Modular Construction: Design Considerations and Opportunities

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Abstract: The realization of Modular Construction (MC) is impeded by several barriers, e.g., initial investment, logistics constraints, and negative perception. Design, a profoundly creative process to alleviate difficulties in the built environment, is prospected to enhance this construction method. Under this circumstance, many guidelines, recommendations, and avoidances have been proposed to design. However, every coin has two sides. This research, therefore, argues that MC also provides new design opportunities, which have not been yet extensively investigated. It does so by comprehensive literature review and detailed archival study of successful case studies. The result unveils that although MC, by nature, may impose several design limitations, e.g., design simplification, standardization, and limited dimension, it can also serve demands and construct an outstanding architectural design by, for example, a composition of three-dimensional unit, mass customization, and product prototype. This research creates a balanced view of MC in a design process, and highlights the new approach for further design and research development in this discipline.

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1 Introduction

Modular Construction (MC) is an innovative construction method, basically comprising the room-sized free-standing integrated units manufacturing in a factory-like environment, logistics, and installation to form an architecture [1, 2]. These units are preassembled with finishes, fixtures, and fittings to minimize work in-situ [3]. If comparing this prefinished volumetric unit to the other prefabricated products, MC is classified a high level of prefabrication [4]. This construction method has been applied to many building types, especially in cellular-type building, including hotels, student dormitory, governmental building, and social housing [5].

MC is becoming more widely used, since it has offered numerous advantages to the industry. They include quality improvement [6], construction time reduction [5, 7], productivity enhancement [8], workforce safety [9], and waste minimization [5, 10]. In spite of these various benefits, MC also experiences criticism. The method implementation in the real-world cases is undermined by, for example, the significant investment on the production line establishment [11], and transportation regulations and constraints [12]. In addition, this modernized construction process and machinery need an experienced workforce and technician for operation [13]. These shifts in the procedures also require more attempts from stakeholders and alterations in construction practices [14]. Moreover, there is a somewhat stereotypical perception in the architecture, engineering, and construction (AEC) industry, or even the general public that architectural design is limited by the drawbacks of MC [15, 16].

Many efforts have already been made to support this innovative construction realization. Design, as an initiation process shaping the following activities [17], is currently prospected to be a new faith to alleviate MC difficulties. In such circumstance, organizations and researchers worldwide provide MC design requirements, recommendations, lessons, instructions, and practice examples for practitioners [18-20]. Nonetheless, everything has two sides. While design considerations and avoidances for MC have been extensively studied, the new design possibilities occurred from MC have not been widely debated in the previous research.

This paper, therefore, aims to explore both benefits and limitations of MC to an architectural design process. It is also expected to highlight new design opportunities, derived from MC, for the further design and research development. This is achieved by reviewing literature and revisiting successful case studies. The remainder of this paper consists of four sections. Section 2 provides the background information of MC and architectural design. It is followed by the research methods adopted. Section 4 displays the design considerations and prospects, distinguished in this study. Finally, it reaches the discussion and conclusion parts.

2 Literature Review

2.1 Modular Construction

Modular Construction (MC), sometimes called volumetric prefabricated construction, refers to a construction process of prefinished 3D unit assembly to be a part of or create the whole building [1, 2]. In general, MC consists of three main stages. It begins with manufacturing in a factory-like environment. This system borrows the concept of the production line, the industrial workstation, and repetitive duties, to reduce the amount of work in-situ [21]. Then, a wide range of such modules, from basic structure to fully furnished units, are transported to construction sites for assembly. Finally, all modules are installed, and structural, mechanical, electrical, and plumbing (MEP) systems are connected to form buildings [2]. The method current application includes student accommodations, hotels, hospitals, and governmental buildings [5].

Gibb [4] provides a taxonomy of such units: Level 0 A system uses zero forms of prefabricated units; Level 1 Component and sub-assembly (e.g., lintels); Level 2 Non-volumetric assembly such as 2D precast concrete wall panels or tie beams without usage space enclosed; Level 3 Volumetric assembly such as kitchen, bathroom, utility rooms with usable space enclosed; and Level 4 Modular building like a living unit with full usable space enclosed and some utilities installed. If sticking to the above definition, MC can be considered in Levels 3 or 4 in Gibbs' taxonomy, representing a higher level of sophistication in terms of production, transportation, and assembly.

