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Constraints Hindering the Development of High-Rise Modular Buildings

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Abstract: Off-site construction has been increasingly employed due to its advantages, for instance, improved quality control, reduced skills labour, faster construction time, decreased material wastage and safe working environment. As the most cutting-edge off-site construction, modular buildings have been utilised for residential building, student accommodation, and hotel projects. However, because of existing and underlying constraints, the adoption of modular buildings is still relatively low. To reveal factors hindering the development of high-rise modular buildings, a comprehensive literature review, coupled with a focus group study, were conducted. A questionnaire survey inquiring about all stakeholders was implemented to quantify constraints. The results were further examined according to a real-life case study. This paper manifested that "Lack of coordination and communication among stakeholders", "Higher cost", "Lack of government support", "Lack of experience and expertise", "Lack of building codes and standards", "Poor supply chain integration", and "Complexity of connection" are the top barriers curbing the uptake of modular buildings. The findings should provide a valuable reference for stakeholders adopting modular buildings, whilst mitigating risks amid modular construction. Future research is expected to exploit building information modelling and design for manufacture and assembly to alleviate these existing constraints and promote the performance of modular construction as well.

Keywords: modular buildings; high-rise; building information modelling; design for manufacture and assembly

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1. Introduction

To bridge the gap between the capacity of housing supply and the explosion of housing demand in connection to rapid urbanisation, the construction industry has been seeking innovative materials and technologies that can provide more high-quality housing using less construction time. Within this context, off-site construction has been acknowledged worldwide to play a key role in providing housing with enhanced quality, productivity, safety and efficiency [1–3]. With the development of industrialisation, off-site construction has been embraced by the construction industry in an array of countries and regions, involving the United Kingdom, the United States, Japan, Sweden, Germany, Australia, Singapore, Malaysia, mainland China, and Hong Kong [4–9].

Following the level of prefabrication adoption, Gibb [10] divided off-site construction into four categories, in terms of “Component manufacture and sub-assembly”, “Non-volumetric pre-assembly”, “Volumetric pre-assembly” and “Modular Building”. Along with the increasing degree of completeness, more components of the construction are produced in a factory, forming non-volumetric and volumetric (three-dimensional) modules. Peaking the highest level of prefabrication, modular buildings are identified as a state-of-the-art technology reshaping the construction industry [11]. Modular buildings endeavour to produce maximum prefabricated modules in off-site manufacturing factories, whilst minimising on-site construction activities. Volumetric pre-assembly modules have been installed with finished floors, walls, ceilings, cabinets as well as mechanical, electrical and plumbing (MEP) services, in advance of transporting from domestic or overseas factories to the construction site where the modules are assembled [12,13].

In recent decades, modular buildings have been implemented in both public and private sectors, providing an eligible solution for buildings composed of repetitive units, for instance, residential buildings, hotels, student accommodations and hospital wards [14–18]. Previous works and projects demonstrated the strengths of modular buildings involving reduced construction time, diminished materials waste, improved quality, decreased labour demand and safe work environment [5,19–23]. Considering the great underlying potential of modular buildings, the industry coupled with academics and endeavoured to propose varied solutions involving building information modelling (BIM), and design for manufacture and assembly (DfMA) facilitating the application of modular buildings [24–29]. However, in comparison to conventional buildings, the application of modular buildings is still relatively low, especially for high-rise buildings. For instance, off-site construction in Australia accounts for merely 3 percent of the total construction industry’s output, of which most adoptions are precast components and panelised walls [9]. The most uptake of modular construction is modular houses and low-rise buildings, by contrast, high-rise modular buildings are emerging with the slow pace of development [11].

This paper aims to identify the constraints of high-rise modular buildings to promote its application as well as exploiting the potential market. A comprehensive literature review is firstly conducted to list preliminary constraints. Following that, a focus group study is carried out to extract crucial factors forming questionnaires for all stakeholders of modular construction. Based on the responses of the questionnaires, constraints of high-rise modular buildings are further analysed and discussed in association with an empirical case study. This research will contribute to getting the whole picture of modular construction and propose valuable solutions to the dominant constraints.

2. Research Methods

This work follows a four-step research process including multiple research methods, as shown in Figure 1: (1) identifying factors to create a preliminary list of constraints that hamper the development of high-rise modular buildings using a literature review, (2) refining factors of the preliminary list to achieve the final list of constraints through a focus group study, (3) analysing the result of the questionnaire survey to determine domain constraints in modular construction, (4) discussing the constraints with experts based on a real-life case study to seek solutions to the development of modular buildings.

