduction in construction time. For instance, the level of indexation can vary from 10% to 70%, and the reduction in construction time can range from 15% to 60% [126]

Steel construction has proven to be reliable in the commercial building industry, where its advantages of quick construction and the ability to integrate services into long spans are widely recognized. Similarly, steel and composite technologies are utilized in the medium-rise residential sector for buildings such as apartments, hotels, and student residences [126].

However, the choice of material is not simple. As previously mentioned, several factors can influence this decision. Abundance, tradition, and market expertise are just a few of them. In that sense, the suggestion for the use of steel for emergency building scenario is based primarily on the speed of assembly, a parameter in which it arguably performs best. On the other hand, cases need to be studied individually and several other parameters could be considered.

4.6.3 CONNECTING ELEMENTS

One of the most important attributes in modular undertakings is the performance of the connecting systems, which confer rigidity, stability, and correct serviceability to the constructions. Those elements may vary according to the intended use of the building, design requirements, material of fabric, function, and positioning [76-77].

Connections may be grouped into three categories, (1) Inter-module, (2) Intra-module, and (3) Module to the foundation [82].

- i. Inter-module connections - used to attach individual modules to each other, joining two or more modules together side by side and providing structural stability and rigidity to the building.
- ii. Intra-module connections are used to attach components within a single module. Intra-module connections may involve attaching walls, floors, ceilings, or other elements within the module, and are typically designed to ensure that the module is structurally sound and able to withstand the stresses of transportation and installation.
- iii. Module-to-foundation connections: These connections are used to attach the modules to the foundation or base of the building. Module-to-foundation connections are typically designed to ensure that the building is securely anchored to the foundation and that it is able to withstand the forces of wind, earthquake, and other external loads.

To perform such connections, a variety of techniques can be used, namely bolting, welding, clamping, and embedding, each of them presents different manners and contributes to the work's feasibility. Bolted systems are dismountable and require reduced site work, however, are susceptible to tensioning or slip. Welding, on the other hand, is compact and does not slip, but it is not dismountable and may be corroded [78].

For wooden buildings, adhesives can be used to bond and provide a strong and permanent connection that is resistant to vibrations, present reduced weight and allow for faster assembly. In the meantime, quality parameters are harder to measure, thus, they are not recommended for environments with extreme temperatures or humidity, which could impact the strength and durability of the bond.

Several interlocking system that can enhance the structural integrity of multi-story modular buildings have been studied [104]. This type of development is primarily concentrated zones subjected to seismic actions. In that a regard, a system that involves the use of interlocking steel plates that can be bolted together to create a rigid frame, contributing to distributing loads more evenly throughout the building, which can reduce the risk of structural failure during extreme events like earthquakes or high winds. Those specific systems will be another focus for the simulation that will be conducted as case study, recent innovations on seismic-resistant connections will be proposed and analyzed as well.

Another concern relates to the end of the life cycle, when those elements may facilitate (or not) dismantling operations, contributing to sustainable practices due to the possibility of reuse of parts in future projects and preventing them from being simply discarded. In this sense, investigated different means to promote and stimulate such re-employment, resorting above all to new technologies and software that allows the mapping of all parts and elements of the structure, including technical specifications and replacement data [89].

Each case and its peculiarities must be carefully studied before defining the type of connection to be used and the best way to perform such. Some factors that might give the first guidelines include the climatic conditions of the implementation site, the fabric material, the cost, and the expected performance or design requirement. In addition, different technologies may be used and also combined to meet strength and stability requirements.

4.6.4 OTHER COMPONENTS

4.6.4.1 INSULATION

It is estimated that people spend more than 90% of time indoors [87], such value has tendentially increased since the beginning of the pandemics, which led to the establishment of home-office or hybrid work policies. On the one hand, such a transformation reduced daily displacements to the office and the consequential emission of pollutants, on the other hand, it increased individual consumptions and the average costs with energy, which somehow ends up by mitigating the problem instead of solving it.

Additionally, an effective insulation system can reduce the need for heating and cooling systems, leading to lower energy costs and a reduction in equipment maintenance requirements. However, if the insulation system is not properly installed, it can lead to problems such as moisture buildup, mold growth, and air infiltration, which can result in longer building times.

The evolution of building techniques emerges, bringing quality and safety while, parallelly, the least edification impact is generated for future generations. Business today is moving faster than ever; technology is enabling rapid development of innovative new products and services in every industry, parallelly, global competition is reducing the length of time customers will wait for new features and increasing the pressure on the market to continuously reinvent themselves to stay competitive.

In that regard, clients' demands for thermal and acoustic insulations are solidly higher. To provide such expected comfort, building techniques and appropriate insulators need to be employed, granting that for the future, customers will have to spend much less with heaters and energy bills. To meet the best conditions for energy efficiency, assessments concerning the implementation site conditions need to specify climate, geographic positioning and the desired reductions.

In modular constructions, insulation is positioned in the beginning of interior/exterior walls assembly, when batting insulation plates are placed. The use of closed volumetric units allows superior quality insulations, partly due to the 'double skin' nature of the construction, also called DSF (double skin façade), which provides a thermal buffer zone, solar preheating of

ventilation air, energy saving, sound protection, wind and pollutants protection, night cooling and space for energy collection with devices like PV cells [87].

The structure's material and the arrangement of components may increase or decrease thermal transmission coefficients; in Europe, and other temperate countries, the solution primarily prefers the heat trapping, meaning that the better is the insulation condition, the lower will be heating consumptions, however, it also needs to be adequately balanced to perform towards both the summer and the winter.

Not limited to the thickness, other important aspects to consider on modular insulation are namely [134]:

- i. Type of Insulation – flammability, insulation properties, water resistance, rigidity;
- ii. Density of Insulation – which would most often determine the insulation capacity of the wall, floor or roof in question;
- iii. Insulation Application System and Coverage – the insulation tends to sag and has many areas left exposed, leading to poor insulation levels in the building, thus, fasteners and overlaps are often required;
- iv. Safety – when SIP panels are used with infills such as Mineral Wool or Glass Wool especially in roofs, and if there is a water seepage into the panel there have been instances where the weight of the water that fills the voids between the insulation leads to a total failure of the roof and causes a collapse.

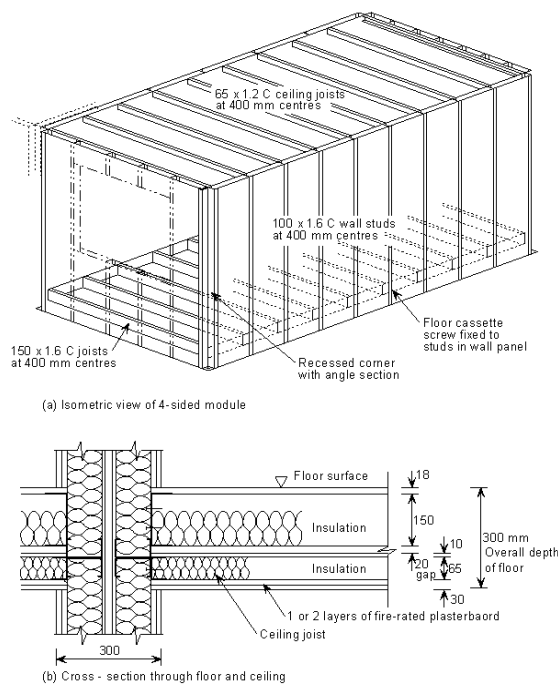


Figure 4.5 Details of 4-sided modules showing recessed corners with additional angle sections [35].

