MODULAR SYSTEM APPLICATIONS IN HIGH-RISE BUILDINGS

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ABSTRACT
With the development of industrial revolutions, progress has been made in construction systems and construction techniques, depending on features such as increasing population and intense urbanization. Along with the presence of many technological innovations in the fields of construction and architecture, one of the stages applied in urban planning and building production processes is mass production and prefabrication. As a result of the proliferation of urbanization, the production rate in factories has also increased. With the emergence of fabrication and advanced production methods, while it took days to manufacture a product or object in the past, effective outputs and final products can be obtained in a short time with today's technology. The construction sector has also been greatly affected by the rapid manufacturing developments that ensure maximum efficiency in a short time in many industrial and industrial sectors, and monologue construction methods such as on-site casting, which is one of the traditional construction techniques, have been replaced by prefabricated production at the factory. Prefabricated productions vary and one of these product types is pre-production modular systems. These systems are generally preferred in low-rise temporary buildings. On the other hand, with the developing technologies, these systems are used in mass housing projects and even in complex building mechanisms such as high-rise buildings. With the development of modular construction systems in high-rise buildings, many negative situations such as high cost, long construction period, and generation of environmental wastes are prevented. This study, is aimed to determine and explain the advantageous aspects of the modular system compared to other systems, the methods used in building construction and the parameters to be considered when integrating it into high-rise buildings. The importance of modular systems has been emphasized through literature review and attention has been drawn to the way they are used in high-rise buildings through sample structures.
Keywords: High-rise building, Modular System, Cell System, Prefabricated construction technique

INTRODUCTION
The Industrial Revolution, in other words, the Industrial Revolution, the effect of new inventions on manufacturing in Europe in the 18th and 19th centuries, and the fact that steam-powered machines gave birth to industry, and these developments increased capital and production accumulation. With the Industrial Revolution that took place in the 1750s and 1850s, extensive and comprehensive changes were witnessed in terms of art, design and architecture. The works produced by hand workmanship and human power have begun to leave their place in the standard works in which the machines operate (Karabacak and Dilmaç, 2021).

With the emergence of the industrial revolution, especially after World War II, industrialization, population growth, intense urbanization, the resulting intense demand for housing and developments in technology led to the construction of factories and the production of buildings. In this century, the idea that the house of the future should be mass-produced ready-made housing has started to be advocated (Erturan and Eren, 2012). With the advent of the first industrial revolution, the use and development of water and steam power strengthened the mechanical production systems by influencing them. With the second industrial revolution, mass production plans were introduced with the support of electric power (Karabacak and Dilmaç, 2021). Many designers focused on mass-produced industrial housing and worked in this direction (Erturan and Eren, 2012).

With the industrial revolution opening the door to the modern age, modular construction systems have made progress. Modular structures generally involve the assembly of completely independent units to form a complete building block, manufactured in factories outside the building site and transported to the building site. These structures can consist of wood, steel, reinforced concrete and combinations of these materials (Gunawardena and Mendis, 2022). With the prefabrication technique, modular structures that go beyond the standard two-dimensional designs have taken their place today in volumetric dimensions (Knaack et al., 2012). Reducing construction costs, seeing the use of sustainable technologies by creating standardization with modern materials, and providing energy savings have brought modular construction systems. The application of rapid construction techniques has enabled the construction of different functional structures such as offices, warehouses, sanitary and special-purpose facilities by spreading the building elements such as columns, beams, floors and walls, as well as equipment such as cladding and plumbing, to wide standards. (Generalova et al., 2016). A modular structure built with the prefabricated production method is given in Figure 1.



(a) (b)

Figure 1. (a) Wooden wall system inside a steel-framed modular unit, (b) modular structure created with light steel structure (Gunawardena and Mendis, 2022)

Module box systems reduce the possibility of various on-site injuries compared to conventional construction systems, and construction workers in conventional systems are generally exposed to high levels of noise, dust and airborne particles, adverse weather conditions, and other factors that reduce productivity and production. Working conditions of construction workers can be improved with the modular construction technique. Another advantage of modular box systems is the reduction of site preparations, including the rental of construction site sheds and other facilities. In general, site preparations constitute 8 to 15% of the total construction cost. Therefore, a 50% reduction in on-site time results in proportional savings in preliminary preparations (Lawson et al., 2014).