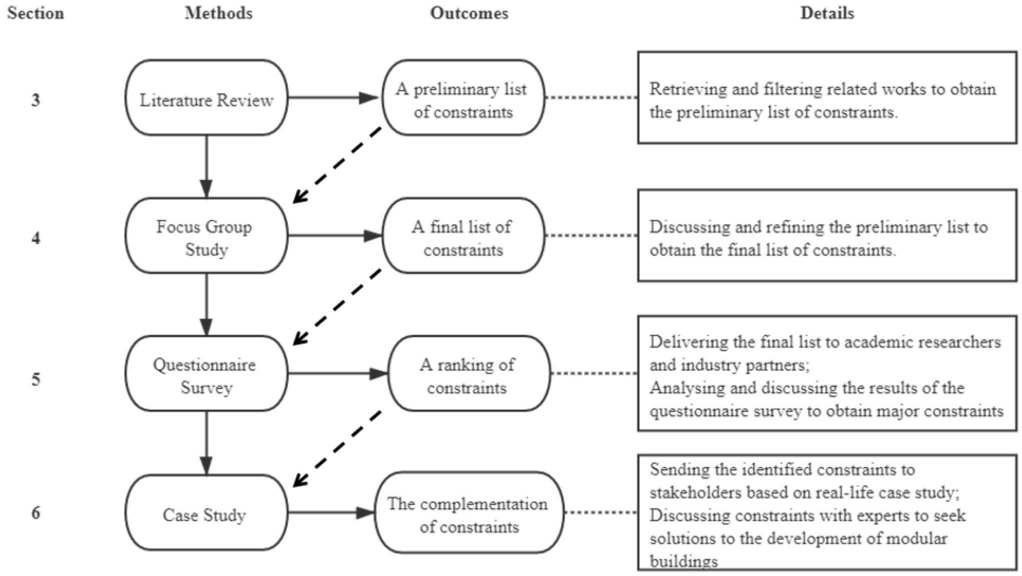

Figure 1. Research design flow.

3. Literature Review

3.1. Data Collection

To formulate the preliminary list of constraints, a literature review was carried out systematically involved two steps: (1) retrieving previous works from the academic database following pre-defined keywords; (2) filtering selected articles in accordance with constraints hindering the application of modular buildings.

First, using a pre-defined keyword searching approach, previous works were retrieved from two academic databases of Scopus and Web of Science focusing on "Article title, Abstract, Keywords and Topic" to obtain a comprehensive literature review. Keywords deployed in this searching were composed of ("constraint" OR "barrier" OR "risk" OR "challenge" OR "issue") AND ("modular building" OR "modular construction" OR "industrial* building" OR "prefabricated building" OR "prefabricated construction" OR "prefabrication" OR "modularisation" OR "modularization"). As a result, there were 1412 and 489 articles retrieved from Scopus and Web of Science, respectively. The preliminary research results were filtered in the next step over two rounds to screen out articles related to the topic addressing constraints of modular buildings. The first-round filtering was administered concentrating on the "Title", "Abstract" and "Keywords" of papers. Based on the results of first-round filtering, selected papers were reviewed by reading the whole paper to identify corresponding constraints, which impede the development of modular buildings. At last, 89 articles were selected and managed by EndNote.

3.2. Related Works

According to related works, the uptake of modular buildings is still relatively low in construction industry. Clients remain reluctant to boost their investment in modular buildings as a result of insufficient experience and expertise [30,31]. The construction market and society have pervaded a sense of unacceptance of modular buildings, because of few renowned projects and perceived underestimation of "prefabrication" [32]. Moreover, economic performance is an important benchmark for evaluating modular buildings from the perspective of clients whose opinion is decisive in determining the construction method. Zhai et al. [33] indicated that perceived higher capital cost is a severe drawback in modular construction. Investigating multiple case studies, Mao et al. [34] exposed that the capital cost of modular construction comprised design cost and construction cost soars over 25 per cent compared to conventional construction. In addition, Jiang, et al. [35]

and Gan, et al. [36] suggested that the lack of government's policy support including incentives and guidance curb the spread of modular construction. Regarding the design of high-rise modular buildings, the scarcity of relevant codes and standards is a vital obstacle in the path to the extensive utilisation, although few guidelines related to modular construction have been established recently [13,37–39]. Modular building design, not as mature as traditional building design, has difficulty in the paucity of designers with plentiful experience and knowledge [6,40]. To guarantee error-free drawings delivered to manufacturers, designers have to devote excessive time in modular design resulting in a long lead-in time for the adoption of modular buildings [41]. Furthermore, modular buildings presenting high-level modularisation and standardisation, notwithstanding, are disputed for underdeveloped design flexibility [42,43]. In addition, the capacity of suppliers and manufacturers cannot keep pace with demand from growing utilisation of modular construction. It is identified by Blismas and Wakefield [40] that domestic supply-chain of prefabrication cannot satisfy the progress of modular buildings. Developers and designers are reluctant to adopt modular buildings due to the incompetence of suppliers and manufacturers. Moreover, considering the market size of modular construction, prefabrication manufacturing barely achieves economies of scale to advance its development [44]. Despite reduced labour in the construction site, modular construction needs a vast amount of skilled labour for manufacturing prefabricated modules, which increases the construction cost [45]. On the other hand, transportation is an indispensable part of modular construction in order to deliver modules from factories to construction sites, which accounts for approximately 10 per cent of overall costs [19,46]. Lu and Yuan [47] indicated that transportation cost can increase to over 18 per cent of the total cost, taking into account the long-distance transport due to offshore manufacture. Apart from that, weight and dimensions of modules is another constraint, which not only restricts the transportation route but also elevates the expenditure resulting from the specific requirement for vehicles [48,49]. Regardless of which methods of transport are utilised, cargo, rail or road, the damage to modules during the transit is not to be neglected. Transportation teams who supply transportation services should spend considerable time and money on extra protection to avoid severe damage to modules, which may be the trigger for construction delay [50]. In the process of on-site assembly, a substantial amount of equipment, especially cranes, are supportive of installing prefabricated modules, which gives rise to the increment of the overall cost [8,34]. Contractors should pick up competent mobile cranes or fixed cranes based on the crane capacity of radius, load and height. Moreover, Salama, et al. [51] revealed that numerous complex connections of modular buildings are a critical issue during the installation of modules. Due to the paucity of corresponding inspection criteria, contractors have to spend a large amount of time on connection installation to diminish underlying quality issues such as water leakage [45].