The most employed solutions include rigid foams, spray foam, stone wool, expanded polystyrene (EPS), extruded polystyrene (XPS), polyisocyanurate (Polyiso, ISO). Moreover, silica aerogels are thermal superinsulation materials that have found increasing application in the modular building sector in the last ten to fifteen years [62]. Each of them presents different behaviour with regard to water vapour diffusion, permeability, thermal efficiency and overall performance; moreover, different insulators can be combined and employed in different stages of the work.

4.6.4.1 CEILING AND ROOF

As with traditional construction, a variety of materials can be used for roofing in modular construction. The specific process mostly rely on the interior ceiling being used, which in wooden structures its typically hard deck type.

The first step is to lay the drywall panels on the ceiling and then install the roof trusses according to the engineering design. Large timber joists are then used to support the weight of the ceiling and loads, trusses provide proper support for tiles, shakes, or shingles and are designed with proper angles and enough strength. It's important to note that dimensional variations are to be expected due to the fixed framing tables used to assemble the roof sections and must be accounted for in the design.

Alongside, when steel is the chosen material, painted trapezoidal steel sheets are placed over the metallic purlins as a coating, optionally trapezoidal tile plates can also be used. The ridge, rafters and sleepers are made of PVC with approximately 20 cm height overhangs and galvanized steel sheets with vents are after applied. Finally, rain gutters and accessories that can be made of steel too [69].

After being lifted and placed, the roof cavity is ready to accommodate all the electrical wiring and HVAC ducts. For the finishings, plaster and gypsum boards are preferred due to their lightweight, lower prices and easy moulding conditions, it performs adequately for fine finishings and décor as well [79].

4.6.4.2 CLADDING

Cladding panels are prefabricated elements which are commonly attached to the façade of prefab buildings in order to form the completed building envelope and provide a certain level of customization and uniqueness to the construction [127]. Usually made of timber, steel and stones, its finishings may be time-consuming however, they can be designed to ease compatibility questions and provide proper conditions to be fitted, attached or bolted to the main frame. Cladding it is becoming widely implemented for façade renovations, providing both thermal and aesthetics earnings.



Figure 4.6 (left) Modular cladding INTERCEPT™ [128]

Figure 4.7 (right) Timber cladding TIMBECK [129]

4.7 PROGRESS AND QUALITY MONITORING

During the operation and maintenance stage, managers currently rely on two-dimensional drawings to obtain relevant information, which can be a difficult and time-consuming task, particularly in large, multi-unit complexes such as condominiums and apartments [100]. To ensure a highly efficient operation and maintenance system for prefabricated components, real-time data regarding the status of the components is necessary. This type of information can be obtained by scanning software, that can process this data, store into a Cloud or to a dedicated BIM platform.

The evaluation and control of quality were predominantly adopted to determine the structural integrity of existing structural elements in the construction sector. The division of labour and the introduction of machinery and new mechanisms led to the need for quality control. In turn, the increasing complexity of production processes and industrial mass production required quality assurance and quality management [136].

The slow growth observed in the earlier stages of a project allows us to modify and intervene on construction works for reasonably lower costs which, as the time passes by, will tend to get higher. Therefore, the sooner potential flaws are detected, the cheaper is going to be the proposed resolution. To exemplify, it was found that the costs to demolish and rebuild are approximately three times higher when compared to the premature detection, a difference that could be paramount to the determination of work profits, or losses [130].

This premise has been widely studied over the years and it is represented by the S-curve, traditional reference for the Project Management field and which provides crucial assessment

regarding the unroll of activities, as well as their current performance and progress. Other curves and KPIs may be combined for cash flow forecasts, quality and overall development outputs [118].

Although in a different manner, such a concept can also be applied to mechanised production lines through continuous supervisioning and assessment over the assembly performance. In this sense, the japanese principle “Poka Yoke” may act as a mitigation action that values the interruption of the production when an error is detected, preventing it from being perpetuated and avoiding unnecessary expenses and losses. After its correction, improvements are applied and, once perfected, the production line is allowed to work again.

Instrustialized constructions benefit from this division of work and offer a favourable environment for the implementation of monitoring systems in the entire production chain. Control checks and extensive monitoring of all activities involved in the manufacturing process allow its constant correction and improvement, reducing defects and waste whilst improving productivity. In addition, the increasing levels of automation promote streamlined coordination of repetitive activities, which combined with the controlled factory environment and lean offsite manufacturing process leads to a much rapid pace when in comparison with onsite undertakings [1-2].

It is important to foresee maintenance requirements so that modifications and replacements can be easily performed. Modular buildings benefits from highly symmetrical structures, which allows the establishment of strategic paths to access inspection points and technical amenities. Digital compatibility allow accurate arrangements to be previously established after multiple iterations, harmonizing the structure’s aesthetics with these installations [74].

In that regard, a novel approach to quality control in prefabrication through the use of 3D digital templates framework was considered, it entails improvements in the precision and speed of quality control checks, reductions in the likelihood of errors, and enhanced collaboration among third parties [33].

4.8 SAFETY RISKS

Modular construction is generally regarded as a safer method than traditional construction methods [70]. Many research studies reported that the adoption of modular construction methods can reduce safety risks and prevent the occurrence of safety accident. However, they also present unique safety challenges that must be addressed to prevent accidents and injuries.

To prevent accidents in modular construction, it is important to establish a comprehensive safety management plan that addresses potential hazards and risks associated with each stage of the construction process. This plan should include measures to prevent falls from heights, secure and protect workers and equipment during transportation, and ensure proper installation and connection of the modules on-site [132-133]

In that regard, accident cases associated with modular construction and employed a causal map to identify key safety risk factors. The analysis focused on accidents related to modular construction that took place in the United States between 2000 and 2018, and investigated various safety risk factors such as the types and causes of accidents, as well as fall height and location [133]. The study assessed a range of factors, including the accident ratio and project cost, in order to gain a comprehensive understanding of the safety risks associated with modular construction.

As mitigation measurement, several strategies can be implemented, such as proper training, adhering to safety regulations, and conducting regular safety inspections [134]. Besides that, cooperation among stakeholders in the industry, including workers, supervisors, engineers, and managers is primordial to reduce incidents [134].

4.9 TRANSPORTATION

Once the modules are manufactured, they must be transported to the construction site. Transportation logistics must be carefully planned to ensure that the modules arrive on time and in good condition. In that regard, JIT strategy has been recognized to have tremendous potential for improving the movement of the components from the production plant to, and within, the construction site [135].

Prefabricated components are typically large, unwieldy, and heavy, which can lead to various uncertainties, such as potential changes in delivery times, site storage requirements, and associated costs. Poor delivery of these components can adversely impact the performance of the prefabricated component supply chain (PCSC), resulting in reduced productivity, increased costs, and longer project durations [93].

The modules have to withstand displacements inside the factory/construction site and also the vibrations caused by transportation, another precaution in terms of that concerns their integrity and, in order to support 20-30% more than their regular structural capacity, structural elements are predicted to be 8-10% higher than the average in traditional constructions [118].

