School of Design and Built Environment

DFMA-based design guidelines for high-rise modular buildings

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Declaration

To the best of my knowledge and belief, this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Human Ethics

The research presented and reported in this thesis was conducted by the National Health and Medical Research Council National Statement on Ethical Conduct in Human Research (2007)—updated in March 2014. The proposed research study received human research ethics approval from the Curtin University Human Research Ethics Committee (EC00262), Approval Number HRE2019-0656.

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ABSTRACT

The Australian construction industry contributes over $150 billion to the gross domestic product, which is around 10% of the total output of goods and services. However, the off-site construction sector (OSC) amounts to just $4.6 billion (i.e. 3% of the construction industry's output). In recent years, OSC has increased because of its advantages such as improved quality control, reduced skilled labour, faster construction time, decreased material wastage and a friendly working environment. Modular buildings, as the most cutting-edge technology in OSC, have been used for residential buildings, student accommodation and hotel projects because they comprise massive repetitive units. However, as a result of existing and underlying constraints, the adoption of modular buildings, especially the application of high-rise modular buildings, remains relatively low.

Derived from the manufacturing industry, the concept of Design for Manufacture and Assembly (DfMA) is a combination of DfM (Design for Manufacture) and DfA (Design for Assembly), and refers to considering the requirements and processes of manufacture and assembly from the design stage. Having witnessed the successful application of DfMA in the manufacturing industry, the construction industry has attempted to embrace DfMA in recent years. However, according to previous studies, the implementation of DfMA focusing on high-rise modular buildings remains limited in empirical projects. The lack of DfMA-based design guideline restricts the growth of high-rise modular buildings as well.

This research aims to develop DfMA-based design guidelines for high-rise modular buildings to facilitate the widespread application and development of innovative OSC technology.

First, to identify the research gaps and problems, an in-depth literature review and a focus group are conducted to reveal the primary constraints hindering the development of high-rise modular buildings. A questionnaire survey involving all stakeholders of OSC is implemented to evaluate these constraints.

Second, to develop the DfMA-based design guidelines for high-rise modular buildings, a comprehensive literature review is conducted concerning the adoption of DfMA in the manufacturing and construction industries. The DfMA-based design guidelines are developed to provide quantitative criteria for the entire life cycle of high-rise modular buildings.

Last, based on two case studies, the proposed design guidelines are validated. Leveraging the developed guidelines considerably promotes the efficiency and quality of each stage of modular construction.

The result of questionnaire survey clearly indicates that lack of design guidelines for high-rise modular buildings is one of the most crucial barriers. Therefore, in this study, a DfMA-based design guidelines for high-rise modular buildings is developed. The effectiveness and efficiency are validated in two case studies. This research contributes to linking the DfMA philosophy with the constructability of high-rise modular buildings in terms of manufacturability, transportability and assemblability. In contrast to previous studies, which concentrated on the qualitative assessment of DfMA application in construction, this study provides design guidelines with quantitative criteria based on the nature of DfMA philosophy. According to two case studies, it is proven that the proposed guidelines can be implemented directly by all stakeholders in distinct projects.

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List of Abbreviations

BCA	Building and Construction Authority
BIM	Building Information Modelling
CAD	Computer-Aided Design
CLT	Cross-laminated timber
DfA	Design for Assembly
DfM	Design for Manufacture
DfMA	Design for Manufacture and Assembly
DfMA	Design for Manufacture, Transportation and Assembly
DfT	Design for Transportation
GDP	Gross domestic product
GLT	Glue-laminated timber
IFC	Industry Foundation Classes
JIT	Just-in-time
LoD	Level of detail
MEP	Mechanical, electrical and plumbing
MiC	Modular integrated construction
NLT	Nail-laminated timber
OSC	Off-site construction
OSM	Off-site manufacture
PPVC	Prefabricated prefinished volumetric construction
PPVM	Prefabricated pre-completed volumetric module
QA	Quality assurance
QC	Quality control

List of Related Publications

Journal Article

Sun, Y., Wang, J., Wu, J., Shi, W., Ji, D., Wang, X., & Zhao, X. (2020). Constraints hindering the development of high-rise modular buildings. *Applied Sciences*, *10*(20), Article 7159. https://doi.org/10.3390/app10207159

Conference Papers

Sun, Y., Wang, J., Wu, P., Shou, W., & Wang, X. (2018). *A framework of BIM-based automated design check system for modular buildings* [Paper presentation]. 1st International Conference on 3D Construction Printing, Swinburne University of Technology, Melbourne, Vic, Australia.

Sun, Y., Wu, J., Fan, J., Wang, J., & Wang, X. (2019). *Rule-based automated design check for modular building* [Paper presentation]. 43rd AUBEA: Australasian Universities Building Education Association Conference, Noosa, Qld, Australia.

Chapter 1: Introduction

Introduction

1.1 Background

The number of households in Australia is projected to increase from 9.2 million in 2016 to 13.2 million in 2041 (Australian Bureau of Statistics, 2019). According to the National Housing Finance and Investment Corporation (2022), more than 1.7 million new households are expected to form between 2022 and 2032. The growing housing demand is stimulating a historically high level of housing supply, with more than 550,000 net new dwellings expected from 2023 to 2035. Furthermore, construction, as a labour-intensive industry, has been subjected to a shortage of skilled labour (Hampson & Brandon, 2004). There is a critical need for an additional skilled workforce to address skills shortages in the Australian construction industry (Oo et al., 2020). As a result of the COVID-19 pandemic, the industry has been suffering a severe labour shortage. A survey undertaken at the end of 2021 found that over 70% of construction firms have been affected by the skilled labour shortage, which is the highest among all industries in Australia (National Australia Bank, 2021). In recent decades, modular buildings have been used in both the public and private sectors to bridge the gap between the capacity of housing supply and the explosion of housing demand while mitigating the influence caused by the labour shortage. The construction industry has increasingly employed off-site construction (OSC) because of its advantages such as improved quality control, reduced skills labour, faster construction time, decreased material wastage and friendly working environment. Modular buildings, as the most cutting-edge technology in OSC, have been used for residential buildings, student accommodation and hotel projects because they comprise massive repetitive units. However, the adoption of modular buildings remains relatively low as a result of existing and underlying constraints.

Within this context, the construction industry has focused attention on OSC, which refers to the manufacture of components at a different location to where they will be assembled permanently (Blismas et al., 2009). Figure 1.1 outlines the procedures of traditional on-site construction and OSC. Compared with traditional on-site construction, OSC can manufacture components in off-site factories while conducting site development and foundations. Furthermore, after prefabricated components have been delivered to the site, the components of OSC can be installed within a short period. As a result, the construction schedule for OSC is shorter than for traditional on-site construction.

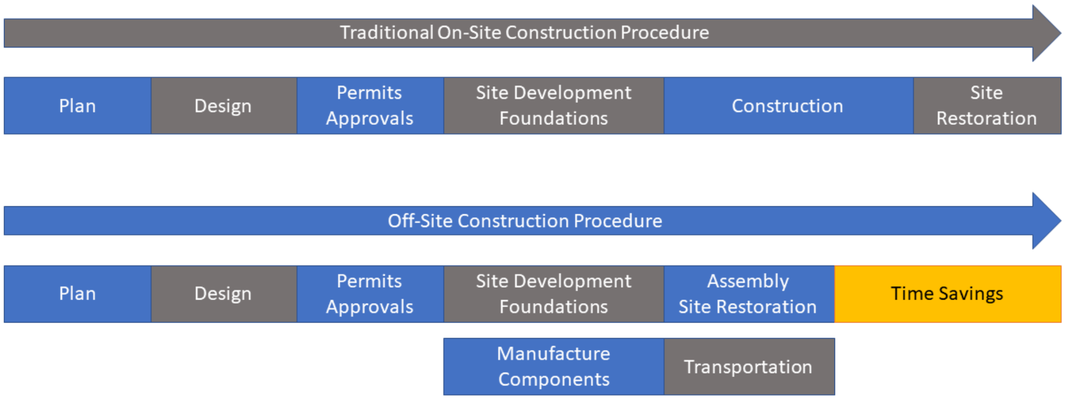


Figure 1.1 Traditional on-site construction procedure v. OSC procedure

OSC is not an innovative concept in building construction; however, the development and process of OSC have been lower than expected until recent decades. The first large-scale adoption of OSC was in the United Kingdom after World War II, when substantial precast concrete panels were used to rapidly reconstruct houses destroyed by bombs. The adoption of OSC was driven by an explosion in population growth and the process of urbanisation. For example, Hong Kong and Singapore, where limited land supply exacerbates the scarcity of housing, have used OSC in mass public sector projects (Jaillon & Poon, 2009). With the development of industrialisation, OSC has been embraced by the construction industry and played an increasingly pivotal role in the United States, Japan, Sweden, Germany, Netherlands and mainland China (Goodier & Gibb, 2007; Steinhardt & Manley, 2016; Tam et al., 2015; J. Zhang et al., 2016).

In Australia, OSC has become a heated topic in the industry and among academics over the past 20 years. Hampson and Brandon (2004) predicted that OSC as a significant construction innovation would dominate the Australian construction industry in 2020. Blismas (2007) investigated seven case studies in different cities, including Perth, Melbourne, Newcastle, Brisbane and Robina, in which OSC revolutionised the approach, process, materials and management of infrastructure construction. Blismas et al. (2009) surveyed numerous experts on OSC through industry workshops, interviews and case studies to determine the major benefits of and barriers to OSC in Australia. Moreover, Boyd et al. (2013) investigated a residential building in the central business district of Melbourne that successfully implemented OSC and benefited from cooperation among all stakeholders.

The abovementioned implementations of OSC show that it is an alternative to traditional construction because of its benefits in terms of decreased construction time, improved quality, enhanced productivity, alleviated skilled labour shortage and reduced on-site risks (Blismas et al., 2006; Gibb & Isack, 2003; Sun et al., 2020).

The adoption of prefabrication in OSC has been promoted consistently in line with industrialisation. Gibb (1999) divided OSC into four categories: component manufacture and sub-assembly, non-volumetric pre-assembly, volumetric pre-assembly and modular building. Along with the increased degree of completeness, more components of the construction are produced in off-site factories, forming non-volumetric and volumetric (three-dimensional [3D]) modules. Modular buildings, which are the highest level of prefabrication, are identified as a new technology reshaping the construction industry (Ferdous et al., 2019).

Modular buildings endeavour to produce maximum prefabricated modules or units in off-site manufacturing factories while minimising on-site construction activities. Volumetric pre-assembly modules are installed with finished floors, walls, ceilings and cabinets, as well as mechanical, electrical and plumbing (MEP) services, before being transported from domestic or overseas factories to the construction site for assembly (Murray-Parkes & Bai, 2017; Nahmens & Ikuma, 2012). In recent decades, modular buildings have been implemented in both the public and private sectors, which are composed of massive repetitive units, such as residential buildings, hotels, student accommodations and hospital wards (Fifield et al., 2018; Generalova et al., 2016; King, 2020; R. M. Lawson & Richards, 2010; X. Liu et al., 2018).

Previous works and projects have found that the strengths of modular buildings include reduced construction time, decreased material wastage, improved quality, decreased labour demand and a safe work environment (Boafo et al., 2016; Kamali & Hewage, 2016; R. M. Lawson et al., 2012; X. Zhang & Skitmore, 2012). Given the enormous potential of modular buildings, the construction industry and academics have proposed varied solutions involving Building Information Modelling (BIM) and Design for Manufacture and Assembly (DfMA) to facilitate the application of modular buildings (Alfieri et al., 2020; K. Chen & Lu, 2018; Gbadamosi et al., 2019; Ho et al., 2018; Hu et al., 2019).

DfMA, an innovative design concept, has been employed in modular construction in increasing projects. According to Trinder (2018) and Safaa et al. (2019), DfMA-based modular design reduced the design period as well as assembly time. K. Chen and Lu (2018) investigated a case study of a curtain wall system using a DfMA-based design to decrease material cost and waste. Moreover, the benefits of DfMA-based design in high-rise modular buildings are significant (Xu et al., 2020). Banks et al. (2018) stated that DfMA-based design for high-rise buildings can deliver optimal solutions involving precast components, prefabricated bathroom pods and modular MEP services, which is proved in a 40-storey modular building design that reduces the entire construction program and improves the safety and quality of the project.

However, in comparison with conventional buildings, the application of modular buildings is still relatively low, especially for high-rise buildings. In Australia, OSC accounts for only 3% of the construction industry’s total output, with the majority being low-level prefabrication involving precast components and panelised walls (Ferdous et al., 2019). The most uptake of modular construction is modular houses and low-rise buildings, whereas high-rise modular buildings are experiencing a slow pace of development (Sun et al., 2020). Meanwhile, DfMA-based design has been implemented in many OSC projects, including high-rise modular buildings. The existing studies revealed various benefits of DfMA-based design. However, most of the studies focused on specified construction stages or components (Gbadamosi et al., 2020; Gerth et al., 2013; Kim et al., 2016; Liew et al., 2019;). A DfMA-based design guideline considering the entire construction period and all building types is necessary.

1.2 Problem Statement

As a cutting-edge construction method, modular buildings have been reshaping the construction industry. The benefits of modular buildings have been verified in a large number of projects. As a result, an increasing number of stakeholders in the construction industry around the world are devoting greater efforts to this modern construction method. However, compared with traditional buildings, modular buildings are far from the dominant construction type; in fact, they are not even the preferred alternative when OSC is applied. The advantages of high-rise modular buildings, in terms of, fast construction, few labour needed, and reduced wastage, have been widely acknowledged. The uptake of this construction method is still very low compard with the traditional construction. To determine the cause of this situation, three detailed problems are summarised in the following sections:

- Insufficient understanding of high-rise modular buildings

The history of construction is approximately as long as the history of humans (Ngowi et al., 2005). Compared with other industries (e.g. manufacturing), the development and progression of the construction industry are stagnant (Pries & Janszen, 1995). Numerous studies have determined that higher levels of innovation in the construction industry may lead to greater economic growth. However, there is a perception that the industry is not innovative in most countries, including Australia (Blayse & Manley, 2004). Gambatese and Hallowell (2011) investigated the factors hindering the development and diffusion of technical innovations in the industry. They found that a lack of understanding of the new approach strongly discourages motivation for construction innovation.

With regard to OSC, many previous studies have found that the lack of understanding is one of the most important barriers to stakeholders when they switch from traditional construction to OSC (Blismas et al., 2005; Goodier & Gibb, 2005; Kamar et al., 2014; Mao et al., 2015; Pan et al., 2007). In facing the more innovative and complex construction approach of modular building, stakeholders in the construction industry tend towards a conversant and conservative method to evade the unknowns and uncertainties derived from insufficient knowledge (X. Gan et al., 2018; Han & Wang, 2018; L. Jiang et al., 2018). According to Wuni et al. (2019), limited knowledge and experience in the application of modular buildings have been crucial risk factors hindering the development and widespread adoption of this innovative construction method. In Australia, an investigation by Ferdous et al. (2019) demonstrated that, as a result of the lack of understanding of modular buildings, investment from the construction industry and financial investors is low compared with investment in traditional construction projects. To bridge this gap, a cooperative training system between industries and universities in Australia has been established to provide essential knowledge and experience to labourers and professionals (CAMP.H, 2016).