Given the above-mentioned previous research, Table 1 manifests the preliminary list of constraints hampering the development of modular buildings. Although previous works disclose a variety of constraints amid modular construction, these works concentrated on qualitative descriptions of the constraints but lacked quantitative and in-depth investigation that could unveil the roots and the interrelation of these constraints. Meanwhile, few previous studies contacted the frontline of the construction sites and module's factories where they could obtain a realistic portrayal of the status of modular buildings. It is worth noting that there were few studies scrutinising constraints of high-rise modular buildings, though the tremendous potential of high-rise modular buildings has been acknowledged. Therefore, a comprehensive study of high-rise modular buildings in association with real-life practices is important.

Table 1. The preliminary list of constraints hindering the development of modular buildings.

Code	Constraints	Key Reference
C1	Lack of experience and expertise	[36,52–55]
C2	Lack of government support	[33,35,36,38]
C3	Poor market and society acceptance	[32,55,56]
C4	Higher capital cost	[8,20,34,43,46]
C5	Higher construction cost	[37,46,57]
C6	Additional transportation cost	[8,47]
C7	Additional crane cost	[8,58]
C8	Lack of R&D and resource support	[59,60]
C9	Lack of coordination and communication among stakeholders	[30,54,55,61–63]
C10	Lack of building codes and standards	[32,33,38,43,44]
C11	Unable to freeze design early	[41,42,63,64]
C12	Poor design flexibility	[42,62]
C13	Complexity of design on seismic performance	[17,65]
C14	Complexity of design on fire-resistant performance	[66,67]
C15	Incompetence of suppliers and manufacturers	[36,40,68]
C16	Unable to achieve economies of scale	[32,44]
C17	Lack of skilled labour	[8,33,43,45]
C18	Limitation of weight and dimensions	[31,48,61]
C19	Damage to modules during transportation	[50,55,62]
C20	Limitation of transport routes	[55,63]
C21	Limitation of cranes to lift modules	[34,51]
C22	Complexity of connection	[32,51,69]
C23	Demand for on-site modules storage	[33,55]
C24	Lack of quality inspection standard	[31,38,62]

4. Focus Group Study

After exploiting a comprehensive literature review, a preliminary list of constraints in modular construction was established. It was then followed by a focus group study to refine critical constraints. According to Morgan [70] and Rabiee [71], a focus group study is an efficient method to observe a large amount of interaction and add related data to a topic in a limited period. In this study, a face-to-face focus group study recruited 12 experts, including two from the academy, three developers, two designers, two manufacturers, two contractors and one transporter. All of these interviewees had practical experience and relative research surrounding modular construction for at least five years (Table 2). The overall process of the interview was recorded by the author. The audio record was transcribed as well as analysed utilising NVivo systematic coding and data retrieval.

Table 2. Information on experts for focus group study.

Role	Job Title	Years of Experience
Academic Researchers	Professor	8
	Senior Lecturer	6
Developers	Design Manager	5
	Business Manager	10
	Operations Manager	6
Designers	Senior Architect	8
	Architect	5
Manufacturers	Design Manager	7
	Operations Manager	6
Contractors	Project Manager	8
	Site Manager	12
Transporters	General Manager	8

The 24 constraints were reviewed and discussed by 12 interviewees, who endorsed that these constraints can portray general issues in modular construction. Combining with practical experience, experts pointed out some critical constraints that emerge in multiple phases throughout modular construction, such as lack of coordination and communication, which hamper the widespread application of modular buildings and should be addressed urgently. Aside from 24 constraints, experts supplemented three factors, namely poor supply chain integration, weather disruptions and lack of relevant application and technical support. Comparing with traditional construction, modular construction highly depends on the reliability and sustainability of supply chain comprising procurement, design, manufacture, transportation, and assembly. However, the integration of the supply chain is limited by existing economic scale and market size of modular buildings, which leads to an array of issues, such as delivery delay of prefabricated modules, and reworking of manufactured components [72]. Additionally, interviewees achieved consensus that the development of modular buildings is subject to the relevant application and technical support. To address this, experts shared experience of utilising building information modelling (BIM) in modular construction as well as discussing the potential of applying more advanced technology. Under the circumstances, the final list of constraints hampering the development of modular buildings was summarised, which was the core content of the subsequent questionnaire survey (Table 3).