The modular structure, by its nature, saves materials and resources. One of the biggest advantages of modular construction is the ability to assemble repeating units in controlled environments.

Another is the reduction of material loss during conventional construction due to weather exposure and construction site thefts. The one-piece modular units are largely completed before being brought to the construction site, can significantly limit the construction waste generated at the construction site and contribute directly to the construction site waste management (Figure 2). For this reason, the modular building industry has been a practitioner of flexible design and reuse for years (Erturan and Eren, 2012). With this system, the need for material storage space is minimized, as the final product of the building is brought to the construction site ready-made from the factory. Since it will not be affected by the climatic conditions during construction, it provides continuity on the construction site without being tied to a certain season and allows fast construction, as well as does not cause damage to the environment and neighbouring buildings due to construction (İlerisoy and Çolak, 2016).

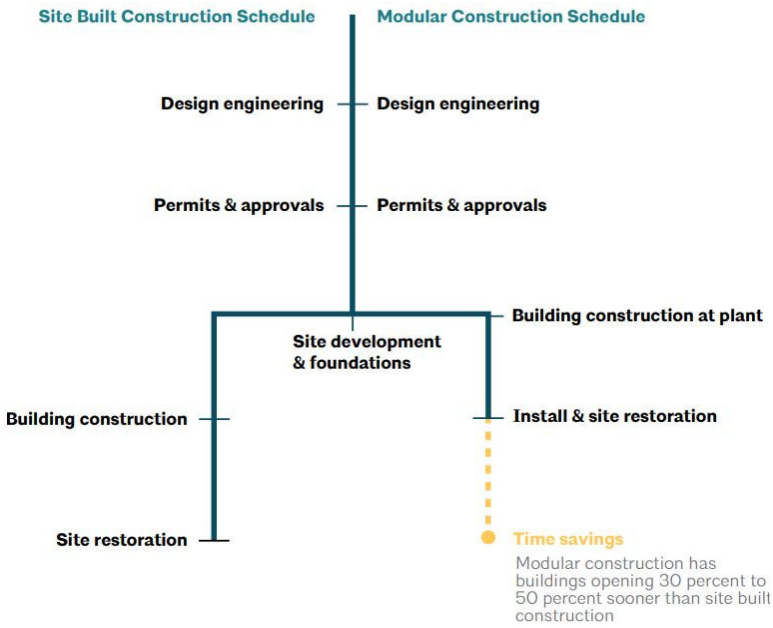


Figure 2. Comparison of traditional and modular construction process (Wilson, 2019).

Modular structures produced in the factory with machines can provide the same building life as a building built with traditional techniques, as well as the structures are long-lasting and can be planned flexibly to meet changing needs. Renovations or modifications that are required to be renewed or changed in the building over time can be made without affecting the entire building. In this way, it is possible to design flexible and changeable spaces. Thanks to this system, the prefabrication degree can be increased up to 90%, thanks to the fact that 60% - 98% of the work can be done in the factory, thus shortening the construction period considerably. This system enables a high level of quality control. Off-site production with maximum efficiency and controlled safe construction before placement is ensured. The systems produced are also carried out within the program in the assembly and construction works at the construction site (İlerisoy and Çolak, 2016).

It is seen that there are not enough land areas for new buildings due to the rapid and continuous structuring of city centers in line with the increasing demand for housing and different functions. As a result, low-rise buildings have been replaced by high-rise buildings. The long construction period of these high-rise buildings, which were built with traditional methods, negatively affects the city. On the other hand, the use of modular systems in high-rise buildings with the developing technology brings solutions to these basic problems. Combination details and integration are also important parameters in modular construction techniques.

Within the scope of the study, after the modular system and its features were explained at the beginning, the methods applied were included. Then, the factors to be considered in the application of this system in high-rise buildings were expressed and evaluations were made in the context of high-rise examples. The importance of modular construction systems was emphasized by looking at examples of high-rise buildings.

METHODS USED IN BUILDINGS CONSTRUCTED WITH A MODULAR SYSTEM

Modular systems, also called cells, are the construction systems with the highest industrialization level among prefabricated systems, as all or most of the building is produced in the factory and only assembled at the construction site (Dalaman, 2000). Modular construction projects include the construction of the main structure, the simultaneous production of other products and their installation in the area to be built. Timing focus may change according to project scale and constraints in order of manufacturing → transport → installation phases depending on work priority (Lee et al., 2019). Modular systems are finalized with the completion of the structural system and its details together at the factory. The elements that make up the system consist of modules. In these systems, 85-90% of the total manufacturing rate of the building is produced in the factories, from floor coverings to paint and whitewash works, from the installation of windows, doors and glasses to the completion of the installation works (Dalaman, 2000).