In addition, due to limitations in size, stacking layer limits, and installation sequence prefabricated components cannot be loaded to 100% capacity. According to specifications, the number of stacking layers for precast laminated slabs should not exceed 6 (six) during transportation and storage. Stacking too many layers can result in deformation and cracking of the precast laminated slabs, which can adversely affect structural safety and the lifespan of the building [157].

Dynamic transportation planning for the PCSC) entails a range of activities, including supplier selection, transportation planning for means and routes, site layout planning, and ongoing adjustments to transportation plans. These activities need to be dynamically optimized to account for the interdependent and coordinated nature of the various stages involved in modular

process, as well as the delivery requirements, installation and construction schedules [93][135-136].

The optimal transportation planning must consider delivery routes and scheduling to maximize potential benefits, including reduced transportation costs, improved project efficiency and better alignment with JIT delivery principles [135]. Another concern is understanding the bounding behavior of modular units during transportation to ensure the safety and efficiency of the transport process. We will examine the applicability of these principles further on.

4.10 INSTALLATION

Even with restrictive working rules and technological processes in place during the installation stage, the building sequence can still be affected by worker delays or errors. As a result, it is critical to apply management processes during on-site building and installation of prefabricated components. Good communication and information exchange between diverse stakeholders at various phases of the building process are critical in addressing these difficulties [100].

Once delivered to the installation place, the units have to be arranged and placed onto the foundation and stacked by using a crane, frame systems or other lifting equipment. Such equipment can be designed with a vertical connection point to the load in order to remove stresses and ensure each module is lifted and installed safely [137].

However, building tall structures in urban areas poses challenges due to the difficulty of working at heights with limited space, requiring skilled labour. Therefore, careful consideration and planning must be considered to ensure the appropriate handling and installation of modular structures. The units will need to be carefully positioned and aligned to ensure they fit together properly, such a process can be quite time-consuming, often accounting for up to 40% of the total project duration [10].

After placed, the next step is to connect and integrate them. This may involve connecting electrical and plumbing systems, installing ventilation or HVAC systems and ensuring that the units are properly sealed and weatherproofed. Once the units are connected and integrated, finishing touches such as flooring, paint, or exterior cladding may be added.

Before the installation is considered complete, the units will need to be thoroughly tested and inspected to ensure that they meet all relevant codes and regulations. This may involve checking for leaks, verifying electrical connections, and performing other tests as necessary.

In the European Union, modular homes are subject to the Construction Products Regulation (CPR), which requires that construction products placed on the market carry a CE marking to show compliance with the relevant harmonized European standards. However, the specific requirements for modular homes may vary depending on the product and its intended use

Finishing equipment, such as sanders, paint sprayers, and other surface finishing machines, are used to apply finishing touches to the modular modules, ensuring they meet the desired appearance and quality standards. Prefabricated buildings face various risks, including transportation hazards, cyclones (such as hurricanes and tornadoes), earthquakes, explosions, progressive collapse, and fires. Those hazards can be categorized into three types: natural, anthropogenic, or technological in nature [78]. The table 4.1, provided below, presents an overview of the key characteristics and requirements associated with each of the main load classes that should be considered.

Load	Characteristics	Design Criteria
Transport & Handling	Lifting: dynamic amplification depending on module and lift arrangement; Transport: acceleration coefficients in three orthogonal directions	Stability, strength and serviceability;
Wind Load	Low frequencies, ~ 0.01 – 2.5 Hz; Mean component and fluctuating component (gust-factor approach)	Deflection criteria to protect components, e.g. $h/500$, $L/500$ Stability, strength, serviceability (inter-storey & overall deflection, and vibration); Deflection limits for serviceability limit state, e.g. $H/600$ for total drift and $h/500$ for inter-storey drift
Debris Impact	Local impact	Local penetration, opening area for internal pressure calculation
Earthquake	Ground motion with frequency contents in the range of 0.5 – 25 Hz; Excites fundamental, low vibration modes resulting in a global structural response	Damage criteria – displacement based i.e. ductility ratio & inter-storey drift e.g. 1.5% inter-storey drift Design criteria – life safety, collapse prevention
Blast	Short duration; local response for close-in blast, might lead to progressive collapse; For far field blast, uniformly distributed loading	Descriptive building damage level and component response
Fire	High temperature	Fire resistance level (time)

Table 4.1 Summary of load characteristics and design criteria [78].

5

ADDRESSING CHALLENGES: CASE STUDIES

During the course of this study, the main advantages, disadvantages, and applications of prefabricated volumetric structures were assessed. Despite the vast range of usage possibilities, the main efforts here were dedicated to investigating the aspects which could denote when a MMC should be preferred over the traditional other as well as the main impacts that such a decision could have on the compression of the work's chronogram.

This construction method is an excellent alternative to traditional on-site construction because of its significant technical advantages, including faster construction speed, better quality, reduced environmental disturbance around the construction site, and convenience in demounting and recycling. On the other hand, the rapid execution of activities will above all be influenced by the dimension of the work, the design complexity, types of connections, materials employed, and even the layout of the factory.

Modular is gaining popularity and being widely embraced across the construction industry, particularly for structures featuring repetitive architectural plans and structural layouts. Especially evident in the construction of hospitals, hotels, classrooms, and dormitories, those types of buildings offer the perfect context for the implementation of modularity due to their high levels of repetitiveness and standardization, enabling the mass production of volumetric units for further installation in cellular arrangements. As an immediate consequence of this highly controlled process, chain activities can be constantly supervised and improved, enabling the establishment of an optimal solution that could be countlessly replicated and reused for future undertakings. Another implication of this factory environment concerns the environmental impact, such a conscious consumption of materials reduces leftovers, and waste, allowing them to be precisely sized when being produced, and largely reused once dismounted.

In this chapter, the previously observed benefits will be applied to the execution of mass housing buildings, not only, its feasibility will be analysed from the perspective of their structural performance for scenarios in which seismic activity could compromise the integrity of those edifications. In order to do so, successful cases of this application will be studied, addressing the main techniques and specificities that a project of this genre should probe.

This part of the study was motivated by the 7.8 magnitude earthquake that hit the border between Turkey and Syria, the 5th deadliest in the last 20 years and that left more than 50,000 dead and thousands of people homeless. My sincere condolences to all the victims and families of this terrible disaster.

5.1 CASE STUDIES

This chapter is based, without being restricted, on the analysis of two case studies related to the theme under discussion:

- 1) Possibilities of Using Prefabricated Modular Panels for Building NZEB Buildings in Earthquake-Affected Areas in Croatia – Case Study (2022).

Hana Begić and Hrvoje Krstić

The authors conducted a study on the feasibility of implementing prefabricated modular panels for constructing homes in earthquake-prone areas in Croatia. Their research compares the traditional construction approach with the prefabricated one in terms of cost, time, and energy consumption. The study focuses on a county located 50 km away from Zagreb, the capital city of Croatia. They also draw attention to the problem of energy poverty, which existed even before the earthquake, and highlight the need to improve thermal comfort in buildings. To achieve this, the study employs techniques and limitations consistent with the principles of Net Zero Energy Buildings (nZEB) and passive house design, resulting in a mitigation strategy to reduce energy consumption and increase efficiency. The authors simulated four cases of ground family houses, two using modular prefabricated panels and two constructed traditionally with hollow bricks. They defend the structural performance of the prefabricated houses and emphasize their role as a building methodology that can effectively address time constraints.

- 1) Seismic performance of mid-to-high rise modular steel construction - A critical review (2020).