Table 3. The final list of constraints hindering the development of modular buildings.

Code	Constraints
C1	Lack of experience and expertise
C2	Lack of government support
C3	Poor market and society acceptance
C4	Higher capital cost
C5	Higher construction cost
C6	Additional transportation cost
C7	Additional crane cost
C8	Lack of R&D and resource support
C9	Lack of coordination and communication among stakeholders
C10	Lack of building codes and standards
C11	Unable to freeze design early
C12	Poor design flexibility
C13	Complexity of design on seismic performance
C14	Complexity of design on fire-resistant performance
C15	Incompetence of suppliers and manufacturers
C16	Unable to achieve economies of scale
C17	Lack of skilled labour
C18	Limitation of weight and dimensions
C19	Damage to modules during transportation
C20	Limitation of transport routes
C21	Limitation of cranes to lift modules
C22	Complexity of connection
C23	Demand for on-site modules storage
C24	Lack of quality inspection standard
C25	Poor supply chain integration
C26	Weather disruptions
C27	Lack of relevant application and technical support

5. Questionnaire Survey

5.1. Data Collection

A questionnaire survey is considered to be a preferred approach to collect data about general opinions aiming at a series of questions under one topic [73]. In this research, a questionnaire survey composed of two sections was administrated. The first section of the questionnaire was to collect the respondents' basic information involving occupation type and experiences in modular construction. Section two was to inquire about the aforementioned 27 factors related to constraints hindering the implementation of high-rise modular buildings. Respondents were requested to use a five-point Likert scale from five ("strongly agree") to one ("strongly disagree") to evaluate every single factor.

The initial respondents were mainly from the Australian Research Council (ARC) Training Centre for Advanced Manufacturing of Prefabricated Housing, a highly collaborative research institute involving four universities and 12 industry partners, aiming at promoting productivity and quality of modular buildings, whilst unlocking the underlying market of modular construction [74]. In order to expand the sample size, this study utilised a snowball sampling method, which was proven as an efficient approach to increase the number of respondents of questionnaire surveys towards architecture, engineering and construction (AEC) industry [37,75]. Within this research, the initial respondents shared the questionnaire to their colleagues and others who have adequate experience in modular construction. As a result, 140 questionnaires were issued via email as well as an online survey platform SurveyMonkey. Ultimately, 72 questionnaires were received and identified as valid responses at a response rate of 51.4%. Specifically, 34.7% of respondents worked in universities, and mainly were professors, lecturers, and research fellows. The others worked for relevant stakeholders of modular construction. Around 33% of the respondents had more than five years of experience in modular buildings, and over 72% had at least three years of experience in this field. Table 4 indicates the profile of respondents in the questionnaire survey.

Table 4. Information of respondents.

Role of Respondents in Modular Construction		
Roles	Number of Cases	Frequency (%)
Academic researchers	25	34.72
Government officials	4	5.56
Developers	10	13.89
Designers	9	12.50
Contractors	9	12.50
Manufacturers	6	8.33
Suppliers	4	5.56
Transporters	3	4.17
Unknown	2	2.78
Experience of Respondents in Modular Construction		
Years	Number of Cases	Frequency (%)
<3	18	25.00
3~5	28	38.89
5~10	17	23.61
>10	7	9.72
Unknown	2	2.78

The coefficient of Cronbach's alpha was implemented to estimate the reliability of the questionnaire survey by inspecting the internal consistency of 27 factors. Based on Cronbach's alpha test, the outcomes are reliable when the value is higher than 0.7 [76]. Leveraging IBM SPSS 26.0, the value of this survey was 0.821. As a result, the collected data from this questionnaire survey was satisfactory for further analysis.

5.2. Data Analysis and Discussion

Table 5 indicates the ranking of 27 constraints of modular construction conforming to mean values as well as standard deviation. In order to identify the importance of these constraints, the ranking of the survey is divided into three groups, higher rate group, middle rate group, and lower rate group. The top nine constraints from the higher rate group are discussed below.

Table 5. Ranking of constraints hindering modular buildings.

