Few strategies are proposed in this section to support future research on emissions measurement from the non-road equipment. Improvement is required in several steps of the MOVES. It will be useful if the equipment names are incorporated in addition to SCC numbers. Fuel type and its usage is not considered in this study. MOVES have an option to change the fuel type and check the change in emission quantities. This might be a useful study to focus on in the future. Idle time of the equipment plays a major role in the change of the emission quantities measured. Idle time must be considered while estimating emissions. There should be an input variable in MOVES for idle time too.

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High-Rise Modular Building: Ten-Year Journey and Future Development

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Abstract

Along with the sweeping adoption of prefabrication in the construction industry there has been increasing attention to and practice of exploring volumetric modular building technologies. While the modular approach has been reported with the benefits including shortened construction period, improved site health and safety, reduced construction waste, enhanced life cycle cost performance, lessons have also been learnt. More recently there have been cases of adopting modular construction for high-rise buildings that are a significant building type in cities. The aim of this paper is to review the 10-year journey of high-rise modular building and elicit learning for its future development. The research was carried out through a critical literature review, case studies with seven representative high-rise modular buildings constructed during the 10-year period from 2007 to 2017 selected worldwide from U.K., U.S., Singapore, Australia and China, and interviews with the project teams for verification and with industry stakeholders for consultation. The case studies together enabled a longitudinal examination of the adoption of high-rise modular buildings. Despite the available modular buildings in concrete and composite materials, steel framed solutions appear to be the norm for high-rise. Compared with the normal design decision criteria for prefabricated buildings, structural stability, wind load resistance, connection details emerge to be prominent considerations for high-rise modular solutions. While the many benefits claimed from prefabrication also apply to the use of modular building for high-rise, policy promotion, and client leadership are revealed to be the main drivers. Partnering between the client and its professional advisors and supply chains, particularly early contractors' involvement, proves to be essential to secure project success. While there is in general premium direct building cost, cost neutrality can be demonstrated taking into account financial gains and operational savings. Learning for the future development of high-rise modular building is presented.

Keywords: Modular building; High-rise building; Prefabrication; Off-site construction.

1. INTRODUCTION

Modular building represents a game-changing approach to construction, and is known in different terms in different regions, such as Permanent Modular Construction (PMC) in the United States (Smith, 2015), Prefabricated Prefinished Volumetric Construction (PPVC) in Singapore (Building and Construction Authority, 2014), and Modular Integrated Construction in Hong Kong. Modular building offers an innovative way of construction, in which room-sized volumetric units are fitted out in the factories, delivered to the site and installed as the main structural elements of the building. Lawson et al. (2011) reported that modular construction has been a viable and widely used approach for residential buildings of 4 to 8 storeys high. While the modular approach has been reported with the benefits including shortened construction period, improved site health and safety, reduced construction waste, enhanced life cycle cost performance, lessons have also been learnt (Pan et al., 2008). More recently there have been cases of adopting modular construction for high-rise buildings that are a significant building type in cities. However, the number of high-rise modular buildings worldwide is still limited (less than 1%). Mills et al. (2015) reported that there was only one completed modular building more than 30 stories at the time. Many studies have contributed to the managerial and technical know-hows for delivering modular buildings, such as feasibility studies (Velamati, 2012), decision-support tools development (Pan, 2006, Pan et al., 2012a), process visualization (Olearczyk et al., 2009) and factory design (Nasereddin et al., 2007). However, previous studies largely focused on low-rise modular buildings, while the understanding of challenges to and strategies for implementing high-rise modular buildings is insufficient. Therefore, the aim of this paper is to review the ten-year journey of high-rise modular building from 2007 to 2017 and elicit learning for its future development. This paper is organized as follows: Section 2 explains the methodology used to examine the development of high-rise modular buildings. Section 3 examines the challenges to the adoption of high-rise modular buildings identified from previous research. Section 4 summarises the case studies of seven examples of pioneering high-rise modular buildings worldwide and reveals learning for future development. Section 5 concludes the paper.