In summary, an insufficient understanding of modular buildings prevents their rapid development and progression. Stakeholders` confidence and interest in high-rise modular buildings cannot be increased due to a lack of experience and knowledge. Therefore, a comprehensive understanding of modular building is important.

- Low adoption of high-rise modular buildings in Australia

Modular buildings are preferred in structures with massive repetitive units such as hotels, apartments, dormitories, offices and hospitals (M. Lawson et al., 2014). Therefore, high-rise buildings with an increased number of repeated rooms can fully exploit the benefits of modular buildings (Liew et al., 2019). However, the implementation of modular buildings for high-rise buildings is limited, in contrast to the booming market in low-rise buildings (Pan et al., 2018).

As a result of the high density of the population coupled with the limited land supply, high-rise modular buildings have been identified as a solution to the enormous demand for housing in metropolises such as Singapore and Hong Kong (Thai et al., 2020). In Singapore, the government has promoted the uptake of high-rise modular buildings known as prefabricated prefinished volumetric construction (PPVC). Several guidebooks on Design for Manufacture and Assembly (DfMA) and Building Information Modelling (BIM) technologies have been published to provide practical direction to stakeholders throughout the entire life cycle of modular construction (Building and Construction Authority [BCA], 2016, 2017). According to the Singapore BCA, by 2020, there were 16 architectural firms, 17 engineering firms and 25 main contractors involved in PPVC projects, which mainly consisted of residential buildings and hotels (BCA, 2020). The two 40-storey residential towers (Clement Canopy Tower) using the PPVC method became the tallest modular buildings in Singapore and achieved a marked improvement of 72% in productivity (Seng et al., 2021). This height record will be broken by two 56-storey, 192 m-tall PPVC-built apartment towers in 2023, and approximately 3,000 prefabricated modules have been produced in Malaysia, not Singapore (CNN, 2020).

The implementation of modular buildings in Australia has been delayed in comparison with Singapore, Hong Kong, the United States and the United Kingdom. When OSC began in Australia, stakeholders focused on low-rise buildings and modular houses. However, in recent years, practitioners have increasingly shifted their attention to high-rise buildings (Blismas et al., 2009; Ferdous et al., 2019; Navaratnam et al., 2019). Hickory group developed the Hickory Building System (HBS), which is a volumetric pre-assembly unit composed of varied precast components and panels and adopted for high-rise modular buildings. The HBS was used in the La Trobe Tower (44 storeys) and Collins House (60 storeys) projects and resulted in over 30% reduced construction time (Thai et al., 2020). In addition to 3D volumetric modules, two-dimensional (2D) precast panels and precast components in HBS are connected to buildings by wet joints (Kumar, 2018). The complete modular building is rarely employed for high-rise buildings in Australia. SOHO Tower comprised 29-storey complete prefabricated volumetric units (10 × 4.2 × 3.9 m, 22 tonnes) and was the tallest modular building upon its completion in 2014 (Lacey et al., 2018).

Thus, OSC has been widely utilised in low-rise buildings and modular houses. The prospect of its application for high-rise buildings is bright because its application is less than 1%, in which the smallest part is modular building (Pan et al., 2018). In order to improve the development of high-rise modular buildings in Australia, it is necessary to promote all stages of modualr construction. Since the design stage is the initial stage of the entire construction cycle, proposing an efficient high-rise building design guideline can facilitate the efficiency of the entire construction project. This will further increase the proportion of high-rise modular buildings in Australia.

- Low efficiency and effectiveness of modular building construction

Different from traditional on-site construction, OSC can install prefabricated elements or units that are manufactured in controlled off-site factories. Thus, this construction method has numerous benefits in terms of reduced construction time, improved quality, decreased material wastage, ameliorated labour shortage, and enhanced construction safety and health

(Y. Gan et al., 2017; Goodier & Gibb, 2007; Jaillon & Poon, 2010; Royal Institute of British Architects [RIBA], 2013).

However, construction overruns have been found in some OSC projects. Low efficiency and effectiveness have been detected in each stage of OSC (Blismas, 2007; Sun et al., 2020; Wuni & Shen, 2019). Architects have had to spend more time and effort on modular design because of the lack of relevant experience and standards (Jaillon & Poon, 2010; Tan et al., 2020). Moreover, concerning fragmented stakeholders, communication and coordination are significant challenges for OSC. However, embedded with substantial repetitive prefabricated modules, high-rise modular buildings may not achieve the predicted productivity attributed to the heavy and complex supply chain (Luo et al., 2019; Wuni et al., 2019; Xu et al., 2020). Thus, there is a need to develop an effective and efficient solution for high-rise modular buildings.

1.3 Research Aim and Objectives

To address the three problems summarised in Section 1.2, this thesis aims **to develop DFMA-based design guidelines for high-rise modular buildings**. To achieve this aim, there are four objectives as follows:

Objective 1: To obtain a comprehensive understanding of modular buildings.

To develop a feasible design guildeline for high-rise modular building, a comprehensive understanding of modular buildlings is important. It consists of understandign of overall modular buildings development, stakeholders' views on current situation and future development, and the impact of DfMA in modular construction. An in-depth understanding of both the benefits and constraints of modular buildings can provide a solid base for the establishment of design guidelines. Consequently, the first objective is to review relevant studies to uncover the constraints hindering the development of modular buildings. In addition to the literature review, a focus group and questionnaires will be used to discover potential issues related to modular design in each stage of modular construction.

Objective 2: To develop a design guideline for high-rise modular buildings based on DfMA theory.

Benefiting from the outcome of the first objective, the second objective is to explore workable design solutions to the underlying issues in downstream phases in terms of manufacture, transportation and assembly. The systematic design solutions will be summarised as a design guideline for modular building design. The assessment criteria for the design guidelines derive from the constructability of modular buildings, which will be specified into manufacturability, transportability and assemblability—the nature of DfMA philosophy.

Objective 3: To validate DfMA-based design guidelines for high-rise modular buildings.

The last objective is to validate the proposed design guidelines in case studies to highlight potential problems and improvements, and to evaluate the outcomes of the adoption of the design guidelines in relation to effectiveness and efficiency. Limitations and future works will also be discussed in accordance with the evaluation results.

1.4 Significance and Contribution of the Research

Although the adoption of OSC has rapidly expanded in recent decades, current practices in high-rise modular buildings, especially in Australia, remain relatively low. The Australian construction industry contributes over $150 billion to the gross domestic product (GDP), which is around 10% of the total output of goods and services. However, the OSC sector accounts for just $4.6 billion (i.e. 3% of the construction industry's output). The aim of OSC is to maximise off-site manufacture while minimising on-site activities. The higher degree of prefabrication is a symbol of the successful adoption of OSC. However, in current practices, modular buildings peaking at the highest level of prefabrication lag behind precast components and panels. In addition, high-rise modular buildings embedded with massive repetitive units can maximise the potential of OSC. Nevertheless, high-rise modular buildings account for less than 1% of all OSC projects. Therefore, there is a need to promote the application and development of high-rise modular buildings in Australia. The detailed contribution of this research is explained below.

First, Objective 1 explores the current achievements of high-rise modular buildings in academic research coupled with the construction industry. A comprehensive literature review summarises the existing body of knowledge about high-rise modular buildings. A further investigation consisting of questionnaire surveys, in-depth interviews and case studies examines the underlying issues in each stage of modular construction. Thus, the contribution of Objective 1 is to provide a better understanding of this advanced construction approach. It will also outline the constraints hindering the development and progression of high-rise modular buildings while coordinating cognitive differences between academics and the construction industry.

Second, the establishment of DfMA-based design guidelines for high-rise modular buildings makes a significant contribution (Objective 2). The lack of design standards and code has been identified as one of the primary constraints affecting modular building design

(Luo et al., 2015; Wuni et al., 2019). Traditional construction design uses a set of criteria relating to stability, strength and serviceability. Designers use these criteria to complete and deliver design drawings and models on time. However, traditional design guidelines and codes are not applicable to modular building design, which has distinct design requirements. Design teams spend considerable time and effort on traditional design codes, which results in a long lead-in time and delays construction progress (Lacey et al., 2018; X. Liu et al., 2018). In recent years, researchers have gained new insights into guidelines for the design of modular buildings. Murray-Parkes and Bai (2017) published a handbook for the design of modular structures that provides guidance to improve safety, productivity and quality in industrial practices. Tan et al. (2020) proposed construction-oriented DfMA guidelines that take into account five aspects: contextual basis, technology rationalisation, logistics optimisation, component integration and material-lightening. To promote the uptake of high-rise modular buildings, specific design guidelines integrated with the DfMA concept are necessary.

Last, validation in this study can not only verify and promote the feasibility of the guidelines, but also explore the development situation of regional modular construction. In case studies, relevant information—for instance, regional supply chain data and local traffic regulations—are achieved following the criteria for design guidelines. By accumulating relevant information and data on modular construction, it is possible to discover the weakness hidden at any stage and suggest a future direction to stakeholders.

1.5 Organisation of Thesis

As shown in Figure 1.2, this research is formulated into six chapters, each of which is described below.

Chapter 1 is an introductory chapter that presents the background of this research. It presents a statement of problems, followed by the aim and objectives of this research. The chapter also clarifies the research significance and contribution, and outlines the organisation of the thesis.

Chapter 2 presents the literature review in the fields of modular buildings and topics involved in DfMA. The first section of Chapter 2 corresponds to Objective 1 and reviews previous studies regarding the definition, benefits and challenges of high-rise modular buildings. It highlights the underlying constraints throughout the entire life cycle of modular construction in terms of the design, manufacturing, transportation and assembly stages. The second and third sections are devoted to DfMA and constructability applied in modular buildings, which sets the foundation for the design guidelines and corresponds to Objectives 2 and 3.

Chapter 3 presents the research methodology used in the research. It first discusses the research philosophy that underpins the approach taken with the thesis. Moreover, the research design is outlined along with an explanation for the adoption of the research methods for each objective. Last, the chapter outlines the methods of data collection applied in this research, as well as the methods of data analysis.

Chapter 4 identifies the constraints hindering the development of high-rise modular buildings. Through a literature review, a focus group and questionnaires, issues in the underlying design and issues in the downstream stages (but derived from the design stage) are disclosed. This chapter fully addresses Objective 1 while raising questions for Chapter 5.

Chapter 5 establishes Design for Manufacture, Transportation and Assembly (DfMA)-based design guidelines for high-rise modular buildings (Objective 2). With reference to the assessment criteria for constructability for traditional construction, the guidelines contribute to the assessment criteria for modular design by considering three factors: manufacturability, transportability and assemblability. Two case studies are conducted to validate and improve the effectiveness and efficiency of developed design guidelines (Objective 3).

Chapter 6 provides a conclusion to the thesis and discusses the contributions, limitations and practical implications of the research. Recommendations for future research are also discussed in this chapter.

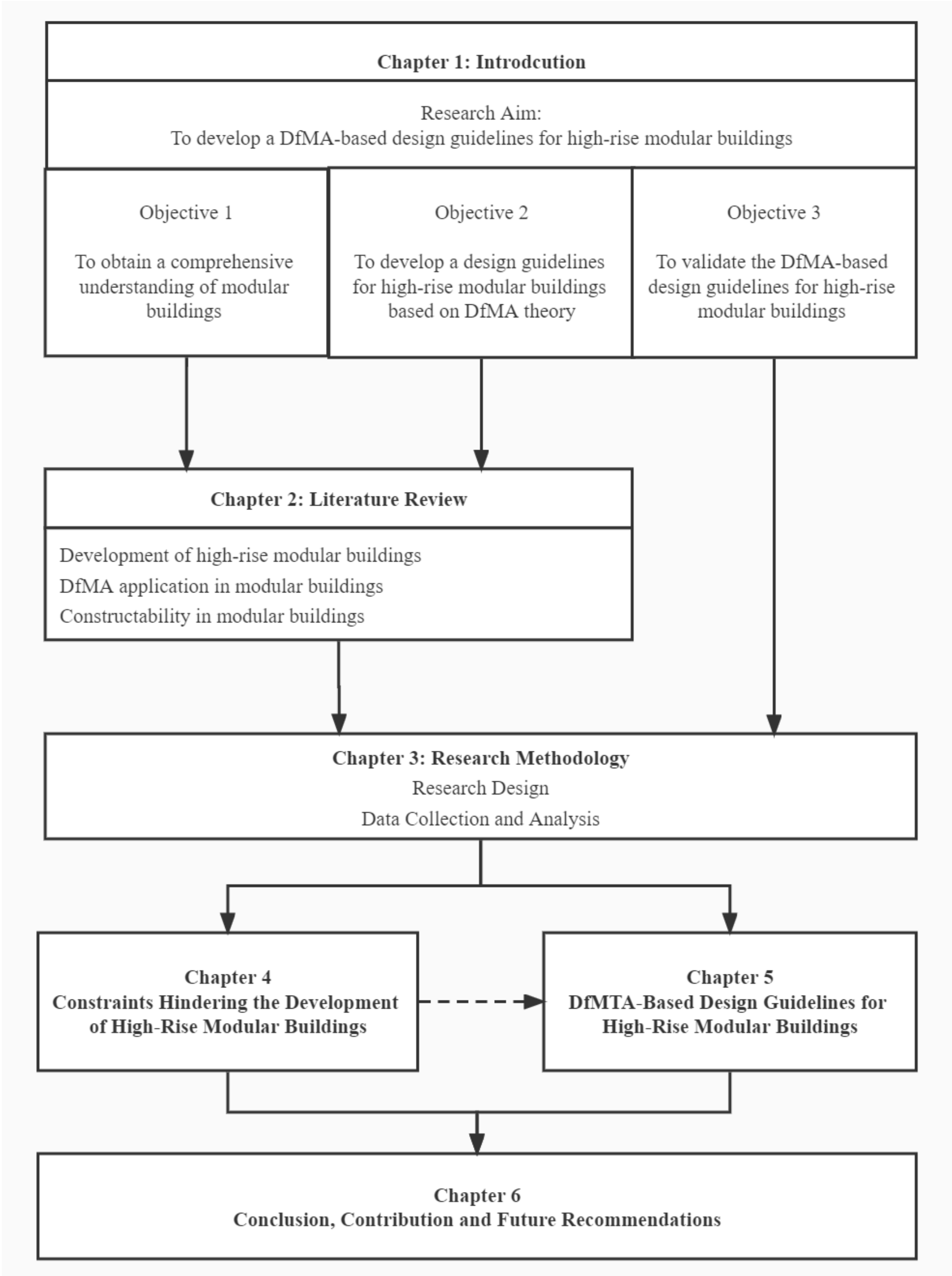


Figure 1.2 Structure of the thesis

1.6 Summary

This chapter described the background of the research and then clarified the urgency of this research associated with three research questions. To address these questions, the aim and objectives of the research were proposed, followed by the significance and contributions of the research. The organisation of the thesis was also outlined.