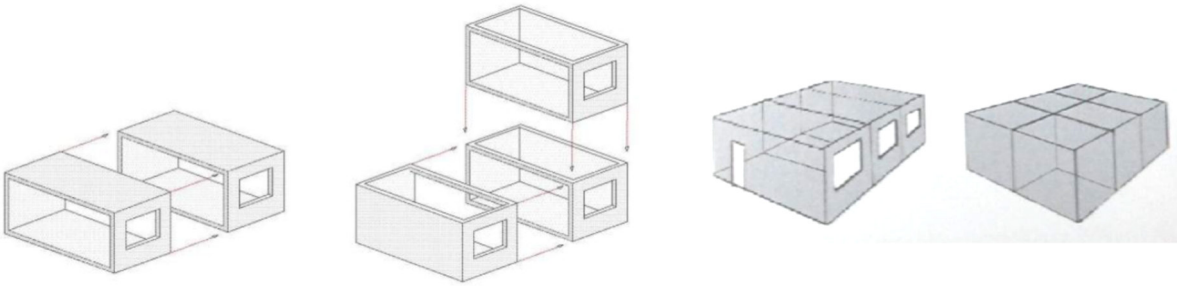
Modules are classified as steel, precast concrete and wooden frame systems according to the main construction material. With the development of modern materials and technological manufacturing techniques, light steel-framed modular systems have come to the fore. Mixed systems can be created by adding different material classes to steel frames. Modules are also prepared according to floor fasteners and details, and structural behaviour configurations (Lacey et al, 2018).

Modular box systems are categorized according to static aspects, spatial characteristics, assembling type and function situation as another classification type. (Table 1). Depending on the function situation, statically modular box systems can only carry their own loads as well as the load transferring on them. Modules can be produced in one piece in the form of reinforced concrete boxes or by making various combinations in the factory (Erturan and Eren, 2012).

Table 1. Classification of modular box systems (Erturan and Eren, 2012)

Classification	System Type
Static Perspective	Load-bearing modular box systems
	Self-supporting modular box systems
In Terms of Space Features	Open modular box systems
	Closed modular box systems
According to Assembling Type	Modular box systems for masonry construction
	Modular box systems assembling on the structure system
	Mixed modular box systems
According to Functions	Modular boxes with living space
	Modular plumbing systems

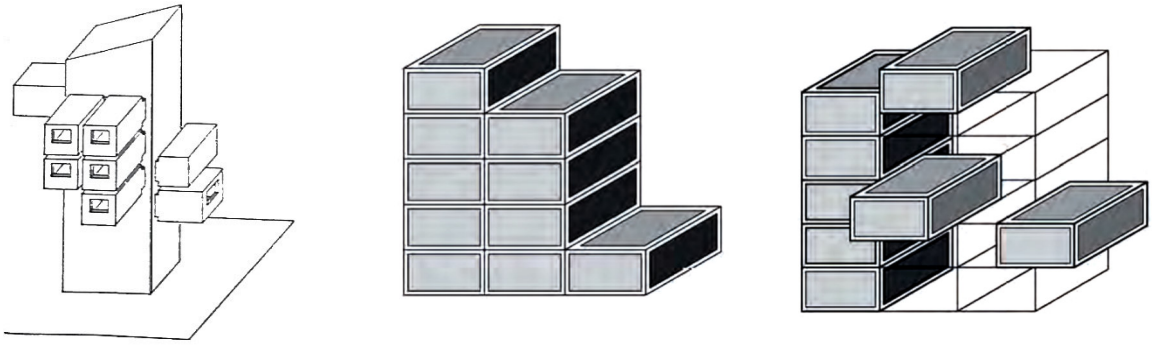
In terms of space features, modular box systems are divided into two as open and closed (Figure 3). Enclosed modular box systems are fully finished units bounded on all three sides. They are structurally supported by their longitudinal or both longitudinal and transverse walls. They can also be built as a 'masonry block system' by placing them next to each other and on top of each other, or by placing completely finished cells in a structural system. Open modular box systems are limited only to two sides. In the transverse direction, the plan has the freedom to form. Units are 2.50 meters wide and limited for transport reasons. As a constructive solution, the masonry block system in multi-storey buildings is preferred. There are two different types, which are placed transversely and placed longitudinally (Tanatmış, 1986).