2. METHODOLOGY

This study reviews the ten-year journey of high-rise modular building and elicits learning for its future development. Work presented in this paper was carried out through a comprehensive literature review, case studies with seven representative high-rise modular buildings constructed during the ten-year period from 2007 to 2017 selected worldwide from UK, US, Singapore, Australia and China, and interviews with the project teams for verification and with industry stakeholders for consultation. Case study as a research method enables the researcher to "undertake an investigation into a phenomenon in its context" and to answer "why?" and "how?" questions (Rowley, 2002, Yin, 1994). The case study in this study aimed to highlight the challenges that real-life projects encountered and to identify how these challenges were addressed. A holistic perspective was used to analyze each case as a unit (Rowley, 2002). Projects information was firstly collected from multiple sources, including each project's websites, articles in academic journals and conference, press release, books, reports from relevant institution. Secondly, site visits and face-to-face semi-structured interviews with different stakeholders representing clients, contractors, architects, module suppliers and engineers were conducted in Singapore, Mainland China and UK. The following questions guided the case studies: (1) What were the benefits from the adoption of modular approach for high-rise buildings? (2) What were the challenges to the adoption of modular approach for high-rise buildings? (3) How were the challenges addressed?

3. IDENTIFIED CHALLENGES THROUGH LITERATURE REVIEW

Challenges to the use of prefabrication and modular approach in construction have been examined in previous research worldwide. For instance, the study carried out by McGraw-Hill Construction (2011) identified three major challenges perceived by the clients in terms of using prefabrication and modularization in USA, which were (1) the early commitment to design and engineering work, (2) the higher requirements for transportation, and (3) the constrained number of suppliers. In respect of technical challenges, Blismas (2007) identified four factors that will hinder the design and construction of modular construction, which were (1) a longer lead time in comparison with traditional practice, (2) the inability to change design, (3) the low level of Information Technology integration in construction industry, and (4) the fragmented nature of the construction sector.

Modules are usually the largest units that are transportable and will travel long distance from factories to the site. The design of modules should meet customers' demand, aesthetical, structural and functional requirements and be subject to regulations and manufacturing feasibility. Lawson et al. (2011) stated that "the design of high-rise modular buildings is strongly influenced by structural, fire, and services requirements". Manufacturing and installation tolerance has a strong impact on the structural design of module (Lawson et al., 2011). Javanifard et al. (2013) identified logistics constraints in the course of tall modular buildings construction, including module storage issues, vertical transportation for site workers and crane options and operations. Blismas (2007) concluded three difficulties in in logistics and site operations, namely (1) module stock control, (2) site-specific constraints and (2) high risks in crane operations. The transportation limitation is associated with the size/weight of modules, road widths, bridge load capacity, transport curfews and requirement of escorts (Mullens, 2011).

Numerous studies showed consistency in the findings that cost is of vital importance to stakeholders during the decision-making stage (Pan et al., 2007, 2012b). Blismas (2007) suggested that offsite construction is deemed to be costly in comparison to conventional construction because of the additional costs associated with initial set-up, design, cranes and transportation. Similarly, a higher initial cost, a perceived higher capital cost, the difficulties in attaining economies of scale were also identified by Pan et al. (2007) and Rahman (2013) as challenges to the adoption of offsite construction in UK and China. However, it is suggested by Lawson that, the reduction of site preliminaries, consultant fees, improved quality and faster construction could yield 11 to 19% of the total building cost savings in comparison with conventional construction.

Previous studies also suggested that it is more challenging for the building industry to use modular approach if the lack of relevant guidelines, official policy, specific legislation has not been addressed (Blismas and Wakefield, 2009). Furthermore, improving the social acceptance of offsite construction is deemed as one of the primary challenges facing the modular building industry (Jellen and Memari, 2013).

4. CASE STUDIES AND LEARNING FOR FUTURE DEVELOPMENT

Seven representative high-rise modular buildings constructed during the ten-year period from 2007 to 2017 selected worldwide from UK, US, Singapore, Australia and China were examined through literature review, face-to-face interviews and site visits. An overview of the seven selected cases (Figure 1) is provided in Table 1, with their details provided in Table 2.