Literature Review

2.1 Introduction

This chapter reviews three topics related to this research. The first part reviews the literature to explore the historical development, benefits and challenges of modular buildings, which contributes to Objective 1 to obtain a comprehensive understanding of modular buildings. The second part reviews the concept of DfMA coupled with applications in modular buildings, and the third part reviews constructability in modular buildings. The second and third parts play a key role in achieving Objectives 2 and 3.

2.2 Modular Buildings

This section presents a holistic view of modular buildings, followed by the benefits and challenges discovered in practical applications.

2.2.1 Overview of modular buildings

OSC is not a new phenomenon. Gibb (2001) claimed that the application of OSC dates back to 1851, when the Crystal Palace in London was constructed of factory-made pre-assembly components. The first large-scale application of OSC was also in the United Kingdom. A large number of precast components were used to quickly restore houses that had been damaged or destroyed in World War II. OSC is a modern method of construction in which prefabricated components and modules are manufactured in off-site factories that provide a controlled environment for high-quality production. After sea and road transport, the produced components and modules can be erected and installed in the on-site buildings (Khalfan & Maqsood, 2014). Construction industry participants and academics in different countries have embraced the opportunities and challenges of OSC and rethought the holistic construction process and environment to explore a feasible solution that makes full use of the advantages of OSC (Blismas et al., 2009; Pan et al., 2008).

As a result of the development and maturity of OSC, an increasingly higher degree of prefabrication has been applied. Not confined to a simple precast component, the construction industry developed sophisticated prefabricated modules embedded with various manufactured components, which fulfil the immense potential of OSC. By conforming to the degree of prefabrication, Goodier and Gibb (2007) categorised OSC into four levels: component manufacture and sub-assembly, non-volumetric pre-assembly, volumetric pre-assembly and modular building (see Table 2.1).

Table 2.1 Level of OSC

Level	Category	Definition	Sample
1	Component and sub-assembly	Small components manufactured at an off-site factory	Precast beam and column, Preassembled mechanical and electrical elements
2	Non-volumetric pre-assembly	Pre-assembled panels not enclosed usable space	Panelised wall, flat pack
3	Volumetric pre-assembly	Pre-assembled units enclosed usable space with internal finishing	Bathroom pod, kitchen pod
4	**Modular building**	Pre-assembled units formed a building with fully internal finishing	PPVC, PPVM, MiC

Modular buildings, which symbolise the highest level of OSC, maximise prefabricated modules at off-site manufacturing factories while minimising construction activities in-situ (Murray-Parkes & Bai, 2017). Modular buildings strive for a high prefabricated rate aiming at completed finishes and MEP systems in the factory environment. Nearly completed modules are then delivered to the construction site for assembly and to complete the installation (Liew et al., 2019; Nahmens & Ikuma, 2012).

These prefabricated modules are classified as steel, concrete and timber frame modules (see Table 2.2) in accordance with the primary building material (Lacey et al., 2018). The timber frame module is the most sustainable module for low-level buildings and housing. Along with increasingly advanced techniques used in timber frame modules, such as cross-laminated timber (CLT), glue-laminated timber (GLT) and nail-laminated timber (NLT), timber frame modules have better strength and durability (Foster et al., 2016). As more common prefabricated modules, concrete and steel frame modules dominate the market of modular buildings, especially for high-rise modular buildings. Concrete modules leverage load-bearing walls to transfer gravity loads to the foundation while resisting lateral loads. The concrete module system is the preferred solution for residential buildings, which benefit from its outstanding performance in fire resistance, thermal insulation, sound insulation and durability (Liew et al., 2019). However, thick and solid concrete walls increase the weight of the concrete module unit to approximately 20–35 tonnes (BCA, 2017). In contrast to concrete modules, steel modules have a light weight of 15–20 tonnes. In recent years, as a lighter option, a light steel frame module has increasingly been applied to modular buildings in consideration of the bulk transportation and lifting in modular construction (Gorgolewski et al., 2001). This system adopts a different structure—namely, corner-supported modules—in which loads are transferred by way of edge beams to corner posts (Hough & Lawson, 2019). Furthermore, steel modular units offer architects more flexibility in design, which is attributed to the fully open-sided framing system and larger beam span (M. Lawson et al., 2014). The construction industry has had doubts about the fire resistance and strength of the steel modules used for high-rise buildings; therefore, hybrid structures are widely used in modular construction. Steel modules are commonly installed on a podium or around a concrete core in high-rise buildings (R. M. Lawson & Ogden, 2008; R. M. Lawson & Richards, 2010; Thai et al., 2020).

Table 2.2 Classification of prefabricated modules

Category	Advantages	Disadvantage	Structures
Steel module	Lightweight Easy installation Flexibility	Fire resistance Strength Corrosion	Corner-supported modules
Concrete module	Fire resistance Thermal insulation Acoustic insulation	Heavy Connection grout	Load-bearing modules
Timber module	Sustainability Easy fabrication	Fire resistance Durability	CLT modules GLT modules NLT modules

2.2.2 Benefits and challenges of modular buildings

Various benefits of modular buildings have been found in previous studies. Modular buildings endeavour to promote the efficiency and productivity of construction. R. M. Lawson et al. (2012) reported that modular construction can reduce the construction period by 50–60% in contrast to traditional construction. As a result of massive repetitive units, high-rise modular buildings can achieve significant savings in construction time (Kamali & Hewage, 2016). Moreover, construction is a high-energy consumption and high-pollution industry. Traditional on-site construction generates materials wastage, including plaster, concrete, rubber and blocks (Pons, 2014). Nahmens and Ikuma (2012) used several case studies to determine the considerable effects of reducing material waste by 64%. Tam and Hao (2014) also pointed out that modular buildings can achieve a significant reduction of wastage generation, including plastering (100%), timber formwork (73.91–86.87%), concrete (51.47–60%) and reinforcement steel (35–55.52%). Furthermore, prefabricated modules comprising modular buildings are manufactured in factories secure pertinent supervision, consistent quality and prompt rectification (Ho et al., 2018; Tam et al., 2015). As a result of the minimised on-site activities and maximised factory manufacturing, health and safety risks are reduced significantly in modular buildings (Boyd et al., 2013).

However, the uptake of modular buildings in the construction industry is still relatively low. Clients are reluctant to boost their investment in modular buildings because of insufficient experience and expertise (Y. Gan et al., 2017; B.-G. Hwang et al., 2018a). The construction market and society have pervaded a sense of unacceptance of modular buildings because of few renowned projects and underestimation of prefabrication (Luo et al., 2015). 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. (2013) indicated that the perceived higher capital cost is a severe drawback in modular construction. Mao et al. (2016) investigated multiple case studies and found that the capital cost of modular construction, including design and construction costs, was 25% higher compared with conventional construction. In addition, R. Jiang et al. (2018) and X. Gan et al. (2018) suggested that the lack of government policy support, including incentives and guidance, curbs the spread of modular construction. Regarding the design of high-rise modular buildings, the scarcity of relevant codes and standards is a major obstacle in the path to extensive utilisation, although a few guidelines related to modular construction have been established recently (Mao et al., 2015; Murray-Parkes & Bai, 2017; Xu et al., 2020).

Modular building design, which is not as mature as traditional building design, has experienced difficulty because of a lack of designers with experience and knowledge (Blismas et al., 2009; Kamar et al., 2014). To guarantee error-free drawings delivered to manufacturers, designers have to devote excessive time to modular design, which results in a long lead-in time for the adoption of modular buildings (Pan et al., 2007). Furthermore, although modular buildings present high-level modularisation and standardisation, they are disputed for underdeveloped design flexibility (Jaillon & Poon, 2010; X. Zhang et al., 2014). In addition, the capacity of suppliers and manufacturers cannot keep pace with demand from the growing utilisation of modular construction. Blismas et al. (2009) identified that the domestic supply chain of prefabrication cannot keep up with the progress of modular buildings. Developers and designers are reluctant to adopt modular buildings because of 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 (Goodier & Gibb, 2005). Despite reduced labour at the construction site, modular construction requires a vast amount of skilled labour for the manufacture of prefabricated modules, which increases the construction cost (Choi et al., 2017).

In addition, transportation is an indispensable part of modular construction, with the delivery of modules from factories to construction sites accounting for approximately 10% of overall costs (Hong et al., 2018; R. M. Lawson et al., 2012). W. Lu and Yuan (2013) indicated that transportation costs can increase to over 18% of the total cost when taking into account long-distance transport resulting from offshore manufacture. Moreover, the weight and dimensions of modules restrict the transportation route and increase the cost as a result of specific vehicle requirements (Navaratnam et al., 2019; Wei et al., 2014). Regardless of the method of transport used (cargo, rail, road), damage to modules during transit must be considered. Transportation teams that supply transportation services should spend considerable time and money on extra protection to avoid severe damage to modules, which may trigger construction delays (Z. Liu et al., 2018). In the process of on-site assembly, a substantial amount of equipment—especially cranes—is required to install prefabricated modules, which increases the overall cost (Mao et al., 2016; Tam et al., 2015). Contractors should pick up competent mobile cranes or fixed cranes based on the crane capacity of radius, load and height. Moreover, Salama et al. (2017) revealed that numerous complex connections of modular buildings are a critical issue during the installation of modules. As a result of the lack of corresponding inspection criteria, contractors must spend a significant amount of time on connection installation to reduce underlying quality issues such as water leakages (Sun et al., 2018; Xu et al., 2020).

2.2.3 Summary

Modular building is a state-of-the-art OSC with the greatest degree of prefabrication. Modular buildings reflect the comprehensive advantages of OSC in terms of improved quality, reduced waste, enhanced sustainability, increased quality, and decreased health and safety risks. However, the application of modular buildings is still relatively low, especially for high-rise buildings. Although previous studies have disclosed a variety of constraints that hamper the development of modular buildings, these studies concentrated on qualitative descriptions of the constraints but lacked quantitative and in-depth investigations that could uncover the roots and interrelations of these constraints.

2.3 Design for Manufacture and Assembly

This section reviews the concept and development of DfMA and then introduces the application of DfMA in modular buildings.

2.3.1 Overview of DfMA

Derived from the manufacturing enterprise, the concept of DfMA is a combination of DfM (Design for Manufacture) and DfA (Design for Assembly). The concept of DfA emerged in the late 1960s and early 1970s, when companies realised that design is the first step in production. With the rapid development of automatic production, more manufacturers wanted to upgrade their traditional manual assembly. However, manufacturers were compelled to adjust the original design to meet the requirements of automated assembly. DfA grew out of the process of redesign, which sought fewer assembly parts coupled with simplified assembly procedures (Boothroyd, 1994). In 1977, Boothroyd and Dewhurst developed a relatively mature DfA method to estimate the time and costs of automated assembly on machines that contribute to the economic selection of materials and processes (Boothroyd, 2005). In 1980, Boothroyd published *Design for Assembly: A Designer's Handbook* and interpreted it into a computer program (Boothroyd & Dewhurst, 2011). In contrast, the concept of DfM stemmed from the successful application of DfA in the practice of manufacturing (Kuo et al., 2001). Concentrating on lower manufacturing costs while ensuring quality, DfM compares selected materials and processes to achieve the most efficient use of the component design (Ashley, 1995; Ulrich et al., 2020). Andersson et al. (2014) pointed out that DfM can be adopted in the detail design stage with the aim of minimising manufacturing costs, which is a large part of the entire product cost. However, even in manufacturing, few design engineers have exhaustive knowledge and experience of manufacture and assembly technologies. As a result, delivered designs are not optimised designs, and various issues lead to amendments in the processes of manufacture and assembly (Bogue, 2012). Meanwhile, hi-tech products now are sophisticated. Effectiveness and efficiency of manufacture and assembly are essential requirements in manufacturing (Gao et al., 2019). The DfMA method and principles provide a methodological approach to quantify potential shortages and improve product design for both economic manufacturing and assembly (Boothroyd, 2005).

Based on DfMA practices in manufacturing, Boothroyd (1994) summarised the typical procedure of DfMA as shown in Figure 2.1. DfA is the first step in developing the conceptual design. Within this step, two targets—the simplification of the product structure, and economic selection of materials and processes—should be achieved. Depending on the final selection of materials and processes, DfM is able to perform a detailed design of the parts for minimum manufacturing costs. Concerning the typical DfMA procedure, Bogue (2012) demonstrated three approaches to administering a DfMA process in accordance with the development of DfMA. The first method, in conjunction with the original DfMA concept, is to follow a general set of rules or qualitative guidelines, which requires design engineers to interpret and implement these non-specific guidelines in each case. The second method, attributed to more practices of DfMA, employs a quantitative evaluation of the design. Boothroyd and Dewhurst (2011) established a set of evaluation criteria to rate each part of the design with a numerical value depending on its 'assemblability'. The calculated value for the entire design is linked to the overall design quality, and the resulting values of each part are used as a guide in the redesign process (Boothroyd & Dewhurst, 2011). The third method achieves the automation of the entire process, including quantitative analysis through computer software. The design rules and criteria for DfMA are interpreted as programs that can automatically analyse the product design and then optimise it repeatedly until the evaluation result meets the requirements of design quality (Bogue, 2012).