The characteristics of MC offers numerous advantages to the industry. For example, product quality improvement is given by the factory-like environment in the production line

[6]. It makes a variety of actions in construction more repetitive, controllable, and reliable, and contributes to an accurate monitoring system and immediate inspection. Secondly, the settings of MC provide labourers with a safe working environment and reduce their risky behaviours. The number of accidents can be decreased by 80% if adopting MC [5, 9]. Its production line system also boosts the construction productivity by a process revitalization and efficient project schedule [8]. Furthermore, construction waste management gains several benefits from the natures of volumetric prefabrication. It is able to minimize waste from timber formwork, plastering, and smoothening process. By using MC, solid landfill waste can be decreased by 70% [5, 10]. Finally, as on-site and production line tasks can be done simultaneously, it is estimated that the use of 3D unit prefabrication can decrease construction time by 50% and saved 7% of the total project finance [5, 7]. For developers, the shortening of time means a considerable reduction in interest charges and early return of investment capital [22].

On the other hand, MC is also challenged by several drawbacks. Firstly, MC incurs an increase of total construction cost, including the significant initial investment required for the production line establishment and operational cost afterwards. Against the stereotypical view, MC is more expensive than traditional cast-in-situ construction [11]. Moreover, the use of machinery requires experienced technicians, labourers, and experts to handle the modernized processes [13]. In addition, logistics becomes a fundamental concern in MC. One must investigate transportation regulations, routes, and traffic before design, since the delivery limitations directly affect the size, weight, and dimensions of modules [12]. A paradigm shift in architectural design and construction professional practices is also required to implement MC. Due to its restrictions, early coordination among stakeholders, and additional project planning and design efforts are necessary to ensure the construction possibility, prevent the risks, and facilitate the flow of the operations [14]. Finally, MC is suffering from a poor image resulted from technical problems, poor workmanship, short material lifespan, and building performance limitations during the first age of MC [15]. Some stakeholders rejected the use of MC amid the anxieties of building aesthetics and the fear of monotony in an architectural form [16].

During the past few decades, researchers have introduced several means to mitigate these barriers, such as process supervision, computational technologies integration, construction knowledge sharing, and materials and joints durability improvement [16]. Recently, the trend has shifted the focus to design, as described in the following section.

2.2 Architectural Design

Design, in architecture, is generally a highly dynamic process, involving a number of explorations, examinations, discussions, and determinations, to resolve difficulties in the built environment [23, 24]. It handles with wide ranges of qualitative and quantitative requirements, e.g., regulations, building codes, functionality, buildability, feasibility, programs, sites, context, and human resources [25]. The Roman architect Vitruvius articulated that the process outcome, an architecture, should be of “durability”, “utility”, and “beauty”, if expressed in modern English [26]. Unlike painting or sculpture, this creative process’s outcome has a huge impact, since it shapes the following activities, namely manufacturing, logistics, construction, occupation, renovation, as well as demolition [17].

Due to the recognition of its significant, design is prospected to mitigate many difficulties and enhance MC. Many recommendations are generated to encourage this strategy. For instance, the Building and Construction Authority of Singapore (BCA) publishes Prefabricated Prefinished Volumetric Construction (PPVC) guidebook to provide fundamentals, requirements, and practical tips on how to design MC [18]. This report introduces many design concerns, e.g., transportation constraints, module configuration, machinery performance, and joints. The American Institute of Architects (AIA) supports design for MC by giving practice examples and lessons discovered from the previous cases [19]. In addition, the book, “Design in Modular Construction”, reviews the generic types of modular construction, displays the application examples, and offers background information for design [20]. Furthermore, previous research encourages an integrated design process and early collaboration for effective design decision making [27]. Another study also highlights the demand for MC design guidelines further development [28].

While many efforts have already been done to corroborate design suggestions and avoidances, the new design opportunities, emerged from MC, have not been extensively explored in the previous literature. Until now, there are many notable modular architectures and successful case studies to be investigated. The new design prospects learned from these cases are expected to be beneficial for designers, and finally, increase the MC adoption.

3 Research Methods

This research adopted a 3-step method to investigate both design constraints and opportunities, emerged from MC, as shown in Figure 1. It started from a literature review of MC definitions, advantages, and drawbacks, to understand its characteristics and current circumstance. The process and significance of architectural design are also clarified in this step. Then, the second step intended to explore design guidance, suggestions, limitations, as well as new options, arisen from MC. This was achieved by a comprehensive literature review related to architectural design and MC. At this stage, the archives of notable modular architectures, e.g., records from designers, research papers, and drawings, are also revisited. By using these methods, it is able to examine a complex dynamic of architectural design and construction projects from a real-life context, provide an explanation, and identify the causality [29]. Finally, this research analyzed the collected data, and highlighted both design restrictions and possibilities, derived from MC.