Code	Mean	Standard Deviation	Ranking
C9	3.569	1.076	1
C4	3.558	1.052	2
C2	3.483	1.324	3
C1	3.471	0.976	4
C10	3.466	1.061	5
C25	3.459	1.250	6
C6	3.451	1.248	7
C22	3.442	1.060	8
C5	3.434	1.342	9
C11	3.428	0.987	10
C16	3.414	1.117	11
C15	3.403	1.184	12
C17	3.382	1.012	13
C27	3.367	0.994	14
C12	3.343	1.049	15
C3	3.324	1.063	16
C7	3.309	1.044	17
C24	3.285	1.031	18
C19	3.274	1.106	19
C26	3.266	0.983	20
C14	3.197	0.994	21
C23	3.144	0.979	22
C18	3.125	0.936	23
C20	3.114	1.142	24
C13	3.097	1.028	25
C8	3.075	0.966	26
C21	3.028	1.151	27

5.2.1. Lack of Coordination and Communication among Stakeholders

“Lack of coordination and communication among stakeholders” is ranked as the most critical constraint of modular buildings. Compared to conventional construction, modular construction is a closely collaborative process, which is relatively dependent on sufficient coordination and communication throughout the entire life cycle including planning, design, manufacture, transportation and assembly, aiming at reducing the construction period while improving the performance of building. However, considering the fragmented stakeholders, modular construction confronts various challenges due to a lack of information sharing [72]. For instance, due to the lack of communication between the transportation team and assembly contractor, excess modules are delivered to construction sites resulting in spatial shortage and traffic jam. On the contrary, inadequate delivered modules can delay the assembly progress as well.

5.2.2. Higher Cost (High Capital Cost, High Construction Cost, and Additional Transportation Cost)

Secondly, “higher capital cost” is another significant obstacle to expanding the market of modular buildings. It is worth noting that “high construction cost” and “additional transportation cost” are taken into account as other two significant constraints related to “higher cost”, ranking at the first half of 27 factors. Some previous works have demonstrated that modular construction is a cost-saving method concerning the entire life cycle of buildings [77]. The initial investment in equipment and land for the production of modules has a direct bearing on soaring capital cost. In addition to the cost of fixed assets, additional transportation cost including shipping and road transport contributes to approximately 20% of the total cost [47]. Numerous investigations manifested that, aligned with the increasing degree of prefabrication, the cost of modular buildings is higher than that of conventional buildings, due to the existing immature market and industry of modular construction [46]. Therefore, taking into consideration the existing profitable traditional construction method, the perceived higher cost becomes another significant constraint hampering application of modular buildings.

5.2.3. Lack of Government Support

After that, “lack of policy support” is ranked as the third critical constraint. To stimulate widespread adoption of modular construction, governments have issued some economic incentives comprising fiscal subsidies, tax break, and preferable loans. However, these incentive policies cannot overcome the perceived risk of higher cost. In contrast to incentive policies, mandatory policies can effectively attract more stakeholders into modular construction. In order to promote the development of prefabricated prefinished volumetric construction (PPVC), Singapore’s government stipulated that the uptake of PPVC for new residential projects shall occupy over 65 per cent of the gross floor area in specific land parcels [45]. Given the tension of land supply, Singapore’s authority established a specific policy system that facilitates modular buildings obtaining a competitive advantage over traditional construction. Nevertheless, there are barely any mature and systemic policies supporting and encouraging the application of modular buildings around the world.

5.2.4. Lack of Experience and Expertise

Lack of experience and expertise has been a vital challenge throughout the entire life cycle of modular construction, especially for high-rise modular buildings. To achieve the technical revolution of the construction industry, implementing modular buildings cannot be divorced from experts and skilled labour with abundant experience and knowledge of modular construction. However, similar to other state-of-the-art technologies, prior to more completion of modular buildings and providing comprehensive training for labour, the undeveloped construction method is unable to reach its full potential, in terms of improved quality, reduced construction time, decreased material waste, and enhanced sustainability. Concerning the current circumstances, limited experts and skilled labours have an adverse effect on the development of modular construction [54].

5.2.5. Lack of Building Codes and Standards

Building codes and standards are the cornerstones that specify corresponding requirements involving structure, architecture, services, durability, safety, and sustainability, for design and construction of conventional buildings as well as modular buildings. Consideration should be given to the distinctive structure and process of modular buildings while the majority of traditional building codes and standards are not pertinent to modular construction. Meanwhile, establishing a series of codes and standards for an innovative construction method requires the accumulation of tests and practices. However, high-rise modular building is a contemporary technology, which has inadequate pilot buildings as benchmarks to accomplish specific specifications, especially in terms of loading transfer, dynamic impact, seismic and fire performances. Adding to “lack of relevant application and technical support”, designers coupled with contractors have to spend a vast amount of time in modular building design and inspection, which results in “unable to freeze design early” as well as the obstacle of quality control, escalating the total time and cost of modular construction.

5.2.6. Poor Supply Chain Integration

The segments of the supply chain in modular construction are comparable with that of conventional construction including tendering, planning, design, procurement, manufacturing, transportation, and assembly (construction). Attributed to the modularisation nature, the supply chain of modular buildings is more complex. Different from conventional construction methods that utilise raw materials and components to construct buildings at construction sites, the innovative technology creates opportunities for synchronously implementing manufacturing and assembly to reduce the construction period that requires a well-integrated supply chain as well as delicate supply chain management. However, given the undeveloped modular construction industry, fragmented participants of the supply chain, in terms of developer, designer, manufacturer, transporter, and contractor, lacks sufficient coordination and communication and are unable to achieve a unified value system, evaluation system, and goal to integrate and optimise the supply chain, which leads to supply chain disturbances amidst modular construction increasing construction cost and time as well [78].