En-Feng Deng, Liang Zong, Yang Ding, Zhe Zhang, Jun-Feng Zhang, Feng-Wei Shi, Li-Ming Cai and Shu-Cai Gao.

China's response to the COVID-19 pandemic included the rapid construction of Huoshenshan and Leishenshan hospitals, built in just 10 and 12 days, respectively, and adding over 3000 hospital beds. This impressive achievement underscores the large applicability and benefits of modular construction's agility. The study, sponsored by the Natural Science Foundation of China and integrated into the COVID-19 resource centre hosted on Elsevier Connect, focuses on the seismic performance of mid-to-high-rise modular steel construction. The authors present a critical review of its structural performance and key technical issues, including the global seismic response analysis methodology, failure modes, and current design criteria. The review provides a comprehensive understanding of the approach's seismic response. Additionally, the authors discuss the importance of mid-rise solutions for densifying growing cities, as well as innovative connection methods and the development of seismic isolation systems. Overall, the review evaluates the construction method's ability to withstand seismic events and provides a detailed assessment of its strengths and weaknesses.

5.2 PROJECT OVERVIEW

As discussed in this study, Modern Methods of Construction (MMC) offer numerous benefits in terms of control and productivity. Given the pressing need to address the current housing crisis, time is of the essence, and the advantages of MMC are particularly significant. In weighing the disadvantages of this technique, the benefits it offers arguably carry greater weight, making it a compelling solution to consider.

Furthermore, many of the drawbacks associated with the adoption of Modern Methods of Construction (MMC) could be mitigated through government incentives or public-private partnerships. This approach is not unprecedented, as it has been successfully implemented in countries such as China and the UK. By leveraging such partnerships, the government could procure a large number of units from multiple manufacturers at reduced costs. This would not only provide homes for displaced families but also stimulate the growth of these businesses and the development of new ones, thus accelerating the expansion of the market.

An external stimulus of this nature could prove vital in addressing the current challenge faced by the industry regarding the scarcity of partners and integrated supply chains. As with any other sector of the market, prefabricated solutions require specific systems and components, and the entry of new players can facilitate easier and less time-consuming access to these components. This could help to overcome the barriers to entry faced by new businesses, allowing them to enter the market and contribute to its growth.

Moreover, the traditional procurement process for public projects often involves multiple contractors who submit bids for the acquisition of materials, labor, and other expenses. This budgeting process can be complex, bureaucratic, and time-consuming, involving extensive negotiations before a final agreement is reached. While the licensing process would still be necessary and time-consuming, the acquisition of modular units could be a more streamlined process. This could be achieved by analyzing the average production capacity of regional factories, resulting in lower and more predictable costs, and a more organic procurement process that is less susceptible to variation.

The feasibility analysis would begin by defining the expected number of units to be manufactured, their composition, layout, and parameters that could significantly influence product quality and cost. While net-zero housing has many advantages, its execution must consider several factors to achieve sufficiently high energy yield levels. Ground-floor houses require adequate land space, which could limit the number of families that can be covered by the initiative. In contrast, mid-rise buildings offer sufficient density to meet demand and require less sophisticated structural systems than high-rise structures.

In addition, many studies that examine productivity and construction efficiency emphasize the need for a high production rate of repeatable components to achieve cost-effective execution.

Consequently, cellular-type buildings such as hotels and student residences, which feature multiple similar units, are the types of projects where Off-Site Manufacturing (OSM) has proven particularly successful.

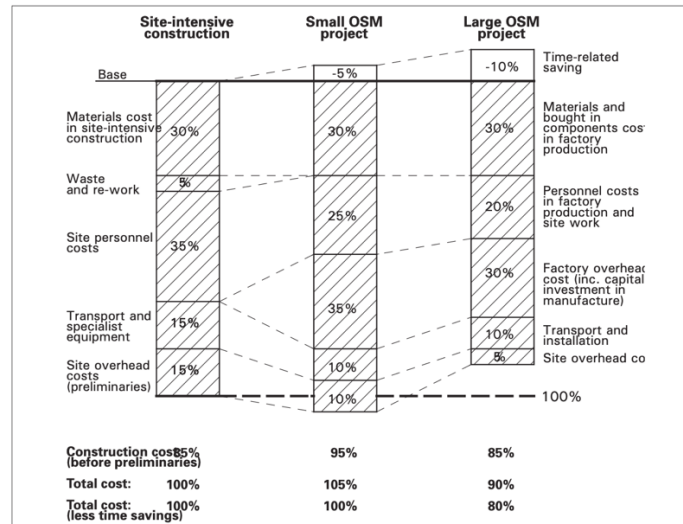


Figure 5.1 Relative economics of OSM and site intensive construction [117].

Modular construction offers a significant advantage in terms of structural integrity compared to traditional construction methods. Unlike traditional construction, where each building element has to be designed to withstand its own weight load and those of the elements above it, each module in modular construction is designed to sustain its own weight load and act as a structural member of the framework. This reduces the overall requirements for foundation works and structural elements, resulting in a more efficient and cost-effective construction process [90]. In this study, we will also examine the influence of the structural system and the height of the building to gain a deeper understanding of why mid-rise structures are preferred to our case study.

The use of modular construction in Turkey can also be justified by the country's diverse geography and climatic conditions. The region affected by the recent earthquake is located in the subtropical and temperate zones, where the Mediterranean climate prevails, characterized by hot and dry summers and mild and rainy winters. The thermal amplitude in Turkey is influenced by its topography, which includes high mountains, inland plateaus, and coastal regions. In the central regions where the epicenter occurred, Gaziantep and Kahramanmaraş, the thermal amplitude can reach up to 20°C in a single day. This variability in temperature and weather conditions can pose challenges to traditional construction methods but can be better addressed by modular construction. Furthermore, the frequency and intensity of meteorological extreme events have been increasing in Turkey since 2000, leading to significant economic losses estimated at around \$100 billion by the government [144]

Modular construction could be an ideal choice for urgent construction projects due to its speed, flexibility, mobility, quality control, and waste reduction. Factory-made prefabricated modules allow for quick on-site assembly, easy adaptation to specific needs, transportation to different locations, ensuring quality and safety, and generating less waste.

5.2.1 TURKISH PREFABRICATION MARKET

Turkey's construction industry is among the biggest globally, with many contracting firms taking on a significant volume of projects abroad. The Construction Confidence Index is the sole economic measure that predicts the level of work to be carried out in the residential and commercial construction sector in 2020 was around 31.5%. In the Eurozone, this value is approximately 46.10% [140-141].

Recently, the government launched the “Project of Development of a Roadmap to integrate Sustainable Consumption and Production within the Housing and Construction Sector for Turkey”, which has its primary focus on enhancing the country's transportation, residential, and energy infrastructure. Through the implementation of sustainable practices, the government's investments aim to achieve a USD 1.1 trillion economy and generate USD 226.6 billion in export revenue by 2023 [140].

In addition, Sustainable Cities Project's current objective in Turkey is to enhance the planning capacity and accessibility of specific municipal services to improve urban living, which can significantly benefit the sector. The total cost of the project is estimated to be USD 159 million [151]. Further, the Housing Development Administration of Turkey has announced a social housing scheme worth USD 2.53 billion as part of its plan to provide affordable housing to low-income groups in the country [140].