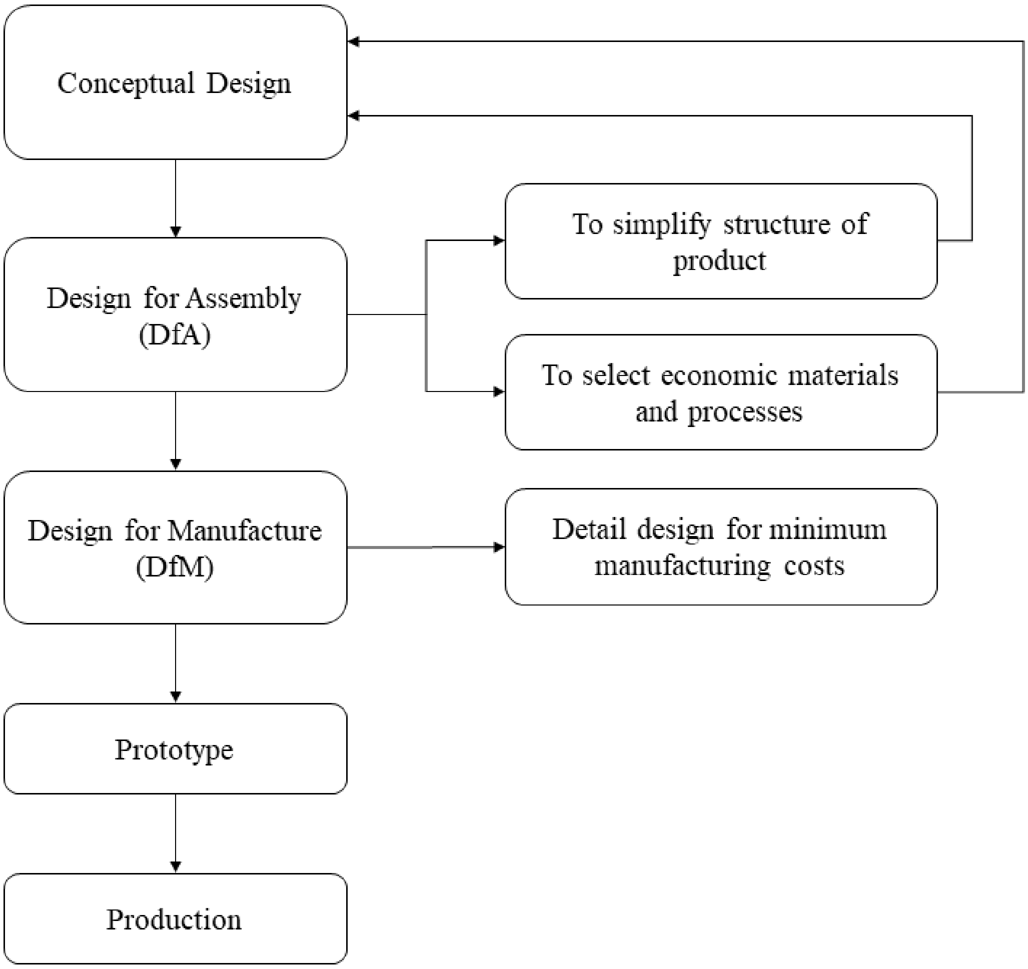


Figure 2.1 Typical procedure of DfMA (Boothroyd, 1994)

2.3.2 DfMA application in modular buildings

Having witnessed the successful application of DfMA in the manufacturing industry, the construction industry has attempted to embrace DfMA in recent years. With the development of OSC, DfMA has provided innovations and opportunities for solving the imbalance between the growing housing demand and inefficient construction productivity. The implementation of DfMA in OSC has been explored in previous empirical projects. Trinder (2018) demonstrated that DfMA-focused management delivers cost, time and quality improvements in water construction projects. Safaa et al. (2019) showed that implementing DfMA in bridge construction projects achieves significant outcomes, including around 28% simplification of design, 8% saving in component materials, 25% ease of handling, 51% assembly time, 23% cost of work and 18% duration. Compared with infrastructure construction, building construction has raised the application of DfMA to a higher standard. K. Chen and Lu (2018) revealed the benefits of a DfMA-oriented curtain wall system in terms of reduced material cost and waste, decreased assembly time on site, and improved quality and performance of the curtain wall system. According to Gerth et al. (2013), the use of DfMA theory can facilitate the identification of potential problems, optimise wall joint design and minimise assembly operation. Banks et al. (2018) embraced the principles of DfMA in the design stage of a high-rise residential building that delivered optimal solutions involving precast components, prefabricated bathroom pods and modular MEP services. Conversely, high-rise modular buildings can reap the full benefits of DfMA because of the large number of modules with high repetition and low variation in types (Xu et al., 2020). Banks et al. (2018) applied DfMA principles to a 40-storey modular building, which led to a reduced program and improved safety, quality and reliability throughout the design, manufacture and transportation stages.

2.3.3 Summary

Combined with DfM and DfA, DfMA is a design philosophy and methodology that considers manufacturing and assembly at the design stage. DfMA stems from the manufacturing industry and is an emerging method adopted in OSC. In relation to the nature of industrialisation and modularisation, a high-rise modular building is an ideal building type to exploit the advantages and potential of DfMA (BCA, 2017). Although many studies have explored the development and progress of DfMA integrated with theory and practice manifesting its drivers, prospects as well as challenges in construction. Few studies have provided a quantitative evaluation criterion of DfMA that transforms abstract design philosophy into a concrete numerical value to offer direction for architects and engineers in the design stage of modular construction. In addition, few investigations have focused on implementing DfMA for high-rise modular buildings, although this cutting-edge construction approach represents the trend of future construction (Pan & Hon, 2020).

2.4 Constructability in Modular Building

This section first provides a definition of constructability. As an alternative to traditional construction, modular buildings have a new interpretation of constructability. From the perspective of the DfMA concept, the nature of the constructability of modular buildings can be classified into manufacturability, transportability and assemblability, which are reviewed in the following sections.

2.4.1 Constructability definition

The following definition of constructability was provided by the Construction Industry Institute (CII): ‘Constructability is the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives’ (CII, 1986). Constructability became an important project management method for evaluating entire stages of a project based on 17 application principles (CII, 1993).

According to the 17 principles, a constructability program can integrate project design coupled with practical knowledge and experience to realise the project’s goal (Jadidoleslami et al., 2018). Fischer and Tatum (1997) stated that constructability should be considered a primary objective throughout all stages of construction. Furthermore, previous studies have shown that designers play a vital role in achieving exceptional constructability (Jergeas & Van der Put, 2001). According to Stamatiadis et al. (2017), the construction industry encourages a constructability review during the design stage to optimise design options based on executive experience and knowledge. Arditi et al. (2002) pointed out that the majority of benefits of constructability reviews, including improved quality and reduced costs, are obtained in the design stage. Therefore, to seek maximum advantages, design teams exploit the constructability program as early as the conceptual planning phase (El Sayed et al., 2021; Pulaski & Horman, 2005). Moreover, the applications of new tools and techniques (e.g. BIM) promote constructability programs during the project design. J. Wang et al. (2016) developed a BIM framework integrated with a constructability review to improve MEP layout designs. Boton (2018) also proposed a four-step approach to support constructability analysis with virtual reality and BIM four-dimensional (4D) simulation technologies.

2.4.2 Constructability in modular buildings

Although numerous studies have explored the considerable benefits of constructability programs from the early design stage, many projects have not obtained constructability input (Jergeas & Van der Put, 2001). The most important reason for this is the lack of unambiguous knowledge and experience of constructability that can assist designers to provide well-developed design solutions that fully take into account constructability involving procurement, construction, maintenance, etc. In relation to modular buildings, transferring related knowledge and experience to designers regarding downstream stages in terms of manufacture, transportation and assembly is key to the success of constructability programs (Fox et al., 2002).

- Manufacturability

In contrast to traditional construction, modular buildings comprise numerous prefabricated modules that are completely manufactured in off-site factories. As a result, the manufacturing stage plays a vital role in modular construction and requires more time than on-site activities such as assembly and installation. To provide an efficient manufacturing process with minimum manufacturing costs, the design team should closely collaborate with the manufacturer to optimise the details of fabrication involving connections for services, standard components and installation methods (Murray-Parkes & Bai, 2017). Furthermore, Kuo et al. (2001) claimed that designers should consider the raw material selection and manufacturing process at the early design stage to enhance manufacturability. Collins and Grubb (2008) and Boarin et al. (2015) also stated that improved manufacturability—for instance, standardised units and rational economic scale—can promote the efficiency of projects and save costs. Blismas (2007) revealed that issues that are hidden in the manufacturing process are unveiled in construction sites, resulting in overrun costs and construction delays.

- Transportability

The main transportation modes applied in modular construction are shipping and road, depending on where the prefabricated modules are produced. The completed volumetric modules are shipped by international carriages from off-shore manufacturers. However, in some projects supplied by domestic manufacturers, prefabricated modules are transported by road only (Murray-Parkes & Bai, 2017). During road transportation, the maximum size and load of the transported modules are limited by local laws and regulations (Sun et al., 2019). Therefore, designers and involved stakeholders should consider the dimension and weight of prefabricated modules from the early design stage in terms of logistics, manufacturers and contractors (Lloyd et al., 2021). Furthermore, the protection of transported modules should be proposed by designers to prevent damage during transportation (W. Lu & Yuan, 2013).

- Assemblability

Module buildings have reshaped the construction industry by leveraging game-changing technologies. Lego-like assembly has taken the place of traditional construction methods and significantly reduces on-site construction activities and time (BCA, 2017). To achieve a well-developed assembly procedure, specific configurations of lifting and erection should be considered by designers, including the tower cranes plant, the centre of gravity and sling angles (Murray-Parkes & Bai, 2017). Moreover, module-to-module connections secure the stability and robustness of the structure of modular buildings (Ferdous et al., 2019). As a result, it is a challenge for designers to propose reliable connection systems with applicable connection types regarding different types of modules (Lacey et al., 2018).

2.4.3 Summary

In recent decades, the architecture, engineering and construction (AEC) industry has employed constructability to interpret construction knowledge and experience in the design stage to promote the performance of buildings (L. Jiang & Leicht, 2015). According to constructability reviews, design teams can optimise design and construction programs to save construction costs and time (Stamatiadis et al., 2017). As a result of the innovative construction method, modular buildings have different perspectives on constructability. It is important to transfer downstream knowledge and experience (e.g. manufacturing, transportation and assembly) to designers who lack the relevant information concerning modular construction (Gao et al., 2018).

Research Methodology

3.1 Introduction

According to Novikov and Novikov (2013), methodology refers to the theory of the organisation of an activity, despite not all activities being organised with methodology. Research is considered an academic activity, and a term requires being adopted in a technical sense (Kothari, 2004). Research methodology comprises a system of methods and techniques that designates principles and procedures for systematically addressing new or existing problems, supporting current theories and establishing new theories (Byrne, 2016; Fellows & Liu, 2015; Knight & Ruddock, 2008).

This chapter presents the research methodology used in this thesis in terms of the method selection, data collection and data analysis for each objective. The next section illustrates the research design, followed by the research methods for each objective. A summary of this chapter is then presented.

3.2 Research Design

A mixed research method, which includes both the qualitative and quantitative research approaches, is used in this research. Figure 3.1 presents the research design of this study. The research methods for each objective are elaborated below.

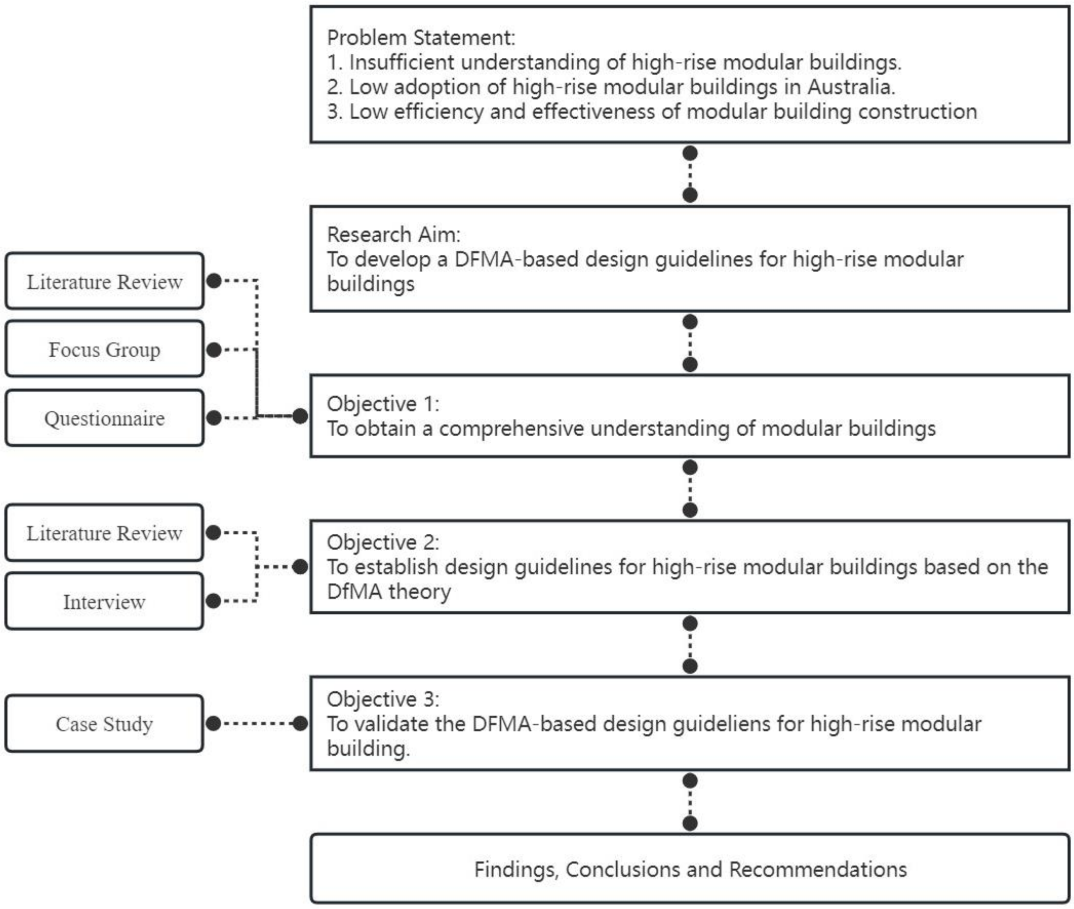


Figure 3.1 Research design

3.3 Research Method for Objective 1

Objective 1 aims to obtain an in-depth understanding of modular buildings, with a focus on the constraints hindering the development and application of high-rise modular buildings. This objective is the cornerstone of this research, which explores the major problems in the industry, while providing feasible approaches and methods.

As shown in Figure 3.2, a three-step mixed research method was designed for the first objective. First, the literature review aimed to establish a preliminary list of constraints of the applications of modular buildings. Second, the preliminary list of constraints was discussed and refined in a focus group to achieve the final list of constraints. Third, a questionnaire survey was conducted, and professionals from the academy and industry evaluated and ranked the constraints.