(a) (b)

Figure 3. (a) putting together open modular boxes, (b) assembly of closed modular boxes (Erturan and Eren, 2012)

Modular box systems are classified as masonry modular box systems, frame-assembled modular box systems and mixed modular box systems according to the way of assembly. (Figure 4). Masonry modular box systems are formed by arranging load-bearing modules side by side and on top of each other. Modules are assembled by stacking, similar to building a brick wall or as if a masonry house is built. The modules used can be open or closed type module boxes. Modules can be the load-bearing of both themselves and the entire system. Double walls or floors that may occur in this system can be used for insulation or installation purposes. Frame-assembled modular box systems are formed by transporting the modules with the help of a load-bearing frame or connecting them to a central core (Figure 4). Modular structures can be placed in the eyes of a pre-prepared skeleton system at the construction site by sliding them from the sides, sliding them up from the bottom or hanging them from the top down. At this point, the main task is the load-bearing skeleton structure system.
Mixed module box systems, on the other hand, use a combination of masonry and skeleton systems. In this system, some of the modules are assembled according to the masonry system principle, while the other part is assembled on a load-bearing frame. Module box systems can be used to create living spaces in the building, as well as only in the installation parts of the building. Living space modules are module box types in which living spaces are created by combining open or closed modules. Plumbing modules, on the other hand, are used in the units of the building with more details and workmanship. In these systems, units and other sections such as kitchens, elevators, bathrooms and stairs are created with other construction systems (Erturan and Eren, 2012).



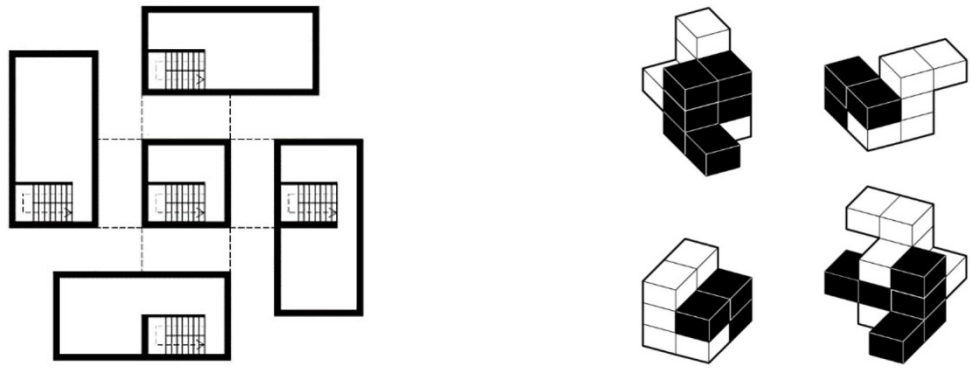
(a) (b) (c)

Figure 4. (a) modular system integrated into the core system (Erturan and Eren, 2012), (b) masonry modular system and (c) planning principles in skeletal modular systems (Eren, 2018)

HIGHLIGHTS IN IMPLEMENTING THE MODULAR SYSTEM IN HIGH-RISE BUILDINGS

Modular cell systems can be placed and combined by stacking on each other without a different support element, up to certain floor heights that vary depending on the form, production and material properties. As the number of floors increases depending on the height, it provides the strength and stability of the building, supports tension mechanisms and methods that transfer horizontal loads to the ground and core. As a result of exceeding a certain height limit, modular building cells must be transported together with a separate structure support elements that will create multi-directional durability and stabilization (Sezer, 2015).

A various sets of hypotheses are developed for implementation within a modular system. The increase in variations also allows outputs in different sizes and dimensions depending on the variables (Figure 5). By adding new technological products and methodologies on top of the construction techniques of existing technologies, comprehensive and complex modular systems are developed. Transferring physical parts from one module to another and integrating them with fasteners, producing and transporting a whole module system are also important features of the modular construction system. By creating mathematical algorithms and adding them to modular systems, the reflections of this system on multi-storey structures can be seen (Correia et al., 2019).