Finally, the CAGR (Compound Annual Growth Rate) for Turkey's prefabricated market is projected to increase by 4.5% until 2028 [140], thus suggesting a favorable context for the adoption of modular constructions.

5.3 FACTORY LAYOUT

Regardless of whether precast production tasks are conducted in a permanent worksite or temporary yard/factory on a jobsite, they are typically executed using job-shop, package production, or flow-shop production methods [119]. Modern factories for modular production are highly automated and can cost around £10M to set up [35], which is significantly less than the £500M required to set up a new automotive production line. However, manufacturing expenses can still add up, with around 20% to 50% of total operating expenses being related to material handling and layout [146].

Although the initial investment cost may vary depending on the scale and level of sophistication desired, this first impact can restrict access to prefabrication or make the operation too costly. As an alternative, the previously suggested partnership between private companies and the state could enable the development of the sector, fostering an increase in stakeholders and resulting in a reduction in this implementation cost.

Furthermore, an effective Factory Layout Design (FLD) can reduce operation expenses by 10% to 30%. In particular, cellular layout is considered the best approach and is often used in the hard disk drive industry, where all machines are organized into one cell to meet the specific requirements of the assigned product [31]. By adopting a well-designed cellular layout, manufacturers can further streamline their operations and achieve greater efficiency, which can lead to improved profitability in the long term.

5.4 DESIGN

Modular building projects are characterized by their complexity, which stems from a range of factors such as the need to integrate various subsystems, the customization of building components, and the involvement of multiple stakeholders in interrelated activities. To overcome these challenges, modular design offers a solution by allowing for the separation of subsystems and defining interactions between functional and physical components, promoting the standardization and modular design of building components [146].

The inadequacy of the design standard for manufacturing unique precast components will also compromise the further transportation of the units. Therefore, those projects require careful planning and precision, as the size and placement of modular components must be more precise than in traditional on-site construction. Such a standardization of the planning grid is important at the scheme design stage, as the planning grid will be controlled mainly by other building components and fitments [146-148].

In that regard, a modular grid is a system of arranging objects in space based on rows and columns of a specific size, which helps to both separate and connect information within the project [146]. By breaking up a large amount of space into smaller units, designers can create areas for placing elements and spaces left empty for visual balance. The gutters and flowlines of a grid help to separate information placed in one module from information placed in another, allowing for groups of related elements to be formed while keeping other groups separate.

A consistent logic of proportions between the elements of the design helps to ensure that the size of modules, fields, and columns adhere to a set of guidelines, imposing a sense of consistency in how we utilize space. The structure of a grid also allows designers to present complex information with greater clarity through the organization of information, making it easier for viewers to read plants and understand them.

Application	Internal wall height mm	Internal module width mm	Internal module length m	Ceiling-floor zone (typical) mm
Study bedrooms	2400	2500–2700	5.4 to 6	300
Apartments	2400	3300–3600	6 to 9	450
Hotels	2400–2700	3300–3600	5.4 to 7.5	450
Schools	2700–3000	3000–3600 open-sided	9 to 12	600
Offices	2700–3000	3000–3600	6 to 12	600–750
Health sector	2700–3000	3000–3600 open-sided	9 to 12	600–750

Figure 5.2 Typical dimensions for planning in modular construction [146].

Grids are typically classified into three categories [147]:

Basic modular grid - This is the smallest planning grid and serves as the basis for developing other grids. It is usually depicted on small-scale drawings to clarify the relationship between building components.

Multi-modular grid - This grid is formed with intervals that are multi-modules, and can be either square with the same intervals in both directions or rectangular. These grids are based on recommended multi-modules and are used in key plans to show the layouts of building complexes, buildings, and the positions of the main building components.

Tartan grid - This is an interrupted modular planning grid in which the intervals or bands of interruption are regularly spaced in both directions and have a different modular order than the general modular planning grid. This pattern may be used in very regular plans, such as those with columns at constant intervals throughout the floor.

In this context, a TLMG (Three-level modular grid) system for industrialized buildings was developed to assist designers in identifying the location, size, and coordination relationships of multi-level building components. By avoiding redundant installation steps, material waste, and collisions between various building parts, a significant amount of construction costs can be reduced [147].

This innovative system enhances the flexibility of modular grid systems by integrating with single- and double-line modular grids recurring to three integration methods. The overlap with support space modular grid supports the identification and positioning of supporting parts like beams, columns, and shear walls, The overlap with unit space modular grid provides a standardized dimensioning basis for space-separating components like partition walls and the overlap with flat (2D) modular grid determines the dimensions of the interior parts components and is widely represented by single lines.

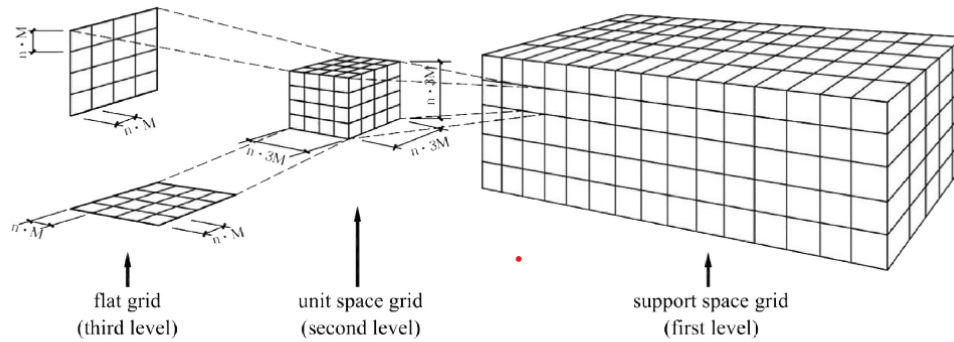


Figure 5.3 Schematic diagram of the three-level modular grid system [147].

Furthermore, previous studies have shown the advantages of the top-down approach over the bottom-up approach for modular design coordination. The top-down approach controls the location of building components in the 3D reference system, avoiding overlap and collision between different building parts. This method can also coordinate the sizes of interior and exterior trim components to optimize modular buildings performance. Moreover, the top-down approach is more suitable when meeting both community block planning requirements and modular building unit standards. The tolerance management method in modular coordination can help alleviate conflicts between supply chain members and improve productivity [147-148].

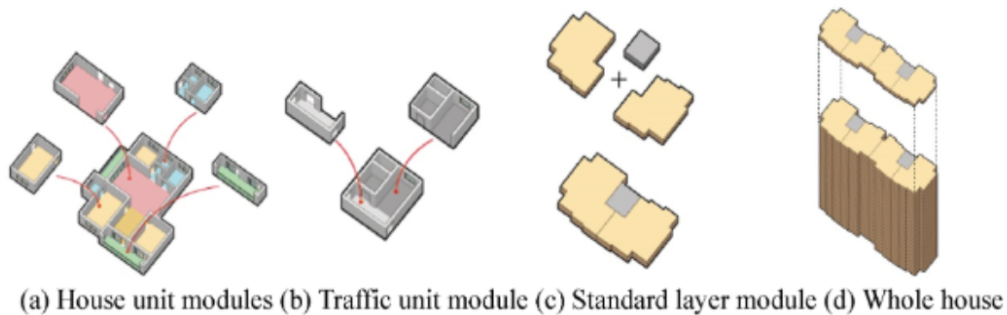


Figure 5.4 Standardized design process based on the bottom-up design method [148].