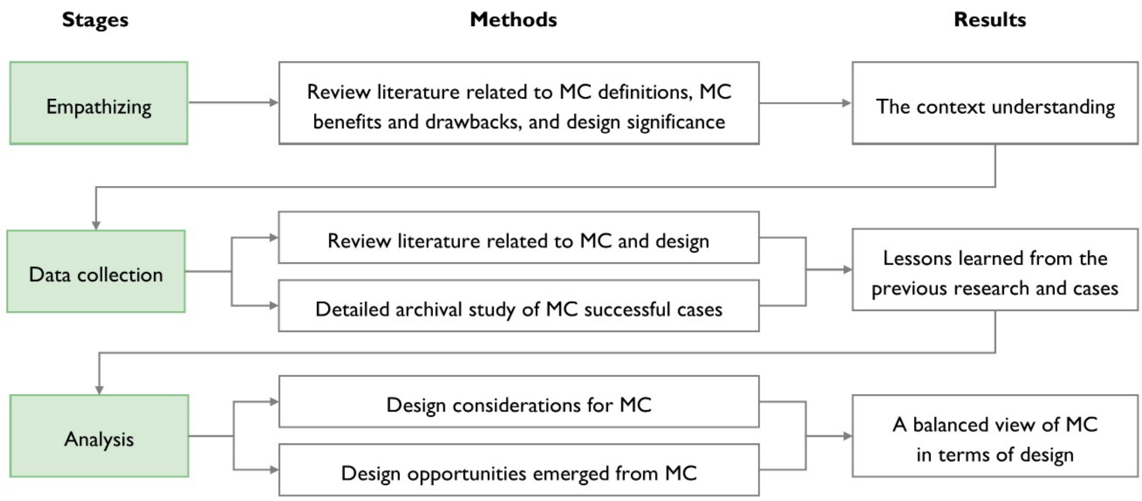

Figure 1 Research Methods

In this paper, Nakagin Capsule Tower (NCT) and Habitat 67 were selected to be the case studies. NCT, designed by Kisho Kurokawa, was studied, as it is the first successful high-rise modular architecture for actual use in Japan in the early 1970s (see Figure 2) [30]. Located at the centre of Tokyo, NCT is a residential building, which consists of two core structures and 140 fully furnished capsules. Described by the architect, NCT aims to create an architecture in anticipation of a new age, achieve full mass production for living modules, and promote industrialization technology in the industry [31]. Praised in the New York Times, the tower is one of the notable magnificent architectures [32]. It has been recorded an architectural heritage by Documentation and Conservation of Buildings, Sites, and Neighbourhoods of the

Modern Movement (DoCoMoMo) organization since 2006 [30].

Figure 2 Nakagin Capsule Tower (NCT) [33]

Habitat 67, designed by Moshe Safdie, is a prototype project for fully mass-produced construction system in Montreal, Canada (see Figure 3) [34]. As the Canadian Pavilion for the World Exposition in 1967, this experiment intends to indicate the construction industry shortcomings and pave the way towards the new direction. Composed of 354 precast concrete modules for 158 living units, the building offered high-quality housing with a variety of spaces for dwellers [35]. It was also able to avoid monotony form in the dense urban environment. This case is currently recognized as iconic architecture, influencing the architectural design throughout the past few decades [36].

Figure 3 Habitat 67 [37]

4 Results

4.1 Design Considerations

After a comprehensive review of previous literature and case studies, several concerns should be pondered during design to encourage MC efficiency, as described below.

Collaboration: Collaboration means a professional practice, which involves stakeholders to work together from the project initiation until the construction completion. It is recommended, since the architectural design for the modular building requires various information from different stakeholders for a precise determination [27]. Both research and practice agree that this approach can improve MC efficiency, prevent redesign and rework, ensure the project constructability, as well as minimize waste generated during construction [38-40]. The early collaboration also provides designers with a clear idea of MC and maximize flexibility in design options [19]. In NCT, designers collaborated with consultants, manufacturer, and main contractor during design to ensure the manufacturability, transportability, and feasibility of the project [31].

Design standardization: This suggestion refers to the repetitive use of industrial components or modules in design [38]. Based on the characteristics of a manufacturing line, MC requires a larger number of repetition in design for construction feasibility [34]. In NCT, It was adopted to ensure the capsule manufacturability in the container factory and enable mass production in construction [40]. The architect of Habitat 67 also realized this issue and applied the repetition of single standardized three-dimensional precast modules to the design. However, the architecture could still provide 15 different house types by combining one, two, or three modules together [34].

***Design simplification**:* It is generally a design method, which aims to reduce a complex design to basic forms or elements. In the mass production system, the complexity of form means additional tasks, efforts, and costs. In both cases, although several choices of interior design and finishing were offered, all capsule’s structure and exterior were kept to be as simple as possible to support the production flow [31, 34-35].

Logistics constraints: Unlike the traditional in-situ construction, MC requires the transportation of a large module from a manufacturing line to a construction site. Transportation-related concerns should be pondered carefully from the project initiation [19]. They may vary, depending on a project condition, transportation route, as well as production location, which can be on-site, off-site, or even off-shore [41]. The case of NCT provided a practice example related to module logistics. According to the architects, the factory and construction locations, transportation route, legal restrictions, stopover point, on-site storage, and delivery schedule, were studied from the project initiation. The module's design, shape, weight, and dimensions, followed these restrictions to ensure the module transportability [31, 42].