(a) (b)

Figure 5. (a) modular plan arrangements, (b) multi-storey modular building combinations (Correia et al., 2019)

While the form production and size limit of prefabricated modular architectural products can be created on a wide scale with the development of technological methods, transportation and assembly of large-scale systems for transportation restrictions and on-site construction processes cause problems after they are designed. For this reason, modular building elements in large-scale projects, as in Figure 6, should be designed modular in themselves and should be easily transported without disrupting transportation. Planning should be done considering that the structural elements should be assembled with rigid connection points. The assembly phase is important for the modules to be durable when combined. It is necessary to use interlocking mechanisms in the connection details (Teribele and Turkienicz, 2018).

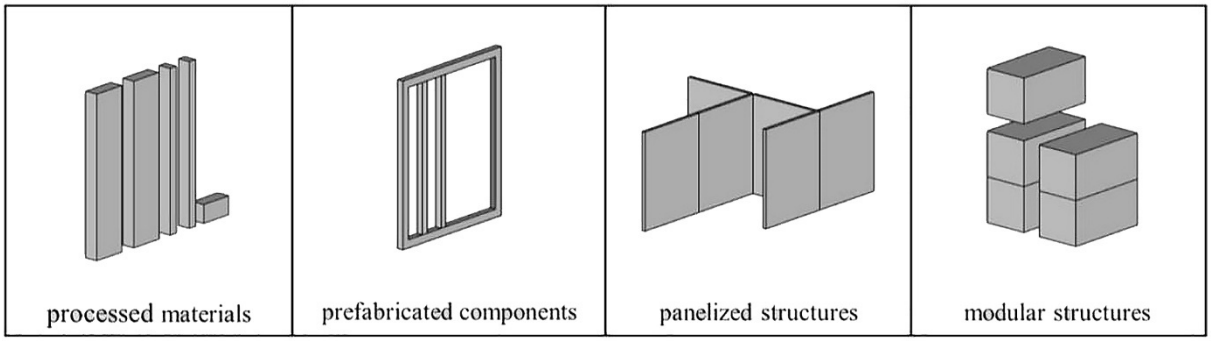
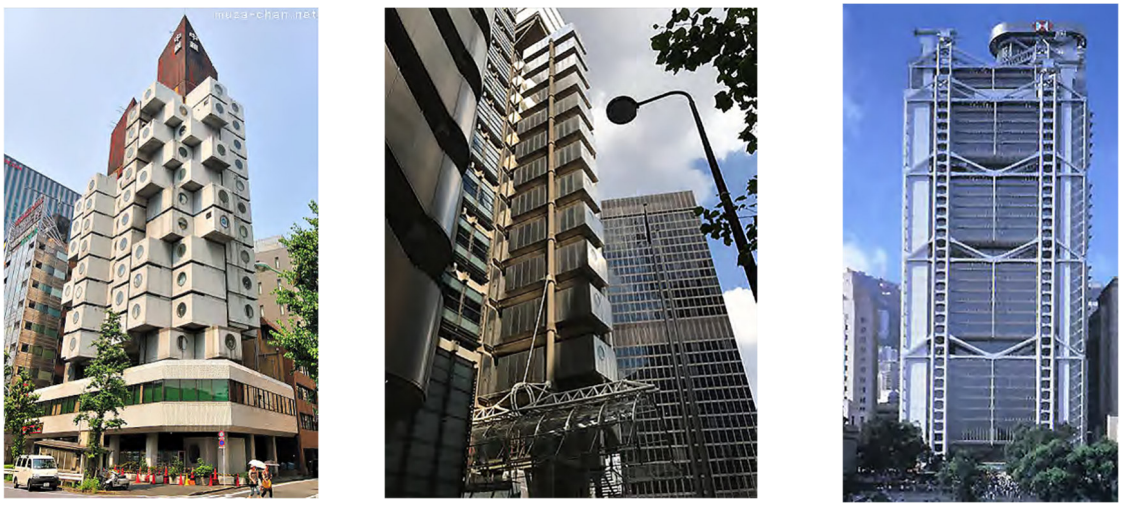


Figure 6. The modular design of structural elements of modular systems (Teribele and Turkienicz, 2018)

SAMPLE STRUCTURES WHERE THE MODULAR SYSTEM IS APPLIED IN HIGH-RISE BUILDINGS

Modular construction is widely used in low-rise buildings. In particular, the United Kingdom, America, China, Singapore and Australia have made progress in this system. Despite the difficulties in the application of modular construction technology in high-rise buildings, high-rise construction has been developing with innovations in manufacturing and material technology in recent years (Thai et al., 2020). There are very few high-rise buildings built on this system worldwide. In the 20th century, pioneering structures using the modular system were built in high-rise buildings, although they were not fully included in this system (Eren, 2018).