5.4.1 BUILDING HEIGHT

However, despite being a superior alternative in terms of housing density, modular buildings must be carefully designed for large-scale buildings as the influence of earthquake becomes critical as the height of the building increases. On the other hand, it was also observed that the maximum base shear that the structure could resist was higher than that of traditional steel buildings [146].

The height of a modular building is limited by the compression resistance of its members and also by the bracing capacity. 4-sided modules are designed to withstand both the vertical load of the modules situated above and the in-plane loads resulting from wind action. The maximum height for fully modular construction is typically between 6 to 10 storeys, depending on the location and the level of exposure to wind or other aggravating. In order to build higher structures, additional bracing to gables and a stabilizing central core are often required [84].

The fundamental period (T) versus total height (H) variation of the selected frames are kept consistent with the empirical relationships proposed by Goel and Chopra in 1997 [84].

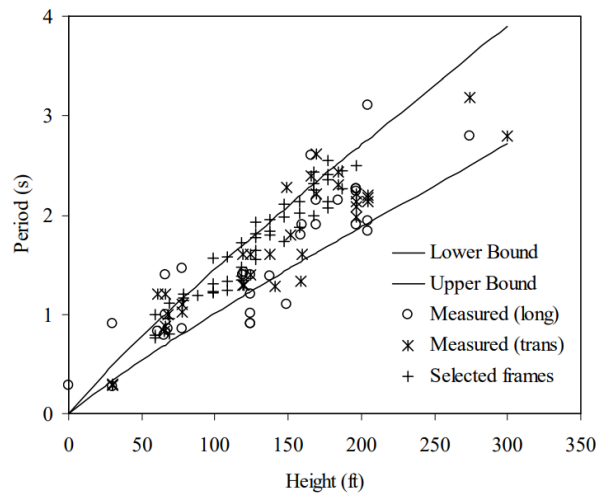


Fig. 5.5 Variation of fundamental period versus height scatter superimposed by empirical boundaries for modular buildings [84]

To conduct nonlinear time-history analyses, it is necessary to obtain earthquake ground motions from past records of the region of interest. However, in situations where recorded accelerograms are not available, artificial accelerograms can be used instead. For the investigating case, these accelerograms could be designed to represent an earthquake that is expected to occur at the site. These earthquakes are generated such that if their response spectra are calculated, they will be approximately equal to a target spectrum [149]

Initially, a set of calculations using the finite element method (FEM) needs to be conducted to establish the relationship between the first frequency of a building and its dimensions.

The existing empirical formula for the fundamental period of braced steel frame buildings may not be applicable in the case of modular buildings. Therefore, it is suggested that the fundamental period should be established directly from the numerical model in preference to the existing empirical formula [84].

The Natural vibration frequency (NVF) of the building plays the most important role in the determination of the dynamic loads and the derivation of the equation of natural vibration frequency of the frame can be described as follows [163]:

The natural vibration period is:

$$T = 2 \cdot \pi \cdot \sqrt{\frac{G}{k \cdot g}} = 2 \cdot \pi \cdot \sqrt{\frac{\Delta}{g}}$$

The Frequency, respectively:

$$f = \frac{1}{T} = \frac{1}{2 \cdot \pi} \cdot \sqrt{\frac{g}{\Delta}}$$

The horizontal displacement in static movement, Δ , can be obtained by:

$$\Delta = \frac{1}{E \cdot I_1} \cdot \frac{P \cdot h^3}{24} + \frac{1}{E \cdot I_2} \cdot \frac{P \cdot l_2 \cdot h^2}{24} = \frac{P \cdot h^3}{24 \cdot E \cdot I_1} \cdot \left(1 + \frac{I_1 \cdot l_2}{I_2 \cdot h}\right)$$

where:

I_1 = the moment of inertia of the pillar

I_2 = the moment of inertia of crossbars

h = the height of one module

l_2 = the span (length)

Hence, the stiffness coefficient:

$$k = \frac{P}{\Delta} = \frac{24 \cdot E \cdot I_1}{h^3 \cdot \left(1 + \frac{I_1 \cdot l_2}{I_2 \cdot h}\right)}$$

And finally, the first natural vibration frequency is:

$$f = \frac{1}{2 \cdot \pi} \cdot \sqrt{\frac{24 \cdot E \cdot I_1 \cdot g}{G \cdot h^3 \cdot \left(1 + \frac{I_1 \cdot l_2}{I_2 \cdot h}\right)}}$$

where G is a distributed load which must be brought concentrated in the middle of a crossbar.

In multi-storey framed buildings, a prevalent form to mitigate vertical discontinuity can be achieved by reducing the lateral dimension along its height. This type of building is commonly referred to as a "stepped" building. Stepped buildings are identifiable by their staggered and abrupt reductions in floor area as the height of the building increases. These reductions could result in decreases in mass, strength, and stiffness of the building [149].

5.4.2 CONNECTIONS

During earthquakes, one of the main concerns for modular constructions is the effectiveness of the lateral force resisting system's seismic performance [82]. Precast concrete walls, commonly used in areas of high seismicity, typically use grouted metal ducts as a connection method due to their simplicity and adequate construction tolerance. In cast-in-situ walls, the effectiveness of diagonal reinforcement embedded in reinforced concrete walls has been demonstrated in enhancing sliding shear resistance and enhancing the seismic performance of walls [150].

The use of inter-module connections is particularly important in seismic-susceptible zones, as they can help ensure the overall stability and safety of the modular building. In areas prone to earthquakes, modular buildings must be designed and constructed to withstand these strong ground motion and lateral forces [149]. Modular constructions require specialized connectors to ensure individual modules are securely fastened together, which helps to distribute seismic forces throughout the building and prevent the modules from shifting or becoming disconnected.

When subjected to lateral loads, modular structures have a tendency to experience failure in their critical members, specifically the columns. The failure of these columns can result in either partial or total collapse of the structure. To address this issue, a solution is to transfer the failure away from the columns to the inter-modular connections, which are allowed to deform in a ductile manner. To achieve this, currently proposed connections incorporate an additional steel plate and resilient layers, enabling them to display desired ductile failure mechanisms and dissipate seismic energy [96].

The connections may include flexible joints or couplings that allow for movement between modules without compromising the overall structural integrity of the building. Additionally, some inter-module connections may incorporate dampening devices, such as elastomeric bearings or friction dampers, which can help dissipate energy and reduce the impact of seismic forces on the building [149].

Several scholars have investigated the effects of the stiffness of the inter-module connection on the seismic performance of modular buildings. Nonlinear analyses indicated that increasing the stiffness of the inter-module connection results in a greater over-strength factor. It has also been demonstrated that a rigid connection is preferred over a pinned connection for pursuing a better seismic performance and reducing the reliance on separate lateral force resisting system [84].

5.5 TRANSPORTATION

Transporting volumetric units is a major concern when considering prefabrication or modular construction [6]. In fact, displacements are not restricted to the end of the assembling activity and the units often need to be moved within the factory. Moreover, modular production

involves various, strongly interdependent, stages that may be operated in parallel; hence, coordination among them is fundamental and allows an appropriate transportation logistics to be developed, crucial step to the performance of the prefabricated component supply chain [93].