5.2.7. Complexity of Connection

Due to the modular nature of modular buildings, massive connections for structure and MEP services between modules are required, while the "complexity of connection" remains a key issue. The vertical connections and horizontal connections of structure, enhancing stiffness and transferring load are vital for structural behaviour, especially for high-rise modular buildings. On the other hand, an array of connections of MEP services are employed for integrating each system between modules, considering the integrity and performance of the systems. Within this context, eliminating redundant connections and enhancing the reliability of connections plays a key role in the design stage that serve to produce prefabricated modules with accurate connection systems, whilst preventing a fall from a height during the connection installation.

6. Case Study

A case study is an appropriate approach for providing supplementary information for across-the-board research in the construction industry. Meanwhile, in-depth interviews embedded with case studies are acknowledged as an efficient method to investigate the prevailing circumstances through real-life construction projects [73]. Consequently, for the sake of explorative and explanatory research, a case study combined with an in-depth interview was utilised in this research.

To investigate hindrances amidst the entire life cycle of modular construction, 27 identified constraints were classified into five clusters in accordance with five stages of modular construction, namely, planning stage, design stage, manufacture stage, transportation stage, and assembly stage (Table 6). It is worth noting that some constraints, such as C1 "Lack of experience and expertise" and C9 "Lack of coordination and communication among stakeholders" were displayed in each stage since these constraints are common issues existing throughout the whole life cycle.

Table 6. Critical constraints in five stages.

Code	Constraints
Planning Stage	
C1	Lack of experience and expertise
C2	Lack of government support
C3	Poor market and society acceptance
C4	Higher capital cost
C5	Higher construction cost
C8	Lack of R&D and resource support
C9	Lack of coordination and communication among stakeholders
Design Stage	
C1	Lack of experience and expertise
C9	Lack of coordination and communication among stakeholders
C10	Lack of building codes and standards
C11	Unable to freeze design early
C12	Poor design flexibility
C13	Complexity of design on seismic performance
C14	Complexity of design on fire resistant performance
C27	Lack of relevant application and technical support

Table 6. *Cont.*

Code	Constraints
	Manufacture Stage
C1	Lack of experience and expertise
C9	Lack of coordination and communication among stakeholders
C15	Incompetence of suppliers and manufacturers
C16	Unable to achieve economies of scale
C17	Lack of skilled labour
C25	Poor supply chain integration
	Transportation Stage
C1	Lack of experience and expertise
C6	Additional transportation cost
C9	Lack of coordination and communication among stakeholders
C18	Limitation of weight and dimensions
C19	Damage to modules during transportation
C20	Limitation of transport routes
	Assembly Stage
C1	Lack of experience and expertise
C7	Additional crane cost
C9	Lack of coordination and communication among stakeholders
C17	Lack of skilled labour
C21	Limitation of cranes to lift modules
C22	Complexity of connection
C23	Demand for on-site modules storage
C24	Lack of quality inspection standard
C26	Weather disruptions

The classified constraints were then sent to corresponding stakeholders, in terms of developer, designer, manufacture, transporter, and contractor, through three real-life high-rise modular building projects. The respondents were requested to pick out the constraints that emerged in the modular building project. In this study, an 18-storey modular building was selected to conduct the case study, which was conducted in conjunction with in-depth interviews with experts from diverse positions discussing the constraints in each stage (Table 7). Thanks to the cohesive cooperation with industrial partners of the ARC training centre, the investigation was not confined to construction sites, surveys were executed at a developer office, manufacture workshop and design consultant office as well. The case study scrutinises identified constraints while providing a holistic understanding of and potential solutions to high-rise modular buildings.

Table 7. Survey of high-rise modular building project.

Project Situation	Project Information	Constraints
Under Construction	18-storey, Hotel, Steel Module	C1, C2, C9, C10, C11, C15, C17, C20, C23, C25, C26, C27

- Case study: an 18 storey hotel in WA, Australia

This case study explored a practical modular construction project, which is the world's largest high-rise modular hotel providing 252 guest rooms in Perth, Australia. This ibis style hotel broke the record for the high-rise modular hotel in response to the burgeoning hotel demand. Entire steel modules were installed upon an in-situ concrete basement and podium slab, embracing the rising trend towards modular construction (Figure 2).

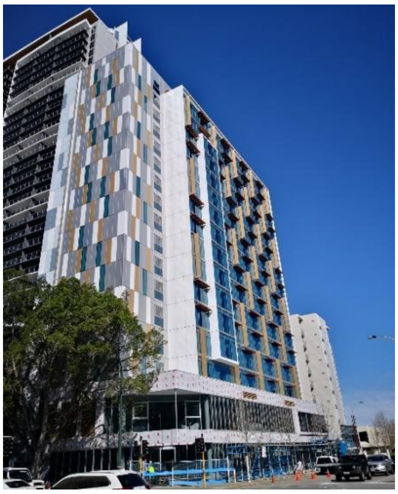

Figure 2. 18 storey modular hotel in Perth (photo by Y. Sun).