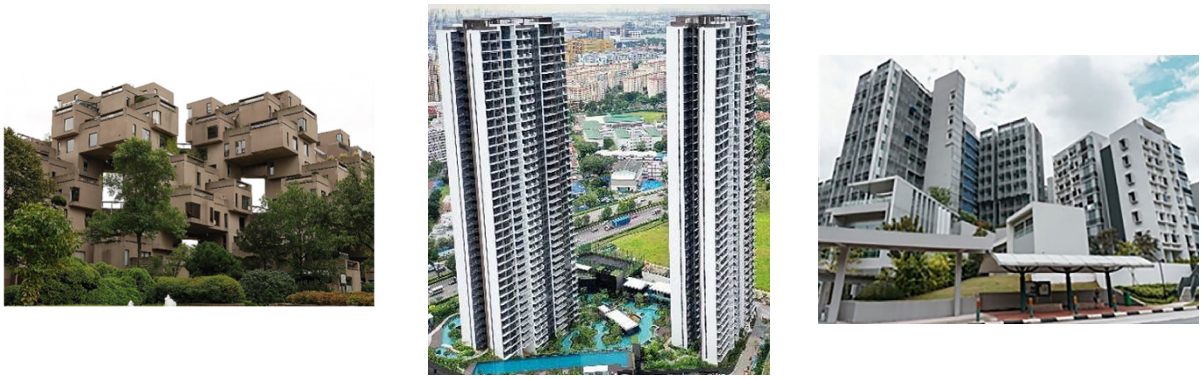
The first of these are the structural elements used in the projects of Japanese Metabolists such as Safdie and Rudoloph in the 1960s, and the modular system applications attached to the service core. One of the most famous modular system projects is the Nakagin Capsule Tower, implemented by Kurokawa in 1972 (Figure 7). Kurokawa believed that modules could be easily removed, such as unplugging them from a plugged-in outlet when tenants need to move or the module needs to be replaced. The project was originally designed as a hotel for workers who cannot go home after work or use their homes sparingly. The capsules are completely produced in modern facilities. In the multi-storey projects of Richard Rogers' "Lloyd's of London" in London in 1982 and Norman Foster's "Hong Kong Bank" in 1984, wet areas were applied modularly and the construction period was shortened significantly (Figure 7). Lloyds Building is located on a very narrow street in the banks district, which is considered the heart of London. In order not to disrupt the work of the employees in this region, work continued at night, and 33 WC units in the service tower were replaced overnight (Eren, 2018).



(a) (b) (c)

Figure 7. (a) Nakagin Capsule Tower, (b) Lloyd Tower, (c) Hong Kong Bank (Eren, 2018)