In that regard, the precast supply chain differs significantly from traditional supply chains due to the interdependence of the precast industry and traditional manufacturing industries. This distinction can be attributed to three main factors. Firstly, the precast supply chain involves both push (repetitive production planning) and pull (just-in-time construction projects) activities, making it more complex and vulnerable than traditional supply chains. Secondly, production scheduling plays a crucial role in the precast supply chain due to the low standardization of precast components. Finally, effective coordination between participants is critical to the success of the precast supply chain.

In addition, prefabricated components are often large, bulky, and heavy, which can introduce uncertainties such as changes in delivery times, site storage space requirements, and associated costs. Meanwhile, late delivery of components can cause work delays on site, extend the construction period, and increase project costs. Conversely, early delivery to the site may result in the need for layout adjustments, storage space congestion, or higher crane-handling costs on site [93].

In the first stage, before the manufacturing starts, building materials need to be transported to the factory. To ensure the integrity of these materials, this place must meet their intrinsic quality and storage requirements, preventing disturbances and vibrations that could influence their durability and performance. Once those materials are delivered, assembling activities will take place at various stations, each of them shelters the pertinent machinery for the different mounting phases. After the units are completed, they can either proceed to be installed or stored until shipment is possible. Those regular processes involve at least three displacements, value which tendentially increases [93][151].

According to what was stated in the previous topic, the final design and layout of the units needs to be comply with both the clients expectations and transport legislations. To address this issue, promoting the aforementioned standardization and modular design of building components units enables them to be proportionally divided, or grouped, meeting clients' sizing requests and ensuring the minimum conditions to the shipment. Due to that, it is arguable that the design also plays a critical role in advancing the development of modular buildings, acting as a first mitigation form for transportation constraints and which can be implemented since the beginning of the building conception.

To enable transportation, the volumetric units must follow the same restrictions imposed to the transport of a container. Typically, modular houses are constructed in sections, and each section can be considered a separate container for transportation purposes. This means that the width and height of the modular house section must be within the limits allowed for regular transport

containers. The total length of the modular house, however, may be longer than the maximum length allowed for a single transport container.

The maximum dimension of a container that can be transported on a truck in Portugal depends on the capacity of the truck, the height and weight restrictions of the roads and bridges that the truck will transit. The Portuguese Diary of the Republic establishes that the maximum height allowed for a vehicle is 4.20 meters and the maximum width is 2.60 meters. The maximum length allowed is 18.75 meters for a two-axle truck and 22 meters for a truck with three or more axles. Additionally, the maximum weight allowed per axle is 11.5 tons. It is necessary to take into account the size and weight of the container itself, as well as the weight of the cargo it contains [152-153].

In Europe, the restrictions are similar and are imposed by The Regulation CE no 561/2006 [154]. Despite the fact that Turkey is not contemplated by the Schengen Zoning, their national code limitations are very alike to the European and it follows the same restrictions aforementioned for Portugal. However, it is important to note that there may be additional restrictions and regulations in place for specific routes, bridges, and tunnels in Turkey [155].

An appropriate logistics should therefore take into account and discriminate any variances that may occur during the journey. In addition, being outside the Schengen area, the shipment would be subject to the issuance of an invoice and consequent taxation, additional costs that should be foreseen during the budgeting phase.

5.6 TECHNOLOGICAL ADVANCEMENTS

Storing and transporting components in an efficient and accurate manner presents several challenges. Poor organization and record keeping can make it difficult to locate specific components in a timely manner, leading to delays and potential quality issues. Additionally, components must be carefully handled to prevent damage or degradation during transportation. Any of these challenges, if not addressed effectively, may compromise the quality of the components and ultimately decrease the overall reliability of the structure.

The issue in cause is in essence, a Linear Programming Transportation Problem, which involves identifying the optimal solution for transportation and resource allocation to multiple destinations while minimizing costs between sites [156]. However, due to the complexity involved in such a type of operation, the parameters are harder to measure and are often conditioned by uncontrollable variables. In order for production and shipping activities to be in sync, the first problem a factory will face actually starts as a scheduling problem. Various scheduling models have been proposed to address process scheduling problems, including single machine sequencing (SMS), parallel machine sequencing (PMS), flow-shop scheduling (FSP), job-shop scheduling (JSS), and line-of-balance (LOB) [119]. The better defined, the easier the application of JIT principles will be.

Recent simulations reproduced the flow-shop production operations to verify the reliability of ARENA-based simulation model. In addition, an innovative two-hierarchy model was established to pursue the minimum production costs and on-time delivery. Several studies have also investigated the transportation of components with a focus on implementing a just-in-time (JIT) strategy to deliver components to the site in the right quantities and at the right time. Those approaches aimed to reduce waste and improve productivity. The JIT strategy has been applied to plan the component supply chain, including determining the optimal number of delivery batches and the optimal number of components in each batch, with the goal of minimizing earliness/tardiness penalties [118].

Furthermore, transport tracking could facilitate the plants and construction sites to acquire the location, status information, and estimated arrival time of the modular units. The tracking is usually investigated together with the modules' identification at storage yards [118]. In that regard, RFID technology has the ability to significantly enhance material tracking operations in the construction sector. Like barcodes, it is a data-gathering technology that is used to identify, locate, and track items, assets, and people. RFID, on the other hand, has extra advantages over barcoding, including the fact that it does not require physical contact or line-of-sight and may operate in situations with noise, pollutants, light, and dirt. This technology has already been shown to be extremely advantageous in a variety of areas, including manufacturing, retail, transportation, and logistics [118-119].

Finally, a mathematical programming model could also be developed support transport optimization and minimize the sum of trucking costs and inventory holding costs. The model has to consider factors such as the distance between the manufacturing plant and the construction site, the number and size of prefabricated components, and the type of transportation used. The usable area for in-situ production is defined by the coordinates of the production module and the layout area for in-situ production is determined by taking into account influencing factors as boundary conditions; the partial resolution is elucidated as follows [166].

$$\begin{aligned}
 \text{Minimize } z = & \sum_{i \in J} \sum_T cp_{it} \cdot P_{it} + \sum_{i \in C} \sum_k \sum_t cpc_{it} \cdot QR_{F_{ikt}} + \sum_{i \in C} \sum_l \sum_t cpc_{it} \cdot QR_{D_{ilt}} \\
 & + \sum_{i \in C} \sum_t cpc_{it} \cdot QRM_{it} + \sum_{i \in C} \sum_t ci_{it} \cdot INVT_{F_{it}} + \sum_{i \in C} \sum_t ci_{it} \cdot INVT_{C_{it}} \\
 & + \sum_{i \in J} \sum_t cbo_{it} \cdot B_{it} + \sum_t cov_t \cdot OVT_t \\
 & + \sum_i \sum_k \sum_t ckm \cdot Dist_{F_i} \cdot Y_{ikt} + \sum_l \sum_t \sum_s \sum_i ckm \cdot Dist_{R_{si}} \cdot X_{ltsi}
 \end{aligned}$$

$$\begin{aligned}
 & + \sum_i \sum_k \sum_t cst \cdot Y_{ikt} + \sum_l \sum_t \sum_s \sum_{i=0} cst \cdot LX_{ltsi} \\
 & + \sum_g \sum_{s \in TM \cup np} \sum_{i \in TM \cup np} \sum_t ckm \cdot f_g \cdot DistR_{si} \cdot M_{gsit}
 \end{aligned}$$

where:

- z = total costs, including production, inventory and transport costs
- J = set of finished goods
- T = set of time periods
- cp_{it} = Purchasing cost of component i during time period t
- QRF_{ikt} = Quantity of product to order to supplier i by the FTL shipping mode on truck k during time period t
- $C.$ = Set of components and raw materials
- $I, S.$ = Set of finished goods, components and raw materials, suppliers, manufacturing plant and virtual node
- QRD_{ilt} = Quantity of product to order to supplier i by routes or the LTL shipping mode on truck l during time period t
- QRM_{it} = Quantity of product to order to supplier i by the milk-run shipping mode during time period t
- ci_{it} = Inventory holding cost of product i during time period t
- $INVT_{F_{it}}$ = Initial inventory level of finished good i in the manufacturing plant
- $INVT_{C_{it}}$ = Initial inventory level of component i in the manufacturing plant
- cbo_{it} = Backorder cost of product i during time period t
- B_{it} = Backorder of finished good i at the end of time period t
- OVT_t = Overtime hours of the productive resource during time period t
- $ckm.$ = Cost per kilometer
- Y_{ikt} = 1 if truck k travels from the supplier to the production plant in the FTL shipping mode, 0 otherwise
- X_{ltsi} = 1 if truck l departs from node s to node i during time period t , 0 otherwise
- cst = Stop cost for picking products at suppliers
- LX_{ltsi} = 1 if truck l arrives to node i from node s during time period t , 0 otherwise
- f_g = Pick up frequency in each node per period in graph g
- M_{gsit} = 1 if the truck in graph g departs from node i to node s during time period t , 0 otherwise

Extensive numerical experiments show that the optimal transport plan generated by the model outperforms the plan obtained by a greedy approach by 10% of cost savings, implying the effectiveness of the model for the construction industry [116].

Storing and transporting components in an efficient and accurate manner presents several challenges. Poor organization and record keeping can make it difficult to locate specific components in a timely manner, leading to delays and potential quality issues. Additionally, components must be carefully handled to prevent damage or degradation during transportation. Any of these challenges, if not addressed effectively, may compromise the quality of the components and ultimately decrease the overall reliability of the structure [100].

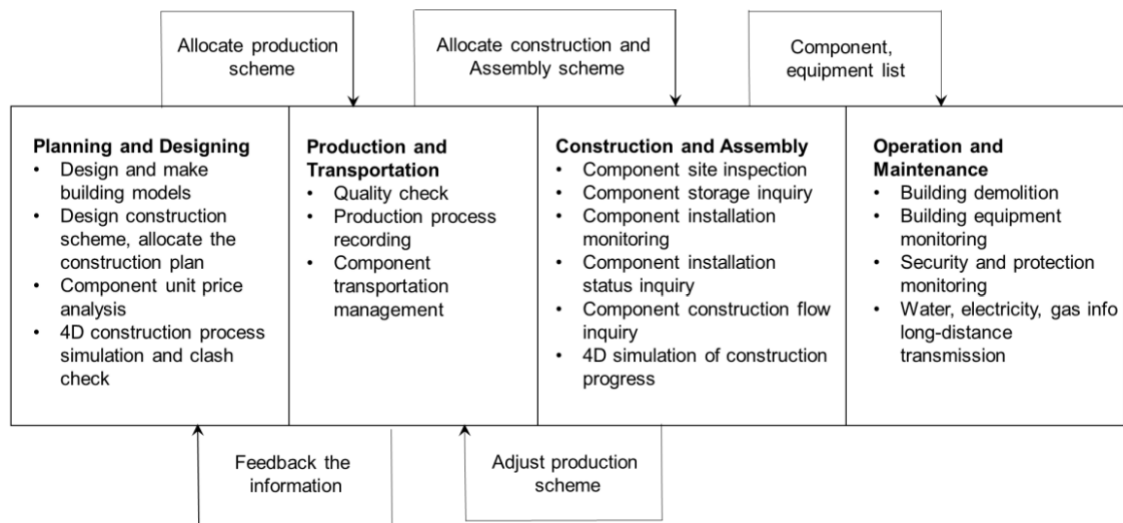


Figure 5.6 Application of prefabricated components management based on RFID-BIM platform [100]

The contractor also needs to be precautions in the development of a conduct plan for both transportation and handling, quantifying (and qualifying) displacement and establishing an accurate map to provide all the concerning information. The construction planning and production planning need to be adjusted timely according to the real-time PC information in the supply chain [118-119]. This is a measure that allows routine practices to be reviewed so that new practices and principles can be introduced to the production, improving the flow and productivity of the chain.

6

CONCLUSION

6.1 FINAL CONSIDERATIONS

This dissertation focuses on the use of modular homes in emergency situations, particularly when rapid and cost-effective construction is needed. Modular alternatives offer advantages such as standardized production, factory productivity, waste reduction, improved safety and quality, and reduced construction time. However, the architectural aspect can be a disadvantage due to possible excessive standardization and impact on surroundings.

Despite having the necessary expertise, there is still market resistance to adopting this methodology, with reasons such as high initial investment, lack of specialized labor, and excessive standardization. However, current investments in comfort, layout, and maintenance plans are new drivers for this type of construction.

Modular construction is most applicable for larger projects with high levels of repetitiveness, but transportation and design requirements can be limiting factors. The use of command-and-control tools can help in developing an appropriate logistics plan.

Several companies specialize in modular construction, with various options for residential models available through catalogs. Customization is possible, making it attractive for new consumers. Hospitals with over 1300 beds have been built in days, highlighting the applicability of modular construction for emergency cases.

The use of quality materials allows for high levels of acoustic and thermal comfort, making this methodology viable for social and student housing. The method's gradual development could be stimulated by government bodies or public-private partnerships, as observed in recent cases in the United Kingdom and China.

Specific regulations in Portugal are still lacking, and successful and failed examples must be studied to establish common points and understand the advantages and disadvantages in different application contexts.

6.2 FUTURE DEVELOPMENTS

The study primarily focused on analyzing situations where advantages or disadvantages would be prominent. However, there is a lack of practical applications to establish a reliable metric for the implementation of this type of execution. Therefore, it is suggested the study of the effectiveness of the methodology in real-world applications. Studies concerning the applicability of the methodology for thermal and acoustic comfort could be furtherly developed and the promised reductions in energy consumption could be tested as a means to prove the impact it could have during the edification life cycle operation.

During the evaluation, a lack of standardization of data for this type of construction was also detected. Modern construction demands intensive planning and coordination between activities to overcome problems with interdependence of activities and stakeholders. A platform that connects information regarding modular projects could advance knowledge and optimize coordination among participants, while simultaneously optimizing scheduling and resource allocation. This platform could be fed by external collaborators, builders, and users.

There is still a need for analytical and empirical verification of the time savings that can occur through off-site land preparation in modular construction. This overlap can result in time savings ranging from 30% to 50% depending on the type of construction and other variables. In that regard, the advantages of the alternative for rough terrain, which would therefore demand greater effort dedicated to the preparation and execution of the foundation bases, could be proven.

Additionally, research on occupational safety and the reduction of personnel in the field can be developed in the optics of accident prevention. The differentiation between the full utilization of modular construction, with volumetric units, could be compared with the utilization of a technique that, although using the concept, may not employ prefabricated components. The advantages and disadvantages could be subsequently studied as well.

Finally, by analyzing the already developed mathematical models, the transportation problem could be studied more thoroughly. The combination of these techniques and resulting outcomes could be simulated in practice and could be used as first directive for an optimization problem.

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