To comply with diversified hotel operation, according to designers, the design team handed over several types of modules to create different functional areas comprising a lounge, a restaurant and bar, a meeting room, a business corner and gymnasium, while avoiding additional manufacturing cost from design flexibility. In addition, interviewees highlighted the adverse effect of C9 "lack of coordination and communication" among stakeholders. The design team played a liaison role in enforcing developer's requirements as well as proposing a feasible design for the manufacturer who produced prefabricated modules in China. Additionally, "Due to lack of building codes and standards (C10), modular building design spends more effort and time in comparison to traditional building design. The overall design process of this project was over three months." was expressed by the designer.

From the perspective of manufacturing, 160 unit modules and 11 roof modules were produced at China's factory in consideration of local incompetence of suppliers and manufacturers (C15) and expensive skilled labour (C17). The manufacturer presented this innovative and exceptional module, namely prefabricated, pre-completed volumetric modules (PPVM), in which interior finishes, bathroom, furniture and MEP service are installed completely (Figure 3). The most remarkable part of this case study is the fact that the façade and curtain wall systems were installed on modules as well, and this breakthrough innovation saved construction time and cost dramatically. Interviewees claimed that total manufacture time was approximately five months, including inspection and modification at the workshop. When asked why they selected overseas manufacturing rather than domestic supply chain, the developer replied "Higher price of material and labour lead to the loss of competitiveness of local manufacturers and suppliers. You can almost forget the additional transportation fee (C6) of overseas supply chain including shipping fee and unloading fee, because poor supply chain integration (C25) may cause serious underlying risks such as construction delay due to the defect in prefabricated modules".

The completed modules were delivered to the local port in two shipments and then it took about one month to unload all the modules from container vessels (Figure 4). Considering the construction site located in Perth CBD (Central Business District), modules were deposited at a temporary station and inspected again before dispatching to the building site. In this project, despite the prefabricated modules having a completely installed façade, curtain wall, and shower screen, only three modules had minor damage due to the sophisticated protection during the transportation process.

Figure 3. Module manufacture at workshop (photo by Y. Sun).

Figure 4. Module transport to construction site (photo by Y. Sun).

Due to the limited parking and unloading area, PPVM was transported to the construction site in accordance with the just-in-time (JIT) delivery, which is relatively dependent on timely communication and coordination. An interviewee explicated that the typical dimension of the module is approximately 3.5 m × 3.2 m × 12.2 m (width, height, and length) laden on a standard flatbed trailer. The trailer had applied for an oversize overmass (OSOM) permit and delivered merely on weekdays in response to main road access limitation. Consequently, understanding local traffic regulatory requirements as well as planning the transport route at the early planning and design stage are significant for modular construction. However, to date, scarce applications and tools are capable of planning an effective and efficient transport route for delivering modules.

The slumped construction period is a key attraction of modular buildings relying on a high-efficiency assembly involving vertical lifting of modules and installation of connections (Figure 5). To achieve this goal, adequate equipment and an experienced construction team act as a pivotal part in the assembly of modules. In this project, two tower cranes, 24 t of lifting capacity, were employed for vertical lifting of all 171 modules. Taking into account the C22 "complexity of connection", approximately 10 modules were installed per day. Although the contractor pointed out that strong wind and heavy rain impacted on crane operation, which delayed installation works. The total installation took less than five months, which is a substantially shorter construction time than traditional building.

Figure 5. Module installation at site (photo by Y. Sun).

According to the case study, a holistic construction process of modular building was illustrated. Interviewees from all stakeholders scrutinised the identified constraints and highlighted some of them that occurred in this project. In addition, authors asked all stakeholders about potential solutions to these identified constraints that could facilitate widespread application of high-rise modular buildings in the future. Developers were more concerned with C2 "lack of government support", and C4 "higher capital cost". An interviewee responded, "Considering the current economic scale (C16), the construction cost of modular building is higher than traditional construction. But, we believe the cost will be decreased dramatically in association with the development and upgrade of supply chain.", the interviewee added, "On the other hand, government support like policy, and financial incentive, of course, could lead the direction of modular construction".

Another point that should be noted in the interview is that the significance of BIM application in high-rise modular buildings has been realised. Designers claimed that utilising virtual design construction (VDC), 15 types of prefabricated unit were generated and assembled by BIM software. Various combinations of units can be presented directly to the developer, which eliminates impact of C12, "poor design flexibility", as well as C11 "unable to freeze design early". At last, seven types of units were selected to form this 18 storey hotel. From the perspectives of manufacturer and contractor, current BIM application in manufacture and assembly stages concentrates on tackling C22 "complexity of connection". Implementing BIM software, all details and accurate location can be indicated clearly in 3D and 4D, which enhances off-site production efficiency and reduces in-situ installation period.