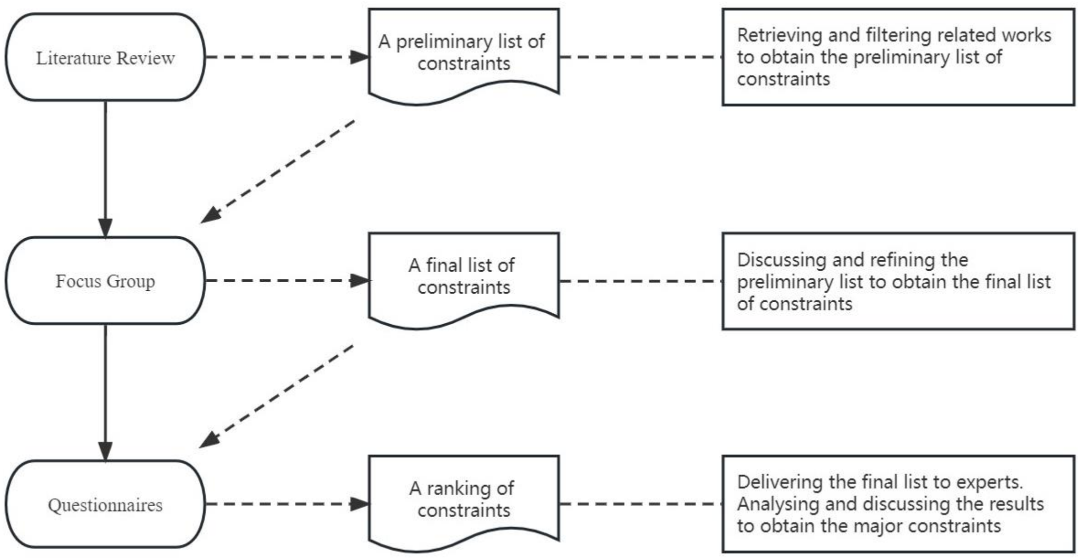


Figure 3.2 Research design for Objective 1

3.3.1 Literature Review

The literature review for Objective 1 can be divided into two parts. First, paper retrieval related to the benefits and barriers of modular buildings was conducted. Second, the final selected papers were then analysed and summarised to establish a preliminary list of constraints of modular building.

To formulate the preliminary list of constraints, a literature review was conducted systematically and involved two steps: (1) retrieving previous works from the academic database following predefined keywords; and (2) filtering selected articles in accordance with the constraints hindering the application of modular buildings (see Figure 3.3).

- *Retrieving*

1) Only academic journals were selected for review. Book chapters, conference papers and non-international journals were eliminated. The two largest academic databases—Scopus and Web of Science—were used to identify relevant publications. The scope of publications was limited from September 2000 to September 2020.

- Data Collection

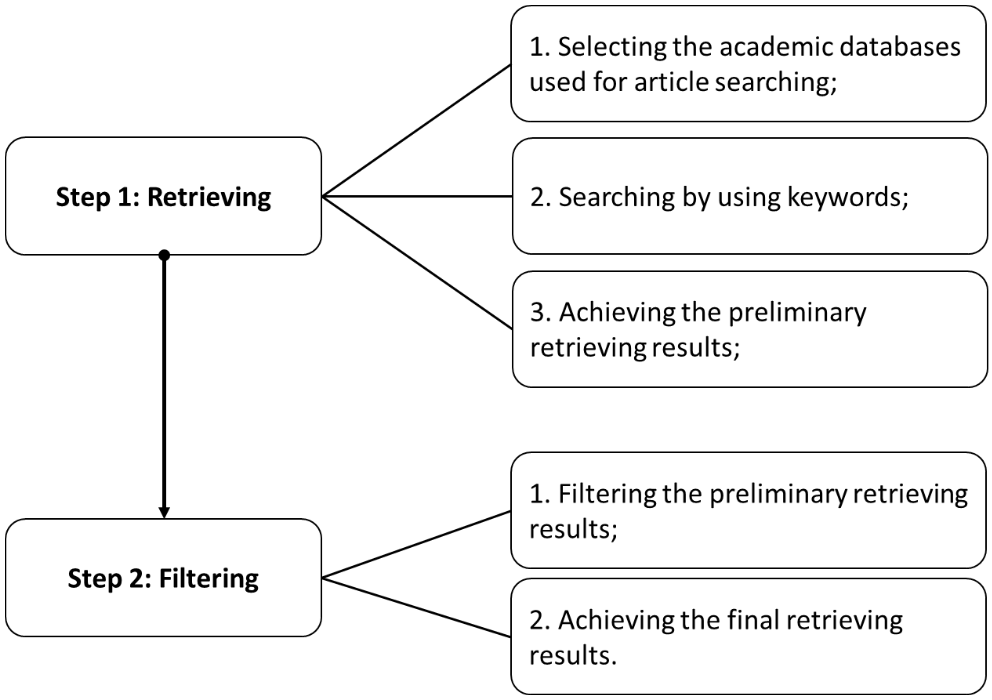


Figure 3.3 Data selection process

2) Document retrieval was performed according to 'Article title, Abstract, and Keywords'. Two sets of keywords were deployed in this retrieval process, including ('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'). A total of 489 articles were initially retrieved.

- *Filtering*

1) To identify publications related to the study, a manual screening review of the abstract and contents was conducted to exclude papers that were not closely related to this research. A total of 102 publications were identified.
2) A manual retrieval was conducted to discover relevant publications that were not identified. A Google search revealed non-academic publications including reports, guidelines and handbooks published by relevant authorities and professionals. For example, several DfMA guidelines were identified from the BCA of Singapore. A total of 118 publications were disclosed for data analysis (see Figure 3.4).

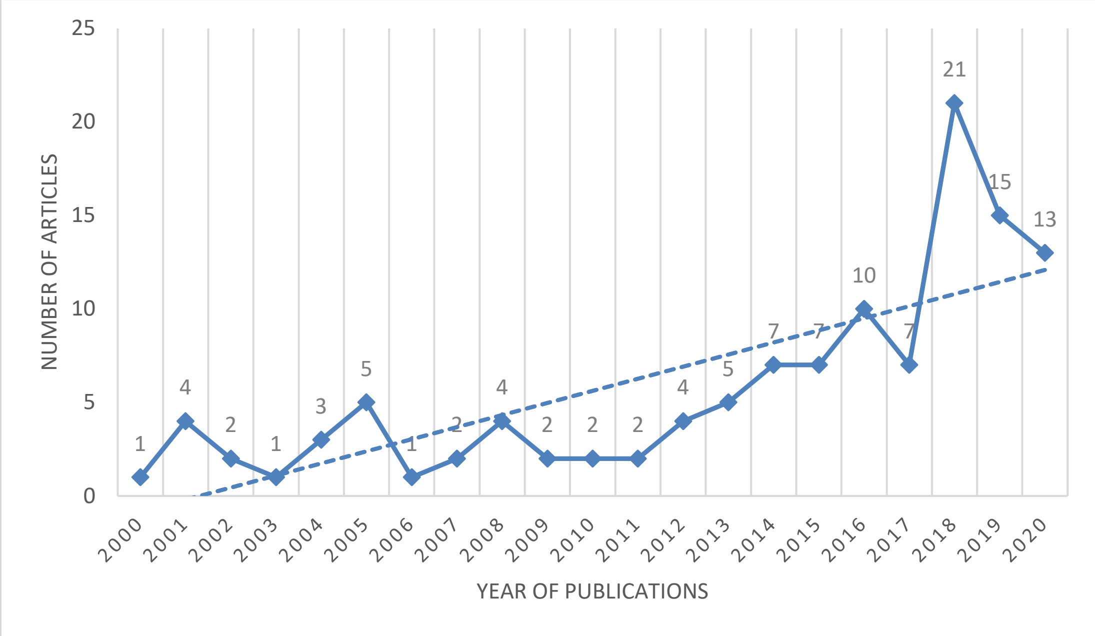


Figure 3.4 Distribution of relevant articles by years (2000–2020)

- Data Analysis

After the data collection, a content analysis of the 118 retrieved publications was conducted. Table 3.1 presents the codes of the content analysis. Figure 3.4 presents the first code of content analysis, year of publication. The number of publications related to the topics increased dramatically from 2014. In 2018, over 20 publications were relatively close to this study. 12 identified papers were pubulished on Journal of Cleaner Production followed by Automation in Construction and Journal of Construction Engineering and Management, which both published 11 papers. Concerning the code of countries UK and China have the most studies within the selected papers. Modular building is a state-of-the-art OSC method that reduces construction time, waste and risks, leveraging an array of prefabricated prefinished modules (BCA, 2017; W. Lu & Yuan, 2013; Tam & Hao, 2014). Considering the highest level of prefabrication, modular building fully shows the strengths as well as the drawbacks of OSC (Kamali & Hewage, 2016; Pan et al., 2018; Sun et al., 2020). As a result, to understand the current development of modular buildings, selected publications were reviewed and analysed from three perspectives: the level of prefabrication, the benefits of modular building application and the barriers of modular building application.

Table 3.1 Codes of content analysis

Codes	**Description of the Codes**
Year of publication	Distribution of selected papers by years
Journals of articles	Journals that published the selected papers
Countries	Countries in which the selected papers were studied
Level of prefabrication	Degree of OSC adopted in the selected papers
Benefits of modular building	Benefits have been reported
Barriers to modular building	Barriers have been reported

3.3.2 Focus Group Study

A focus group study is an efficient method for observing a large number of interactions and adding related data to a topic in a limited period (Morgan, 1997; Rabiee, 2004). As a qualitative approach, a focus group study is adopted in many studies related to the construction industry to obtain a comprehensive understanding of practical applications and experience (Hijazi et al., 2021; Leung et al., 2014; Liang et al., 2018). A preliminary list of constraints in modular construction was established after conducting an in-depth literature review. According to the focus group study, these constraints were scrutinised and refined by 12 experienced experts to achieve a final list of constraints of modular building implementation for the questionnaire survey.

- Participants

To collect practical information related to modular buildings in Australia, there were two criteria for experts' recruitment:

1) over five years of experience in modular construction

2) involved in at least one modular building project in Australia in the last 10 years.

Finally, thanks to ARC trainning centre, 12 experts from different stakeholders in this research project were invited to participate in this study.

Table 3.2 Profile of experts in the focus group study

Role	**Job Title**	**Years of Experience**
Academic Researcher	Professor	8
	Senior lecturer	6
Developer	Business manager	10
	Design manager	5
	Operation manager	6
Consultant	Senior architect	8
	Architect	5
Manufacturer	Design manager	7
	Operation manager	6
Contractor	Project manager	8
	Site manager	12
Transporter	General manager	8

Table 3.2 presents the profile of the 12 invited participants, including roles of stakeholders, job titles and years of experience in modular construction. To obtain feedback covering the entire life cycle of modular construction, the participants of the focus group study consisted of two from the academy, three developers, two consultants, two manufacturers, two contractors and one transporter.

- Data collection and analysis

The author introduced the aim and objectives of this research at the commencement of the focus group study. Next, the ground rules and the confidentiality of the discussion were clarified to alleviate the effect of groupthink during the focus group study (Leung & Chan, 2012). The overall process of the focus group discussion was recorded by the author. Furthermore, as a moderator of the study, the author used worksheets and whiteboards to highlight key points raised by participants.

The author presented the preliminary list of constraints proposed from the literature review to all participants, who then wrote down feedback on the worksheets based on their relevant experience. In line with content analysis, this feedback was classified and presented on the whiteboard for discussion. In addition to the discussion on the preliminary list of constraints, participants posed more challenges in modular construction. As a result, the final list of constraints hindering the development of modular buildings was developed, which is explained in Chapter 4.

3.3.3 Questionnaire Survey

A questionnaire survey is the preferred approach for collecting data about general opinions on one topic (Yin, 2014). It has been widely adopted in research related to modular construction (B.-G. Hwang et al., 2018a; Mao et al., 2015; P. Wu et al., 2019; Wuni & Shen, 2020).

- Data collection and analysis

In this research, the questionnaire survey was distributed among experts from different sectors of modular construction. A total of 140 questionnaires were issued via emails, an online survey platform and snowball sampling. The survey consisted of two sections. The first section collected the respondents' basic information, including occupation type and experiences in modular construction. The second section inquired about the final list of constraints hindering the implementation of modular buildings. Respondents were asked to use a five-point Likert scale ranging from five ('strongly agree') to one ('strongly disagree') to evaluate every single factor. Descriptive analysis was used to evaluate the primary barriers to the application of modular building. More details on the data collection and analysis are provided in Chapter 4.

3.4 Research Method for Objective 2

Objective 2 aims to establish a design guideline for high-rise modular buildings based on the DfMA concept. According to the outcome of Objective 1, a lack of design standards and guidelines affects the quality of modular design. Furthermore, as a result of insufficient experience and knowledge related to the downstream processes of modular construction, including manufacturing, transportation and assembly, designers must spend more time and effort on the modular design. A design guideline integrated with DfMA theory can mitigate these issues. As shown in Figure 3.5, three primary steps were performed to achieve Objective 2.

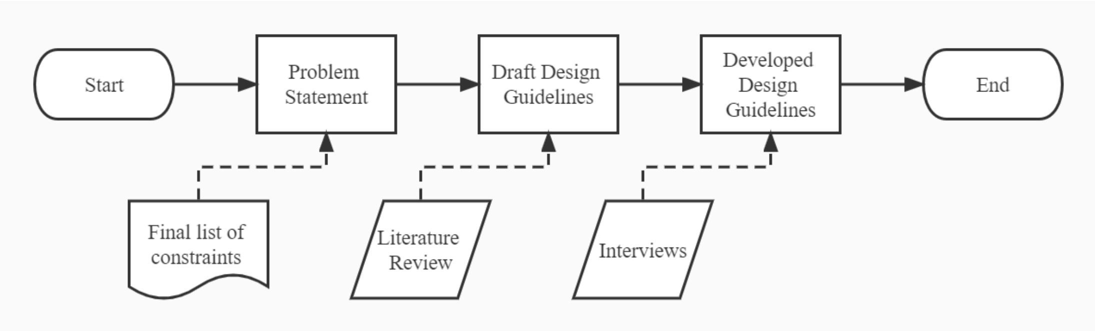


Figure 3.5 Research method for Objective 2

3.4.1 Problem Statement

The final list of constraints hindering the application of high-rise modular buildings (obtained from Objective 1) disclosed the main barriers throughout all of the processes of modular construction, including the design, manufacture, transportation and assembly stages. In comparison with other constraints, the constraints in the design stage have wider implications for all downstream stages. Many delays and overruns can be attributed to the potential issues of modular design (Jaillon & Poon, 2010; M. Lawson et al., 2014; R. M. Lawson & Richards, 2010).

As a result, the first step of the research method for Objective 2 was a problem statement that aimed to identify all factors related to the modular design. After scrutinising the constraints obtained in Objective 1, the factors were categorised into two groups. Some barriers affect the design stage only, whereas others are closely related to downstream stages. An in-depth analysis was then conducted to explore the requirements and gaps based on the current body of knowledge and practices.

3.4.2 Draft Design Guidelines

According to the problem statements, constraints in the design stage affect not only the quality of modular design but also the quality and productivity of downstream stages in terms of manufacture, transportation and assembly. A lack of relevant standards and guidelines for modular design results in prolonged design time and poor design quality (Blismas et al., 2009). Therefore, providing a guideline for modular design based on the DfMA concept is a key solution to improve the performance of modular construction. To develop an elementary design guideline, a comprehensive literature review was conducted in the second step. The literature review investigated existing DfMA guidelines for modular buildings and focused on DfMA applications in OSC, especially in high-rise modular buildings. In addition to journal articles, regulations published by governments were reviewed. For example, during the transportation process, the prefabricated modules might be affected by local road traffic regulations, which stipulate details of oversize and overmass vehicles. Moreover, data collection was conducted from relevant stakeholders. For instance, to consider assemblability, data and information about tower cranes were gathered from local tower crane hire companies. After conducting the abovementioned data collection, a content analysis focusing on the constructability of modular buildings was performed. Limited previous studies have offered a quantitative evaluation criterion of the constructability of high-rise modular buildings. To bridge this gap, a draft design guideline was proposed, which outlined the criteria for the constructability of high-rise modular buildings in terms of manufacturability, transportability and assemblability.