Figure 1. Case modular buildings (From left to right: Apex House, Paragon, Soho Apartment (courtesy of google map), Gangnan Road Housing)

The technical practicability of using modular construction for high-rise buildings in congested areas was demonstrated through the case studies. The seven cases further reflected several challenges to the adoption of high-rise modular buildings, including difficulties in structural system design, low production efficiency, transportation and logistics restrictions, limited capability of supply chains, higher requirements of stakeholders' collaboration for comprehensive planning and design and the limited market preference.

Early decision-making is very essential to the success of modular building project. B2 BKLYN switched to modular approach when the conventional structure design has started, while in Soho Apartment clients decided to use modularization after receiving the planning approval of using conventional construction. The increased complexity in design in the two projects was partly because of the late decision-making. It is found that other projects, such as Apex House, NTU1&2, benefited a lot from the early engagement of all the stakeholders and early decision-making.

Despite the available modular buildings in concrete and composite materials, steel framed solutions appear to be the norm for high-rise. Extended height of modular buildings adds difficulties to for stability and robustness. Compared with the normal design decision criteria for prefabricated buildings, structural stability, wind load resistance, connection details emerge to be prominent considerations for high-rise modular solutions. Manufacturers' qualification, manufacturing efficiency, factory location have great impacts on project quality, speed and cost. Module manufacture, transportation, and storage should be taken into consideration in the early stage of projects. It is found that in the current marketplace, the capacity and capability of module manufacture are very limited.

Through interviews with stakeholders in Singapore, Mainland China and UK, it was found that the policy promotion and clients' leadership are playing crucial roles in driving the adoption of high-rise modular buildings. For instance, promoting the use of PPVC is the focus of the 2nd construction productivity roadmap proposed by the Building and Construction Authority (BCA) in Singapore. BCA has implemented a wide range of strategies and measures to generate sufficient lead demand from public sector, to stimulate private sector's demand, and to increase industry engagement for promoting PPVC and enhancing supply chain capabilities. The number of PPVC supplier has reached 18 in 2016, while in 2013 there was only one. It was found that the modular building industry in UK is mainly motivated by the market and the clients who intend to benefit from faster, safer and quicker construction. In addition, the vast majority of interviewees highlighted the significance of the partnering between the client and its professional advisors and supply chains, particularly early contractors' involvement.

5. CONCLUSIONS

This paper has reviewed seven representative high-rise modular buildings constructed during the ten-year period from 2007 to 2017 and explored the future development of high-rise modular building construction. The cases were selected worldwide from UK, US, Singapore, Australia and China. Personal interviews were conducted with the project teams for verification and with industry stakeholders for consultation. Despite the fact that conducted interviews covered different jurisdictions, there is a strong consensus among the views shared by the interviewees.

The findings contribute to the following learning for the future development of high-rise modular buildings. First, comprehensive studies on structural stability, wind load resistance, connection systems should be carried out. Precise manufacturing and rigid quality control are required to ensure the quality of individual modules as well as the building. Second, government should take the leadership and provide initiatives for promoting the adoption of the modular approach by stimulating market demands and formulating relevant policies. Third, strategies for effective collaboration along the supply chains are needed to facilitate the delivery of high-rise modular buildings. In addition, further studies on the economics and life cycle costs of high-rise modular building are needed.

This paper presents a longitudinal investigation of the adoption of high-rise modular buildings, disclosing the main challenges to implementing high-rise modular buildings and highlighting learning points for future development. Future research should study more cases in a wider context for more comprehensive cross comparison and also explore more insights into the deliveries of the specific cases.

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Table 1. Overview of seven examples of pioneering high-rise modular buildings