7. Discussions and Findings

The findings of the questionnaire and case study demonstrated primary constraints hampering the application of high-rise modular buildings. Through interviews with numerous respondents in different positions, we found that the constraints in each stage of construction are interrelated and interactive. A lot of interviewees mentioned that underlying design issues directly or indirectly provoke harmful influence of downstream processes involving manufacturing, transportation, and assembly. A better modular design can be beneficial to all stages of modular construction. Respondents also provided specific improvement measures, such as utilising BIM technology to propose diverse modular designs and ease complex connection work. The following part is to explore the potential of BIM and DfMA to release these identified constraints.

7.1. Building Information Modelling (BIM)

BIM, presenting elaborated real-time construction information, has been widely used in modular construction. To date, BIM application in modular construction focuses on modular design. It is advantageous to improve the modular building design by the reduction in design coordination errors. BIM-based parametric design takes full advantage of the characteristics of BIM to create prefabricated components with complete attributes. Yuan et al. [79] developed a BIM-based process of parametric design optimising traditional parametric design processes, considering manufacturability and assemblability. Alwisy et al. [80] proposed a BIM-based automatic design application improving the quality of buildings embedded with wood panels. However, few studies concentrated on the application of BIM for high-rise modular buildings. In accordance with findings of the case study, BIM-based parametric design could improve the issues including C12, "poor design flexibility", and C11 "unable to freeze design early". On the other hand, BIM as a real-time information sharing platform makes a significant contribution to multi-disciplinary collaboration and coordination in conventional construction [81,82]. In contrast to conventional construction, modular construction is a typical process-intensive approach, with a relatively interdependent supply chain that needs a mature solution for coordination and communication among all stakeholders throughout the entire life cycle [83]. As a consequence, BIM has great potential to act as a communication platform during modular construction that is a possible solution to C9, "lack of coordination and communication", the foremost constraints from the questionnaire.

7.2. Design for Manufacture and Assembly (DfMA)

The manufacturer in case study pointed out that "Lack of experience and expertise (C1) is a major problem for all participants. Designers cannot propose a good drawing if they have insufficient knowledge and experience of modular design and manufacture. An inappropriate design may result in extra expense and time in the stage of manufacture." Consequently, it is worth considering that proposing a relevant solution or a practical application aiming at the design stage is necessary. In recent years, DfMA provided substantial insights into the modular construction, dealing with manufacture and assembly in the early design stage for improved quality of modules and decreased construction period [84]. Derived from manufacturing, DfMA, a combination of DfM (Design for Manufacture) and DfA (Design for Assembly), embodies an innovative design method and philosophy and has been embraced by the construction industry [84–87]. Given the consideration of the nature of industrialisation and modularisation, off-site construction, especially high-rise modular buildings embedded with completed prefabricated modules, is an ideal implementation scheme of DfMA. Empirical projects have identified its contribution to reduced construction period as well as wastes [26,87,88]. Nevertheless, DfMA still remains at a theoretical phase rather than a concrete tool or a standard operating procedure (SOP) that can be utilised simply for general modular buildings. Consistent with the findings of the case study, in spite of most designers understanding the significance of manufacture, transportation, and assembly in modular construction, only experienced senior designers could comprehensively take account of the entire construction period from the early design stage [89]. Developing an applicable guideline of DfMA can be an effective solution to current constraints in design stage, involving C1, "lack of experience and expertise" and C10, "lack of building codes and standards", which is necessary for the development of modular buildings.

8. Conclusions and Future Work

This paper contributes an exhaustive description of the current circumstances of modular construction with particular focus on high-rise modular buildings. A total of 27 constraints throughout the whole life cycle of modular construction were identified by a comprehensive literature review and a focus group study with experienced experts. The final list of constraints impeding the development and progress of high-rise modular buildings was delivered to a large number of academic researchers and participants in modular construction who have adequate experience and knowledge in a questionnaire survey to rank these factors. "Lack of coordination and communication among stakeholders", "Higher cost", "Lack of government support", "Lack of experience and expertise", "Lack of building codes and standards", "Poor supply chain integration", and "Complexity of connection" were recognised as the foremost challenges. To explore the real-life circumstances of high-rise modular buildings, an empirical case study coupled with in-depth interviews were administrated. The identified constraints were evaluated by corresponding stakeholders. Further underlying barriers and lessons learned were discussed with frontline participants. According to the findings of the survey and case study, the improvement of modular design is the key to the development of high-rise modular buildings. The potential solution implementing BIM and DfMA to optimise modular design were discussed in accordance with the constraints. The investigation consists of multiple surveys to reveal existing constraints hindering the development of high-rise modular buildings, whilst contributing a valuable reference for stakeholders in modular construction. From the perspective of modular design, this paper proposed potential solutions that adopt BIM and DfMA to release relative constraints. The future research could target establishing a guideline that embodies the DfMA concept while aiding the workflow of modular building design. Meanwhile, developing a BIM-based rule checking system could be supportive of modular design.

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