3.4.3 Developed Design Guidelines

To ameliorate the draft design guideline, an interview was conducted with all relevant stakeholders. The draft guideline was initially provided to all participants in a monthly construction meeting. Eight experts attended the interview, including a project manager from a developer, a site manager, two design coordinators from the main contractor, two architects from the consultant, a design manager from the manufacturer, and an operations manager from logistics. After listening to the author’s introduction and reviewing all criteria, the participants put forward questions and suggestions on papers. An in-depth discussion concerning these questions and suggestions was conducted, and the entire interview was recorded. The revised design guideline was developed, which is explained in Chapter 5.

3.5 Research Method for Objective 3

Objective 3 aims to validate the DfMA-based design guidelines for high-rise modular buildings. The developed guidelines consisted of three parts: DfM, DfT and DfA. To identify the implementation of each part, two real-life projects were used to validate the guidelines.

Case study

A case study is an appropriate approach for providing supplementary information for across-the-board research in the construction industry. In-depth interviews embedded with case studies are acknowledged as an efficient method for investigating the prevailing circumstances through real-life construction projects (B.-G. Hwang et al., 2018a; Mao et al., 2016; Yin, 2014; Yuan et al., 2018).

Case description

Project 1

This chosen project involved the development of three blocks of 12-storey residential buildings upon a three-storey commercial building. There was a total of 216 apartment units comprising over 700 steel frame prefabricated modules.

Project 2

This chosen project was an 18-storey hotel comprising over 160 prefabricated steel-frame modules in Australia. It provides 252 guest rooms, a lounge, a restaurant and bar, a meeting room, a business corner, and a gymnasium.

Data collection and analysis

The research was conducted from the design and planning stage in cooperation with all stakeholders involved in the two projects. To validate the DfM of guidelines, manufacturing information was collected. The manufacturer provided details of the manufacturing process and manufacturing materials, which were scrutinised in accordance with the criteria for guidelines, and modified solutions were then delivered to the design team. In the next step, the design team adopted the guidelines coupled with the received manufacturer's solutions to design the prefabricated modules. To evaluate the validity, efficiency and effectiveness were key factors under review. Periods of design and manufacturing were recorded, and all design issues exposed during the manufacturing stage were collected by request for information (RFI) records. Last, experts from the design team and the manufacturer were invited to review the entire process. With regards to DfT, the developed guidelines were provided to the design team and the logistics team. Designers considered transportability based on the criteria for the guidelines, including 1) size of modules, 2) weight of modules, 3) delivery path and 4) delivery protection. The entire period of the transportation stage was recorded. The design and logistics teams were invited to discuss the effort of DfT. To validate the DfA, the design team was provided with details of the criteria in terms of erection and connection information. The next step was to record the period of design and assembly while reviewing all communications between the two parties. Last, the efficiency and effectiveness of DfA were discussed with consultants and contractors, as explained in Chapter 5.

3.6 Summary

This chapter outlined the research design, method selection, and data collection and analysis for each objective. Multiple research methods were used in this study, including a literature review, focus group study, questionnaire survey, interview study and case study.

For Objective 1, an in-depth literature review was adopted to establish a preliminary list of constraints hindering the development of high-rise modular buildings. Then, a focus group study with 12 experts was conducted to develop the final list of constraints, which was delivered to all stakeholders related to modular construction for evaluation in questionnaire surveys.

For Objective 2, a literature review and interview study were adopted. A comprehensive literature review was used to develop a draft of design guidelines for high-rise modular buildings based on the DfMA concept. Then, to ameliorate the draft design guidelines, an interview was conducted with all relevant stakeholders.

For Objective 3, the developed guidelines were validated using two real-life projects. The guidelines were provided to design teams at the beginning of the design stage. Then, all relevant information and data were recorded for each stage. Discussions were conducted to review the efficiency and effectiveness of the guidelines.

CHAPTER 4: Constraints Hindering the Development of High-Rise Modular Buildings

Constraints Hindering the Development of High-Rise Modular Buildings

This chapter explores the constraints hindering the development of high-rise modular buildings. Section 4.2 provides a preliminary list of constraints according to a comprehensive literature review. In Section 4.3, a focus group study is carried out to extract crucial factors, and a questionnaire is created for all stakeholders of modular construction. Based on the responses to the questionnaires (see Section 4.4), the constraints of high-rise modular buildings are further analysed and discussed in Section 4.5. This chapter will provide a clear picture of modular construction and propose valuable solutions to the dominant constraints.

4.1 Introduction

In recent decades, modular buildings have been implemented in both public and private sectors because they provide a solution for buildings composed of repetitive units, such as residential buildings, hotels, student accommodations and hospital wards (Fifield et al., 2018; Generalova et al., 2016; King, 2020; R. M. Lawson & Richards, 2010; X. Liu et al., 2018). Previous works and projects have demonstrated the strengths of modular buildings, including reduced construction time, diminished materials wastage, improved quality, decreased labour demand and a safe work environment (Boafo et al., 2016; Kamali & Hewage, 2016; R. M. Lawson et al., 2012; X. Li et al., 2018; P. Wu et al., 2016; X. Zhang & Skitmore, 2012). Given the significant potential of modular buildings, the industry and academics have proposed BIM and DfMA to facilitate the application of modular buildings (Alfieri et al., 2020; K. Chen & Lu, 2018; Gbadamosi et al., 2019; Ho et al., 2018; Hu et al., 2019). However, in comparison with conventional buildings, the application of modular buildings is still relatively low, especially for high-rise buildings. For instance, OSC in Australia accounts for only 3% of the total construction industry’s output, with the majority being low-level prefabrication involving precast components and panelised walls (Hampson & Brandon, 2004). The most uptake of modular construction is modular houses and low-rise buildings, whereas high-rise modular buildings are experiencing a slow pace of development (Ferdous et al., 2019).

4.2 Preliminary List of Constraints

4.2.1 Data collection and analysis

To formulate the preliminary list of constraints, a literature review was carried out systematically and involved two steps: (1) retrieving previous works from the academic database following predefined keywords; and (2) filtering selected articles in accordance with the constraints hindering the application of modular buildings. Details of the literature review process were provided in Chapter 3.

4.2.2 Results and discussion

According to literature review in Chapter 2, Table 4.1 outlines the preliminary list of constraints hampering the development of modular buildings. Although previous studies have disclosed a variety of constraints for modular construction, these studies concentrated on qualitative descriptions of the constraints but lacked a quantitative and in-depth investigation that could uncover the roots and interrelations of these constraints. Furthermore, few previous studies have contacted the construction sites and module factories to obtain a realistic portrayal of the status of modular buildings. Few studies have scrutinised the constraints of high-rise modular buildings, although the enormous 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 4.1 Preliminary list of constraints hindering the development of modular buildings

Code	Constraints	Key Reference
C1	Lack of experience and expertise	(Azhar et al., 2013; X. Gan et al., 2018; B.-G. Hwang et al., 2018b; W. Q. Liu et al., 2019; Wuni et al., 2019)
C2	Lack of government support	(X. Gan et al., 2018; R. Jiang et al., 2018; Xu et al., 2020; Zhai et al., 2013)
C3	Poor market and society acceptance	(W. Q. Liu et al., 2019; Luo et al., 2015; M. Park et al., 2011)
C4	Higher capital cost	(Hong et al., 2018; Kamali & Hewage, 2016; Mao et al., 2016; Tam et al., 2015; X. Zhang et al., 2014)
C5	Higher construction cost	(Hong et al., 2018; Mao et al., 2015; Tam et al., 2007)
C6	Additional transportation cost	(W. Lu & Yuan, 2013; Tam et al., 2015)
C7	Additional crane cost	(Chiang et al., 2006; Tam et al., 2015)
C8	Lack of R&D and resource support	(Blismas et al., 2005; Kamar et al., 2009)
C9	Lack of coordination and communication among stakeholders	(Y. Gan et al., 2017; Li, Hong, Xue, Shen, Xu, & Mok, 2016; W. Q. Liu et al., 2019; Polat, 2008; Z.-L. Wang et al., 2019; Wuni et al., 2019)

Code	Constraints	Key Reference
C10	Lack of standards and guidelines	(Goodier & Gibb, 2005; Luo et al., 2015; Xu et al., 2020; Zhai et al., 2013; X. Zhang et al., 2014)
C11	Unable to freeze design early	(Blismas, 2007; Jaillon & Poon, 2010; Li, Hong, Xue, Shen, Xu, & Mok, 2016; Pan et al., 2007)
C12	Poor design flexibility	(Jaillon & Poon, 2010; Z.-L. Wang et al., 2019)
C13	Complexity of design on seismic performance	(Gunawardena et al., 2016; X. Liu et al., 2018)
C14	Complexity of design on fire-resistant performance	(W. Chen et al., 2013; Harrison, 2003)
C15	Incompetence of suppliers and manufacturers	(Blismas et al., 2009; X. Gan et al., 2018; L. Jiang et al., 2018)
C16	Unable to achieve economies of scale	(Goodier & Gibb, 2005; Luo et al., 2015)
C17	Lack of skilled labour	(Choi et al., 2017; Tam et al., 2015; Zhai et al., 2013; X. Zhang et al., 2014)
C18	Limitation of weight and dimensions	(B.-G. Hwang et al., 2018a; Polat, 2008; Wei et al., 2014)
C19	Damage to modules during transportation	(W. Q. Liu et al., 2019; Z. Liu et al., 2018; Z.-L. Wang et al., 2019)
C20	Limitation of transport routes	(Li, Hong, Xue, Shen, Xu, & Mok, 2016; W. Q. Liu et al., 2019)
C21	Limitation of cranes to lift modules	(Mao et al., 2016; Salama et al., 2017)
C22	Complexity of connection	(Luo et al., 2015; Rahman, 2014; Salama et al., 2017)
C23	Demand for on-site modules storage	(W. Q. Liu et al., 2019; Zhai et al., 2013)
C24	Lack of quality inspection standard	(B.-G. Hwang et al., 2018a; Z.-L. Wang et al., 2019; Xu et al., 2020)

4.3 Final List of Constraints

4.3.1 Data collection and analysis

After conducting a comprehensive literature review, a preliminary list of constraints in modular construction was established. This was followed by a focus group study to refine the critical constraints. Details of the data collection and analysis were presented in Chapter 3.

4.3.2 Results and discussion

The 24 constraints were reviewed and discussed by 12 experts, who agreed that these constraints could portray general issues in modular construction. Using their practical experience, the experts pointed out some critical constraints that emerge in multiple phases of modular construction, such as lack of coordination and communication, which hamper the widespread application of modular buildings and should be addressed urgently. In addition to the 24 constraints, the experts identified three other constraints—namely, poor supply chain integration, weather disruptions, and lack of relevant application and technical support. Compared with traditional construction, modular construction highly depends on the reliability and sustainability of the supply chain, including procurement, design, manufacture, transportation and assembly. However, the integration of the supply chain is limited by the existing economic scale and market size of modular buildings, which leads to an array of issues, such as delays in the delivery of prefabricated modules, and reworking of manufactured components (Luo et al., 2019). Additionally, the interviewees agreed that the development of modular buildings is subject to relevant application and technical support. To address this, the experts shared their experience of using BIM in modular construction and discussed the potential of applying more advanced technology. The final list of constraints hampering the development of modular buildings was summarised and formed the core content of the subsequent questionnaire survey (see Table 4.2).

Table 4.2 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 standards and guidelines
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

4.4 Ranking of Constraints

4.4.1 Data collection and analysis

A questionnaire survey is the preferred approach for collecting data about general opinions on one topic (Yin, 2014). In this research, a questionnaire survey consisting of two sections was administered. The first section collected the respondents' basic information, including occupation type and experiences in modular construction. The second section inquired about the 27 factors related to constraints hindering the implementation of high-rise modular buildings. Respondents were asked to use a five-point Likert scale from five ('strongly agree') to one ('strongly disagree') to evaluate each 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 and aimed at promoting productivity and quality of modular buildings while unlocking the underlying market of modular construction (CAMP.H, 2016). To expand the sample size, this study used a snowball sampling method, which is an efficient method for increasing the number of respondents to questionnaire surveys in the AEC industry (Mao et al., 2015; Noy, 2008). The initial respondents shared the questionnaire with their colleagues and others with adequate experience in modular construction. As a result, 140 questionnaires were issued via email and the online survey platform Qualtrics. Ultimately, 72 questionnaires were received and identified as valid responses—a response rate of 51.4%. Specifically, 34.7% of respondents worked in universities and were mainly 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 presents the profile of the respondents in the questionnaire survey.

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 (George & Mallery, 2006). Leveraging IBM SPSS 26.0, the value of this survey was 0.821. As a result, the collected data from this questionnaire survey were satisfactory for further analysis.

Table 4.3 Profiles of respondents

Role of respondents in modular construction

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

4.4.2 Results and discussion

Table 4.4 presents the ranking of 27 constraints of modular construction, including mean values and standard deviations. The top constraints are discussed below,

Table 4.4 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

Code	Mean	Standard Deviation	Ranking
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

- 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 with conventional construction, modular construction is a closely collaborative process and is relatively dependent on sufficient coordination and communication throughout the entire life cycle, including planning, design, manufacture, transportation and assembly. It aims to reduce the construction period while improving the performance of buildings. However, considering the fragmented stakeholders, modular construction faces various challenges as a result of a lack of information sharing (Luo et al., 2019). For instance, because of the lack of communication between the transportation team and assembly contractor, excess modules are delivered to construction sites, resulting in spatial shortages and traffic jams. Inadequate modules can also delay assembly progress.

- Higher cost (high capital cost, high construction cost and additional transportation cost)

‘Higher capital cost’ is another significant obstacle to expanding the market of modular buildings, which is repeatedly emphasized by most of participants in the focus group. ‘High construction cost’ and ‘additional transportation cost’ are taken into account as the other two significant constraints related to ‘higher cost’, ranking in the first half of the 27 factors. Previous studies have found that modular construction is a cost-saving method over the entire life cycle of buildings (Pan & Sidwell, 2011). The initial investment in equipment and land for the production of modules has a direct bearing on soaring capital costs. In addition to the cost of fixed assets, additional transportation costs, including shipping and road transport, contribute approximately 20% of the total cost (W. Lu & Yuan, 2013). Many investigations have found that, aligned with the increasing degree of prefabrication, the cost of modular buildings is higher than that of conventional buildings because of the existing immature market and industry of modular construction (Hong et al., 2018). Therefore, taking into consideration the existing profitable traditional construction method, the perceived higher cost becomes another significant constraint hampering the application of modular buildings.