No.	Project	Location	Stories	Building type	Completion time	Site condition	Highlights	**Reference and data source**
1	Apex House	North London, UK	28	Student residence	2017	Congested	The tallest modular building in Europe hitherto	(Horti, 2017, Cousins, 2017, Offsite Hub, 2017) Semi-structured interviews with the designer; Site visit;
2	Paragon	London, UK	17	Mixed-use residential building	2006	Congested	The first high-rise modular building in UK	(Velamati, 2012, Soltani, 2006, Javanifard et al., 2013, Buildoffsite, 2010, Mittal and Staal, 2008) Site visit;
3	Victoria Hall	Wolverhampton, UK	25	Student residence	2009	Congested		(Buildoffsite, 2010, Hayes, 2010, Lawson and Ogden, 2010, Lawson et al., 2011, Kalette, 2009)
4	B2 BKLYN	New York USA	32	Residential	2016	Congested	The highest modular building worldwide hitherto	(Javanifard et al., 2013, Council on Tall Building and Urban Habitat, 2013, Memari et al., 2014, Farnsworth, 2014)
5	NTU1&2	Singapore	13	Student residence	2016 & Mid July 2017	-	The first public high-rise modular building in Singapore	Semi-structured interview with the project manager and the module suppliers; Site visit
6	Soho Apartment	Darwin, Australia	29	Residential building /Hotel	2014	Congested		(Gardiner, 2015, Irwinconsult, 2013)
7	Gangnan Road Social Housing	Zhenjiang, China	18	Residential building	2017	-	The tallest modular building in China	Semi-structured interviews with the project manager, the module supplier, and site workers; Site visit;

Table 2. Summary of seven examples of pioneering high-rise modular buildings

No.	Case	Achievements	Challenges/Problems	Strategies/learning points
1	Apex House	• The tallest modular building in Europe • One-year saved • Awarded BREAAM Excellent	• Constrained access to site as the major limitation during the module installation. • Skilled workers shortage on- and off-site. • Cost savings from manufacturing was not as high as expected. • The slow reaction of the upstream suppliers to the manufacturer partly led to the low productivity and the inconstant output in the factory.	• Digital manufacturing to enhance the capacity and capability of module manufacturer and its suppliers • Training in factory • Comprehensive logistics plan up front • Long-term partnership between main team members •
2	Paragon	• 14-month saved • Reduced over two-thirds of on-site wastes • Reduced noise and dust in site operation • On-site logistics minimized • Excellent acoustic insulation	• The project team could refer to very little knowledge and experience as there is no modular building over 9-storey were constructed before Paragon. • The structure engineer suggested that the key challenge to design was “stability, disproportionate collapse and differential movement between the steel modules and the concrete core”. • Dull and unattractive building design perceived by the public. • Constrained access to site during module installation.	• Early involvement of module manufacturer from the outset of design and planning phases. • An early design freeze and early start of module production. • Working with experienced module suppliers
3	Victoria Hall	• 12-month saved • 60% transportation reduced • productivity increased by 50% • 43% manufacturing waste recycled • 70% reduction of landfill	• Constrained access to site during module installation.	• Early involvement of stakeholders • A comprehensive of technology evaluation and feasibility study beforehand

No.	Case	Achievements	Challenges/Problems	Strategies/learning points
4	B2 BKLYN	• The highest modular building worldwide hitherto	• The design changed to modular approach halfway of construction • Too much time and investment in developing own modular factory; • Poor collaboration between the client and the main contractor • Time and money overrun • Leakage problems due to inferior quality control • Weak buy-in of local labour union	• Early decision-making • Early engagement of team members • Stakeholders' understanding of modular approach • High level of quality control on- and off-site • Closer collaboration among all the stakeholders
5	NTU1&2	• 15-20% saving in construction time • 25-40% saving in manpower	• Complicated and expensive cross-border transportation; • Lack of clear procurement and payment methods • Lack of experience, knowledge and practical skills • Higher complexity in structural and architectural system design • Difficulties in lifting heavy modules on site/module installation	• Considering factory's location, capability, capacity when selecting of PPVC specialist • Considering Crane Capacity and cost, Shipping cost, transportation dimensional limits when designing Module Size and Weight • Clear scope of work among all stakeholders • Comprehensive study of logistic plan upfront
6	Soho Apartment	• reduced complexity • decreased labour demand	• The long-distance transportation of modules (from China to Australia) increased challenges in module design to deal with feasibility and regulatory compliance • Limited capability of module manufacturers • Challenges in structural design	• Providing construction knowledge and training for factory staffs • Concrete poured into the steel-framed column to enhance the structural stability
7	Gangnan Road Social Housing	• The highest modular buildings in China • 83.3% reduction of site workers • Three Star for Green Building Design Label	• Not much time savings observed • Consumers' negative perception of prefabrication • Higher requirements for the vertical transportation and installation of heavy modules.	• Specialized equipment for module transportation and lifting • Providing fully furnished homes to consumers • Increasing the level of completion offsite