Connection: Apart from logistics, a joint or connection between modules is another critical element in MC. While developing a design proposal, the design team is recommended to consider the joint's manufacturing, structural system, thermal performance, water penetration rate, fire resistance, as well as aesthetics. Collaboration is also suggested to assist in this detailed design [19-20].

4.2 Design Opportunities

Although the concerns above could be regarded as the agents of design restrictions and shifts in architectural design practice, MC also offered new design potentials. This is realized by detailed archival studies of previous cases, as follows.

A composition of three-dimensional units: Unlike the focus on the composition of planar elements in conventional construction, MC allows designers to form an architecture by locating standardized volumetric modules together to create various architectural forms and combinations [20]. The way to arrange these modules during design resembles the action of installing prefabricated components together in construction. This is ratified by both cases. In NCT, the architect recognized this opportunity, and introduced "a sum of parts" to make a distinctive architectural form by the composition of the manufactured living cells [31, 38]. While, the form of Habitat 67 was clustered from the grouping of elements [34]. This innovative design technique, together with MC, was able to meet demands and avoid monotony architectural form, while the capsule's price was still reasonable [31, 34].

Mass customization: Mass customization refers to "the ability to provide individually designed products and services to every customer through high process flexibility and integration" [43]. It is utilized as both manufacturing and business competitive strategies. In construction, MC, together with this concept, can serve a variety of space required and enable variations in design. In NCT, it provided eight options of interior design [44]. It allowed users to express themselves by selecting or altering several standardized parts like a vehicle, e.g., interior finishing materials, colour, and alternative equipment [31]. This strategy can be adopted to design outstanding architecture and increase client satisfaction.

Product prototyping: One of the advantages of MC is an exemplary product model from original materials and structure. The capsule prototype can also be considered as a reliable method to demonstrate the design ideas and engineering system to buyers. In the case of NCT, the actual capsule was placed on the ground in front of the sales office to make clients have more explicit ideas about the product before purchasing [31].

Product mobility: Architects have proposed many ideas about architecture as a living organism, which needs to be grown, renovated, and renewed during the building life cycle. MC moves this rhetoric closer to reality by producing mobile modules, which can be transported, attached, detached, and relocated. In NCT, the capsules were attached to the main structure by high-tension bolts, allowing the module detachment or replacement without affecting others. This responded to the architect's belief that architecture can metabolize [45].

5 Discussion and Conclusion

5.1 Discussion

Grounded on the comprehensive literature review and successful case studies revisit, the above section substantiates that MC, by its nature, may establish several additional criteria to architectural design, i.e., collaboration, standardization, simplification, logistics constraints, and connection. However, it also enables several design techniques, i.e., a composition of three-dimensional units, mass customization, product prototyping, and product mobility.

This research creates a balanced view between design limitations and possibilities, when adopting MC. Both of them can be utilized as a guide for design proposal development. It also initiates the discourse about the new design possibilities emerged from MC, which have not been extensively debated. In addition, the outputs from this study support the ongoing development of Design for Manufacturing and Construction (DfMA) in construction. The recent study raises a critical issue that currently, many DfMA suggestions in construction emerges from manufacturing industry background without considering the differences between two industries [46]. The key terms and explanations, identified from the construction cases in this study, can be regarded as a part to support construction-oriented DfMA principles.

On the other hands, this research also has its constraints. First, it is structured based on the literature review and detailed archival study. More investigations from real-life practice and feedback from implementation are necessary. Moreover, this is merely a preliminary study of design considerations and opportunities emerged from MC. The application may include, but not limited to, these design directions. Future research is recommended to focus on both sides to expand the knowledge in this discipline.

5.2 Conclusion

Although Modular Construction (MC) has brought various benefits to the construction sector, it still experiences several barriers. From the project initiation point, design is prospected to mitigate difficulties hindering MC implementation. To support this promising strategy, a plethora of design principles, guidelines, and avoidance are generated; on the contrary, the new design possibilities acquired from MC have not yet been expanded. This research, therefore, reviews previous literature and revisits successful case studies to explore both sides. Eventually, five design considerations and fours opportunities are identified. The outcome corroborates that MC, liked every construction method, may impose several additional concerns to design, but also provides new design prospects.

This research illustrates a balanced view of MC in an architectural design process, and paves the new way for future research development to concentrate on the new design possibilities, occurred from MC. Both identified limitations and opportunities can be utilized to achieve a higher level of stakeholders' satisfaction. The findings also support the current application of DfMA concept in construction. However, the design directions, identified in this study, are merely examples of thousands. More studies and real-life case studies are demanded to develop this sector further.

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