- Lack of government support

‘Lack of policy support’ is ranked as the third critical constraint. To stimulate the widespread adoption of modular construction, governments have issued economic incentives such as fiscal subsidies, tax breaks and preferable loans. However, these incentive policies cannot overcome the perceived risk of higher costs. In contrast to incentive policies, mandatory policies can attract more stakeholders to modular construction. To promote the development of PPVC, Singapore's government stipulated that the uptake of PPVC for new residential projects shall occupy over 65% of the gross floor area in specific land parcels (Choi et al., 2017). Given the issue of land supply, Singapore's authority established a policy that gives modular buildings a competitive advantage over traditional construction. Nevertheless, there are few mature and systemic policies supporting and encouraging the application of modular buildings around the world.

- Lack of experience and expertise

Lack of experience and expertise is a significant challenge throughout the entire life cycle of modular construction, especially for high-rise modular buildings. To achieve the technical revolution in the construction industry, the implementation of 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, the undeveloped construction method is unable to reach its full potential in terms of improved quality, reduced construction time, decreased material wastage and enhanced sustainability. Currently, the lack of experts and skilled labour adversely affects the development of modular construction (Wuni et al., 2019).

- Lack of standards and guidelines

Standards and guidelines specify requirements relating to structure, architecture, services, durability, safety and sustainability for the design and construction of conventional buildings and 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 that has inadequate pilot buildings as benchmarks to accomplish specific specifications, especially in terms of loading transfer, dynamic impact, and seismic and fire performances. Adding to the 'lack of relevant application and technical support', designers and contractors must spend a vast amount of time in modular building design and inspection, which results in 'unable to freeze design early' and the obstacle of quality control, which increases the total time and cost of modular construction.

- Poor supply chain integration

Segments of the supply chain in modular construction are comparable with those of conventional construction, including tendering, planning, design, procurement, manufacturing, transportation and assembly. The supply chain of modular buildings is more complex than that of traditional construction, and this is attributed to the nature of modularisation. Different from conventional construction methods that use 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. This requires a well-integrated supply chain as well as delicate supply chain management. However, given the undeveloped modular construction industry, the fragmented participants of the supply chain (i.e. developers, designers, manufacturers, transporters and contractors) lack 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 amid modular construction, thereby increasing construction costs and time (Z.-J. Wang et al., 2018).

- Complexity of connection

Because of the modular nature of modular buildings, massive connections are required for structure and MEP services between modules, and 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. Conversely, an array of connections of MEP services are used to integrate each system between modules, considering the integrity and performance of the systems. Within this context, eliminating redundant connections and enhancing the reliability of connections play a key role in the design stage that serves to produce prefabricated modules with accurate connection systems while preventing a fall from a height during the connection installation.

4.5 Findings

The constraints were evaluated by all stakeholders (i.e. developer, designer, manufacturer, logistics and contractor) and academic researchers. The findings of this chapter identified the primary constraints hampering the application of high-rise modular buildings. The constraints in each stage of construction are interrelated and interactive. Moreover, the design stage plays a critical role in modular construction. Underlying design issues directly or indirectly provoke the harmful influence of downstream processes involving manufacturing, transportation and assembly. A better modular design can be beneficial to all stages of modular construction. The following section explores the potential of BIM and DfMA to overcome these identified constraints.

BIM, which presents elaborate real-time construction information, has been widely used in modular construction. To date, the application of BIM in modular construction has focused on modular design. It improves the modular building design by reducing design coordination errors. The BIM-based parametric design takes advantage of the characteristics of BIM to create prefabricated components with complete attributes. Yuan et al. (2018) developed a BIM-based process of parametric design that optimises traditional parametric design processes, taking into account manufacturability and assemblability. Alwisy et al. (2018) proposed a BIM-based automatic design application to improve the quality of buildings embedded with wood panels. However, few studies have focused on the application of BIM for high-rise modular buildings. BIM-based parametric design could improve the issues, including C12 ‘poor design flexibility’ and C11 ‘unable to freeze design early’. BIM as a real-time information-sharing platform makes a significant contribution to multidisciplinary collaboration and coordination in conventional construction (Singh et al., 2011; Y. Wang et al., 2013). 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 (X. Hu et al., 2019). As a result, BIM has great potential to act as a communication platform during modular construction, which is a possible solution to C9 ‘lack of coordination and communication’, which was the foremost constraint identified in the questionnaire.

On the other hand, a ‘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 in modular design and manufacture. An inappropriate design may result in extra expense and time in the stage of manufacture’. Consequently, a solution or practical application aimed at the design stage is needed. In recent years, DfMA has provided substantial insights into modular construction, dealing with manufacture and assembly in the early design stage for improved quality of modules and a decreased construction period (RIBA, 2013). Derived from manufacturing, DfMA embodies an innovative design method and philosophy and has been embraced by the construction industry (BCA, 2017; W. Lu et al., 2020; Laing O’Rourke, 2013; RIBA, 2013). Given the nature of industrialisation and modularisation, OSC for high-rise modular buildings embedded with completed prefabricated modules is an ideal implementation scheme of DfMA. Empirical projects have identified its contribution to construction periods and waste reduction (Banks et al., 2018; K. Chen & Lu, 2018; Laing O’Rourke, 2013). Nevertheless, DfMA remains at a theoretical phase rather than a concrete tool or a standard operating procedure that can be used simply for general modular buildings. Despite most designers understanding the significance of manufacture, transportation and assembly in modular construction, only experienced senior designers could comprehensively consider the entire construction period from the early design stage (Balfour Beatty, 2018). Developing an applicable guideline of DfMA is an effective solution to current constraints in the design stage, involving C1 ‘lack of experience and expertise’ and C10 ‘lack of standards and guidelines’, which is necessary for the development of modular buildings.

4.6 Summary

This chapter provided an exhaustive description of the current circumstances of modular construction, with a particular focus on high-rise modular buildings. A total of 27 constraints throughout the entire life cycle of modular construction were identified in 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 standards and guidelines’, ‘poor supply chain integration’ and ‘complexity of connection’ were recognised as the foremost challenges. The improvement of modular design is the key to the development of high-rise modular buildings. A potential solution implementing BIM and DfMA to optimise modular design was discussed against the constraints. The investigation executed multiple surveys to reveal the existing constraints hindering the development of high-rise modular buildings, while contributing a valuable reference for stakeholders in modular construction.

Chapter 5: DfMA-Based Design Guidelines for High-Rise Modular Buildings

DfMA-Based Design Guidelines for High-Rise Modular Buildings

In this chapter, DfMA-based design guidelines for high-rise modular buildings are developed to address the lack of standards and guidelines for modular design, which is a primary constraint unveiled in Chapter 4. Section 5.1 provides a general introduction to DfMA application in modular construction. Section 5.2 conducts a holistic literature review to investigate existing DfMA guidelines for the construction industry. Section 5.3 presents the development of design guidelines based on the DfMA concept. In Section 5.4, two case studies are provided to validate the developed guidelines, followed by the discussion and findings. Section 5.5 summarises the chapter.

5.1 Introduction

OSC has been widely adopted to ameliorate various problems, such as energy consumption, environmental pollution and labour shortage, which hamper the development of traditional construction (Blismas et al., 2006). In the past two decades, which represent the highest degree of prefabrication, modular buildings embedded with completed prefabricated modules have been implemented to construct high-rise buildings (Xu et al., 2020). As an emerging construction method, high-rise modular buildings are facing numerous challenges throughout the entire life cycle of construction (Sun et al., 2020). Given the vast number of modules, final designs should be dispatched to manufacturing factories as early as possible. However, because of a lack of design guidelines and building codes, design teams have to spend more time securing the accuracy and quality of modular design to prevent rework and the delay of prefabricated modules (Jaillon & Poon, 2010).

To improve modular building design and promote modular construction, DfMA, a state-of-the-art design approach and concept, has raised interest in the construction industry. DfMA, derived from the manufacturing industry, takes into account downstream processes in the early design stage to seek maximum prefabricated modules at off-site manufacturing factories while minimising activities at construction sites (Murray-Parkes & Bai, 2017). Experience of implementing DfMA in empirical projects encouraged industrial exponents to embrace this design method (Balfour Beatty, 2018; Laing O'Rourke, 2013). Additionally, the governments of the United Kingdom and Singapore have published guidebooks outlining how DfMA will reshape the construction industry in the future (BCA, 2017; RIBA, 2013). Given the nature of industrialisation and modularisation, high-rise modular building is an ideal building type to exploit the advantages and potential of DfMA (BCA, 2017).

In recent years, many studies have explored the development and progress of DfMA integrated with theory and practice, and identified its motivations, prospects and challenges in construction. Guidelines and strategies based on existing knowledge and empirical experience have been proposed to facilitate DfMA application in OSC (Alfieri et al., 2020;

K. Chen & Lu, 2018; Fatima et al., 2018; Gao et al., 2019; Gao et al., 2018; W. Lu et al., 2020; Safaa et al., 2019; Tan et al., 2020; Trinder, 2018; Yuan et al., 2018). However, few studies have provided a quantitative evaluation criterion of DfMA that transforms abstract design philosophy into a concrete numerical value to offer direction for architects and engineers in the design stage of modular construction. In addition, few investigations have focused on implementing DfMA for completed high-rise modular buildings, although this cutting-edge construction approach represents the development trend of future construction (Pan & Hon, 2020).

Thus, the aim of this chapter is to propose practical strategies and guidelines for the application of DfMA for high-rise modular buildings following the research design flow illustrated in Figure 5.1.

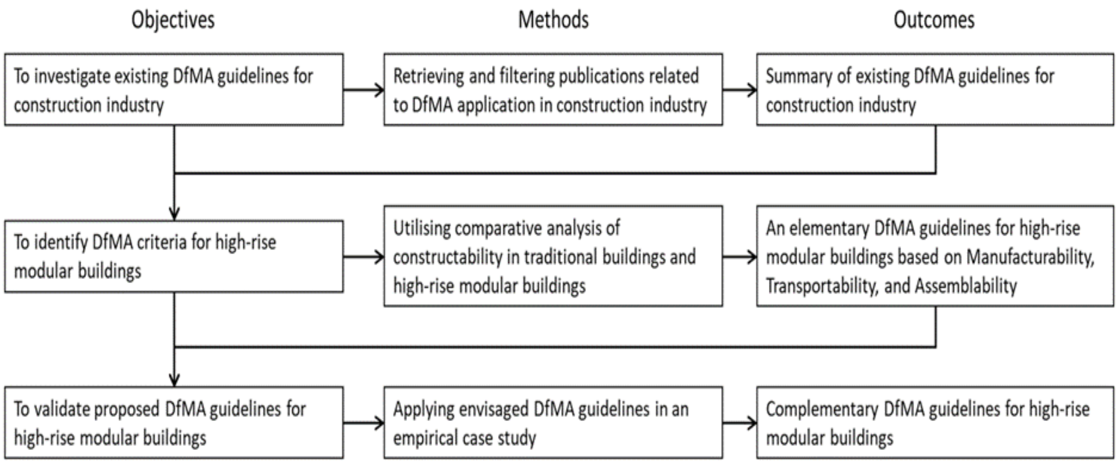


Figure 5.1 Research design flow

5.2 Existing DfMA Guidelines for Construction Industry

5.2.1 DfMA guidelines for manufacturing

DfMA is a technical process as well as a concept or philosophy originating from the manufacturing industry that takes into account the manufacture and assembly processes at the design stage. DfMA has been widely adopted in manufacturing for factory-made, mass-produced components that can be assembled on a mass-produced product line in a factory environment (RIBA, 2021). According to Ashley (1995), Bogue (2012), Boothroyd (1994), and Swift and Brown (2003), DfMA has been adopted in many manufacturing companies, including Texas Instruments, Motorola, Ford Motor, Sony and Dell, which promotes simpler and more reliable products while cutting costs and time (see Figure 5.2). A few studies have investigated these empirical cases to develop some guidelines for the manufacturing industry, as shown in Table 5.1.

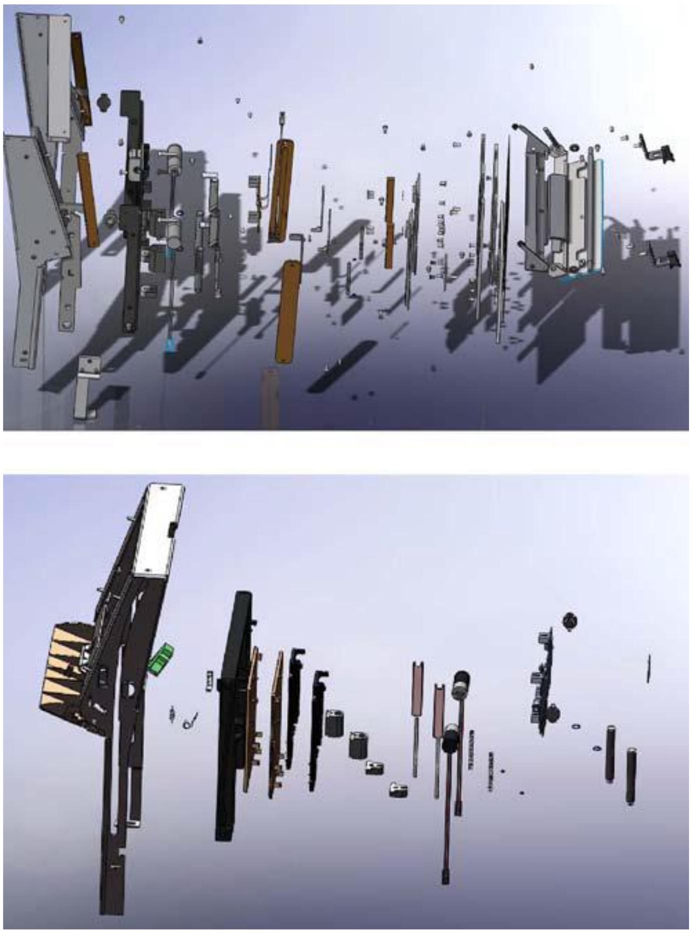


Figure 5.2 Optimal design with DfMA application (bottom panel is the optimal design) (Bogue, 2012)
Source: IDEXX Laboratories, Inc.