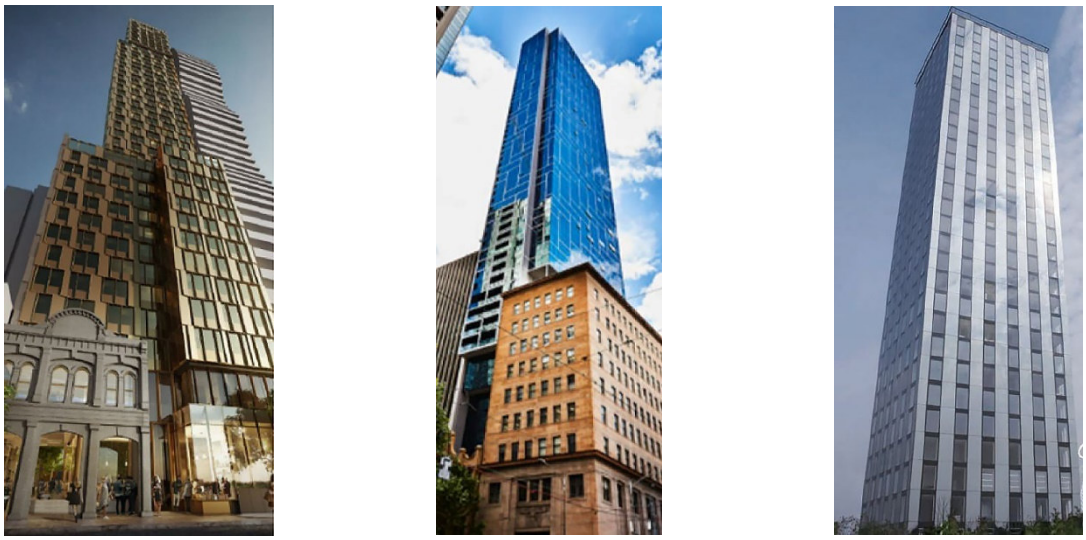
The Habitat 67 structure, designed by Moshe Safdie, is a prototype project entirely mass-produced in Montreal, Canada (Figure 8). This project was implemented in 1967 during the Canadian pavilion times. Consisting of 354 precast concrete modules for 158 living units, the building has created different living colonies with various spaces for the residents. In addition, it has created a building mass that avoids monotony compared to buildings located in a dense urban environment. The Habitat 67 structure is considered one of the iconic architectural works and has influenced architectural design with its different formal configurations (Laovisutthichai et al., 2020). Clement Canopy, on the other hand, consists of two 40-storey tower blocks (Figure 8). There are 505 living units in total in the two tower blocks. Reinforced concrete modular units produced in the factory in a prefabricated manner were transported to the construction site and assembled. There are 8 different living units in the high-rise project. 1866 modular units, 862 in the first block and 1004 in the second block, were used. The maximum module height is 3.15 meters, and the maximum module width is 3.1 meters. The weight of the modules varies between 14 and 29 tons. Composite wall systems support reinforced concrete modules (Seng et al., 2021). NTU North Hill Residence Hall has saved 6 months of construction time compared to the traditional construction method and 40% of manpower has been saved in on-site construction (Figure 8). This project is a reference structure for new technological construction systems. The 13-storey building, consisting of steel modules, is used for a dormitory function (Liew et al., 2019).



(a) (b) (c)

Figure 8. (a) Habitat 67 (Laovisutthichai et al., 2020), (b) Clement Canopy (Seng et al., 2021) and (c) NTU North Hill Residence Hall (Liew et al., 2019)

Looking at the recently constructed tall buildings shown in Figure 9, the 44-story Croydon Tower was built in the UK in 2020 (Corfar and Tsavdaridis, 2022). Built in Australia in 2019, the 60-floor Collins House is a technological building with 2D panels and 3D volumetric modules (Thai et al., 2020). The 32-floor B2 Tower was completed in the USA in 2016 (Pan et al., 2018). In 2015, the 57-floor J57 Mini Sky City Tower was completed in 19 days, and in 2010, the 15-floor Ark Hotel Building was completed in 15 days. The putting into service of these two structures in such a short time was possible with modular box systems (Eren, 2018). The 30-floor T30 Tower structure built in China in 2011 and the 25-floor Victoria Hall student dormitories built in 2009 in England are among the products of modular technology. In pursuit of this line are the 21-floor SOHO Apartments in Australia, the 21-floor Hilton Palacio Del Rio Hotel in Texas, the 19-floor Wembley BNCE Hotel in England, the 17-floor Paragon Development student residence in London, and the 13-floor Nanyang Technical University (NTU) North Hill Hostel student residence building in Singapore comes from (Pan et al., 2018).



(a) (b) (c)

Figure 9. (a) Croydon Tower, (b) Collins House (Corfar and Tsavdaridis, 2022) and (c) T30 Tower (Thai et al., 2020)

CONCLUSION

The main purpose of constructing modular high-rise buildings is to meet the housing need, which is one of the most basic problems of societies, both economically and in the shortest time. It is necessary to pay attention to certain elements to construct high-rise buildings in this system. When the points to be considered in modular systems are reviewed;

- It must be integrated into the core or frame load-bearings.
- Steel ropes with cross dampers should be used for earthquakes.
- Modules should be covered with suitable material for fire, heat and sound insulation.
- There should be spaces suitable for assembling inside the modules.
- Pins should be placed at the junction points to reduce the horizontal and vertical displacements.
- Modules with dimensions suitable for highways should be selected for easy transportation.
- It is necessary to use tower cranes suitable for the transport and assembly of the modules..

As a result, this study gives important information about the modular cell system, which is a construction system that can be constructed with various methods and allows flexible design in terms of rapid production of high-rise buildings, will become a preferred system for both users, designers and engineers in the last century.

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