Table 5.1 DfMA guidelines for the manufacturing industry

No.	Guidelines	Category	Benefits
1	Aim for mistake-proof designs	Others	Avoid unnecessary rework, improve quality, and reduce time and costs
2	Consider design for automated/robotic assembly	DfA	Improve assembly efficiency and quality, and reduce manual assembly labour
3	Consider modular designs	DfA	Reduce time and costs due to simplified design and assembly

4	Design for ease of fabrication	DfM	Reduce time and costs by eliminating complex fixtures and tooling
5	Design for simple part orientation and handling	DfA	Reduce time and costs by avoiding non-value-adding manual effort
6	Design with a predetermined assembly technique in mind	DfA	Reduce time and costs by using proven techniques
7	Use standard and off-the-shelf components	DfM	Reduce purchasing lead time and costs, and improve quality
8	Use as similar materials as possible	DfM	Reduce time with fewer manufacturing processes and simplified jointing
9	Minimise precast component types	DfM, DfA	Reduce time and costs with simplified design, manufacture, and assembly
10	Minimise connector types and quantity	DfM, DfA	Reduce time and costs with simplified design, manufacture, assembly, repair, and maintenance.
11	Minimise the use of fragile parts	DfA	Reduce costs due to fewer part failures, and easier handling and assembly
12	Do not over-specify tolerances or surface finish	DfM	Reduce costs with easier manufacture

Sources: Bogue (2012) and W. Lu et al. (2020)

With the aim of improving manufacturing or assembly, the abovementioned design guidelines can be categorised into three parts: DfM, DfA and others. These guidelines broke the traditional pattern of product design by providing a new design philosophy embedded with an overall outlook for the entire manufacturing process (Bogue, 2012; Boothroyd, 2005). However, these descriptive and qualitative guidelines did not specify quantitative details for the manufacturing industry to adopt in practice. Furthermore, given the differences between manufacturing and construction, it is not possible to directly implement these guidelines in the construction industry.

5.2.2 Differences between manufacturing and construction

The first step to integrating guidelines from manufacturing to construction is to identify the differences between the two industries. Compared with manufacturing, construction has a much longer history—almost as long as the history of humans (Koningsveld & Van Der Molen, 1997). Construction industry consists of three main sectors: building construction, infrastructure, and industrial construction. There are some similarities between the two industries. From the perspective of process, construction and manufacture both collect relevant inputs, including materials, equipment, labour and information, and then add sufficient value to result in outputs such as a building, bridge or bicycle. Moreover, both construction and manufacturing are supported by multiple stakeholders for each phase of the process, including design and planning, procurement, construction/production and transportation. In recent years, an increasing number of professionals from academia and industry have investigated new construction management methods from manufacturing, such as lean construction and DfMA (Gbadamosi et al., 2019).

The development and application of OSC link construction to manufacturing closely. Instead of on-site substantial construction activities, OSC employs an array of precast and prefabricated components that are produced in off-site manufacturing factories and then delivered to the construction site. As a result, manufacturing plays an increasingly important role in construction (Blismas, 2007). As the highest level of prefabrication, modular buildings comprise a mass of pre-completed volumetric modules that significantly reduce on-site construction activities. Modules installed in interior finishes, bathrooms, furniture and MEP service can be fully fabricated in a manufacturing factory. Hence, modular buildings have a stronger connection with manufacturing (Ferdous et al., 2019).

However, compared with manufacturing, the end product of construction is more complex (Bertelsen, 2003). Although a large number of components can be produced at off-site factories, these prefabricated components have to be delivered to the construction site for installation. Even if some modular buildings are embedded with fully pre-completed prefabricated modules, there are still many skilled labours working on construction sites to lift and install modules. That is, the product lines in manufacturing can entirely complete production; however, off-site factories in OSC can only provide key elements for the end product—a building. Furthermore, in the last decade, automation and robotisation have dramatically boosted productivity and efficiency in manufacturing. Product standardisation secures a short production cycle for mass production (Goel & Gupta, 2020). In contrast, the complexity of construction generates various customised designs and construction methods. It is not possible to seek a standard design and a standard workflow for distinct projects. Concerning OSC, prefabricated components or modules are still manually fabricated by skilled labours (see Figure 5.3). Thus, OSC and modular buildings have a closer link with manufacturing. However, the difference between manufacturing and construction should be taken into consideration when DfMA guidelines are interpreted in the construction industry.

Figure 5.3 Module production at an off-site factory

5.2.3 DfMA guidelines for construction

To improve construction productivity and address labour shortage, the construction industry is seeking innovative construction methods. Modular construction, which reduces traditional on-site construction activities, adopts prefabricated components produced at off-site factories. Unlike traditional construction, modular construction must consider downstream processes (i.e. manufacture, transportation and assembly) in advance. This design philosophy refers to DfMA, which has been widely implemented in the construction industry.

Table 5.2 shows the current DfMA guides and roadmaps published in different countries and regions, including the United Kingdom, Singapore, Hong Kong SAR, the United States and Australia.

- United Kingdom

Since the 1960s, the number of households in the UK has rapidly increased, and the traditional construction method has not been able to meet the housing demand and quality standards (Barker, 2004; ODPM, 2005). As a result, OSC has attracted extensive attention from the construction industry (Pan & Sidwell, 2011). For example, Laing O’Rourke (2013) developed a successful approach to DfMA to improve the quality of construction while reducing construction time and waste. In 2013, the British government published a policy paper, *Construction 2025: Strategy*, which noted that OSC will be the key factor in the future construction industry (Her Majesty's Government, 2013). Furthermore, RIBA issued a *Plan of Work 2013: DfMA* to explore how the design team can promote performance and productivity in OSC based on the DfMA concept (RIBA, 2013). This publication, which provided a detailed description of DfMA, also pointed out the benefits and typical processes of DfMA using associated case studies. It has emphasized the significance of applying DfMA and highlighted its positive outcomes, for instacne, 20–60% shorter construction periods; around 40% lower construction costs; over 70% labour reduction on-site; improved quality and safety; and decreased construction waste (RIBA, 2013). In 2021, RIBA updated the new DfMA, *Overlay to the Plan of Work 2020*, highlighting the widespread application of DfMA in construction, which emphasises actions and feedback from the perspectives of the industry as well as the market (RIBA, 2021). Additionally, the publication summarised the best option for implementing DfMA in OSC given the critical data and project management, critical design considerations, and critical logistical issues. Regarding the design considerations for a successful DfMA process, the publication listed following key factors,

a) Connections between prefabricated components;

b) Tolerances to guarantee simple manufacturing and assembly;

c) Standardized components;

d) Optimization of module configuration;

e) Initial analysis of problems that arise during maintenance, repair, and dismantling.

- Singapore

Singapore's government has a clear view of the significance of OSC given its limited land resources and labour shortages (K.-E. Hwang et al., 2022). OSC has been regarded as the most effective solution for reaching the national target of construction productivity growth, which was set in the first *Construction Productivity Roadmap* in 2011 (BCA, 2011). Subsequently, in 2015, the *Second Construction Productivity Roadmap* indicated that the move towards DfMA is a key driver to improve construction productivity (BCA, 2015). Therefore, the construction industry has embarked on the OSC method instead of traditional construction with the adoption of PPVC for high-rise modular buildings increasing gradually (Xu et al., 2020). In 2017, BCA published *Design for Manufacturing and Assembly—Prefabricated Prefinished Volumetric Construction Guidebook*, which demonstrates key aspects of PPVC integrated with the DfMA concept and related success practices. The guidebook provides a holistic understanding of PPVC and DfMA for practitioners, including the entire life cycle of modular construction, such as design considerations, module production, protectiion, transportation and lifting, construction and project management, installation, inspection and quality checks, maintenance, and replacement and renovation (BCA, 2017). In Chapter 3 of this guidebook, design considerations of PPVC were demonstrated including architectural design considerations, structural design considerations, MEP design considerations, and compliance with fire safety requirements. However, only general design considerations were listed in this guidebook. For example, dimension of plan in architectural design considerations stipulated the below two points,

1) To ensure the layout plan design comply with regulatory requirements.
2) To ensure the size of modules allow transportation from factory to site.

Without specificed criteria, it is difficult for design teams to reply on these general considerations to carry out modular design.

- Hong Kong SAR

The construction industry in Hong Kong SAR (HKSAR) has paid attention to OSC since the 1980s because of its scarce developable land and strong housing demand. As a result of the large economies of scale and relatively cheap labour and material costs in mainland China, HKSAR has used a large number of precast components such as staircases, walls and bathrooms (Chiang et al., 2006; Jaillon & Poon, 2009; Tam et al., 2015). In recent years, MiC, which refers to the highest level of prefabrication, has been promoted widely by the HKSAR government (HKSAR, 2017a). It has been identified as an effective approach to address the shortage of labour and manufacturing capability while enhancing the life cycle quality of buildings in line with the greater number of applications of MiC in the city of high-density high-rise buildings (Pan & Hon, 2020). Moreover, HKSAR (2018) developed *Construction 2.0*, which discusses the direction for the future of the construction industry. It emphasises the significance of innovation and new technologies, including DfMA and MiC, in the industry. Codes and references related to MiC were issued by the HKSAR Building Department to clarify the relevant design considerations and requirements for all stakeholders, which is aligned with the DfMA concept (HKSAR, 2017b).

- United States

The OSC in the United States is not dominant in the industry; however, an increasing number of practitioners have embarked on this innovative approach to enhance productivity and quality (N. Lu & Liska, 2008; Razkenari et al., 2020). The International Code Council (ICC), coupled with the Modular Building Institute (MBI), issued two joint standards—

ICC/MBI 1200-2021 Standard for Off-site Construction: Planning, Design, Fabrication and Assembly and *ICC/MBI 1205-2021 Standard for Off-site Construction: Inspection and Regulatory Compliance*—outlining the entire process of modular construction from the perspectives of different stakeholders (i.e. design team, manufacturer, logistical team and contractor). Although this standard doesn't specifically mention DfMA concept, it can be adopted as a guideline to perform DfMA-based design because of the explicit responsibilities of designers, manufacturers, and contractors. Meanwhile, the management requirements throughout the entire life cycle of modular construction were indicated as well (Jung & Yu, 2022).

- Australia

As a result of strong housing demand as well as soaring labour and material costs, the industry has employed various new approaches, including OSC, to improve construction productivity. However, compared with the abovementioned countries and regions, Australia has a relatively low adoption of OSC (Khalfan & Maqsood, 2014). To promote the widespread application of OSC, several associated guidebooks and reports have been published. In 2004, the Australian Cooperative Research Centre (CRC) for Construction Innovation issued *Construction 2020* to disclose the future directions of the industry, with OSC indicated as one key vision to enable more efficient construction processes and improved quality control (Hampson & Brandon, 2004). With the increased uptake of OSC in the Australian industry, more publications have focused on modular construction, such as *Off-site Manufacture in Australia: Current State and Future Directions*, which was published by the CRC for Construction Innovation in 2007 (Blismas, 2007). This publication, according to seven case studies in Australia, identified numerous benefits and challenges of OSC. It stated that design considerations need to meet the requirements of manufacturing, transportation and installation, despite not directly discussing DfMA philosophy. Moreover, in 2017, the Modular Construction Codes Board (MCCB) developed the *Handbook for the Design of Modular Structures*, which was the first holistic guidebook concerning modular structures for the Australian industry (Murray-Parkes & Bai, 2017). This document integrated the DfMA concept and shared the experience and knowledge related to modular design to the industry based on the aspects of structure, building services, façades, architecture, materials and manufacturing, durability, safety, and transportation.

Table 5.2 Primary DfMA guides and roadmaps in different countries and regions

Country and Region	Name

United Kingdom	RIBA Plan of Work 2013 Designing for Manufacture and Assembly DfMA Overlay to the RIBA Plan of Work: Mainstreaming DFMA in Construction
Singapore	Design for Manufacturing and Assembly—Prefabricated Prefinished Volumetric Construction Guidebook
Hong Kong SAR	Construction 2.0 Codes and references for Modular Integrated Construction
United States	ICC/MBI 1200-2021 Standard for Off-site Construction: Planning, Design, Fabrication and Assembly ICC/MBI 1205-2021 Standard for Off-site Construction: Inspection and Regulatory Compliance
Australia	Off-site manufacture in Australia: Current State and Future Directions Handbook for the Design of Modular Structures

The abovementioned guides, based on the regional development of OSC, presented a holistic view of modular construction, with a focus on design considerations for meeting the requirements of downstream processes, which is in accordance with DfMA philosophy. However, the majority of guides emphasised the benefits and significance of implementing DfMA in modular construction using several practices. It is still relatively difficult for practitioners to adopt this innovative approach in future projects without specific guidelines and quantitative criteria. For instance, two publications issued by RIBA introduced the drives and advantages of using DfMA in OSC while providing detailed adoption strategies for each step of the modular construction. However, it is difficult to exploit these qualitative recommendations to generate a standard or codes for modular design. Furthermore, there are few guides related to high-rise modular buildings. There are significant differences between the requirements of various types of OSC. Compared with precast components of OSC, high-rise modular buildings, representing the highest level of prefabrication, have entirely different manufacturing and assembly processes that require distinct design considerations as well as specific DfMA guidelines.

Some studies have investigated the implementation of the DfMA concept in real-life construction projects. As shown in Table 5.3, the different DfMA principles have been adopted in various types of construction projects. In infrastructure construction, precast components and modular structures have been employed for many years (Staib et al., 2013).

Kim et al. (2016) adopted the DfMA concept to achieve the standardisation of UK bridge construction, which overcomes the current limitation. Safaa et al. (2019) developed the DfMA criteria for the evaluation of precast concrete bridge elements, which consists of an analysis of costs, time and risk management. Gerth et al. (2013) proposed a method of 'Design for Construction' based on the DfMA concept to facilitate the identification of potential problems in four-storey houses and improve constructability. Banks et al. (2018) applied DfMA principles to a 40-storey residential building across all engineering disciplines, and enhanced the construction productivity of superstructures, façades, bathrooms, and mechanical and electrical services. K. Chen and Lu (2018) implemented a DfMA design approach to a curtain wall system in a high-rise commercial building, which decreased material cost and wastage and assembly time, while improving quality and aesthetic performance. Gbadamosi et al. (2019) integrated DfMA and lean construction to develop a design evaluation and optimisation system to help the design team with materials and element decisions. Tan et al. (2020) established construction-oriented DfMA guidelines that took into account the contextual basis, technology rationalisation, logistics optimisation, component integration and material-lightening.

Table 5.3 Construction projects adopting DfMA principles

References	**Project Type**	**DfMA Principles**
Kim et al. (2016)	Precast concrete bridge	a) Design simplicity b) Reduced number of components c) Standardisation of elements or material d) Ease of orientation of parts and handling e) Ease of joints and fasteners
Safaa et al. (2019)	Precast concrete bridge	a) Design simplicity b) Reduced number of components c) Standardisation of elements or material d) Ease of handling
Gerth et al. (2013)	Light wall, four-storey houses	a) Reduced fragile material

		b) Reduced number of components c) Ease of fasteners
Banks et al. (2018)	Precast components, prefabricated MEP, prefabricated bathroom pods, 40-storey high-rise residential	a) Reduced number of components b) Reduced waste of materials c) Reduced on-site activities d) Standardisation of elements or material e) Increased prefabricated elements and modules
K. Chen and Lu (2018)	Prefabricated curtain wall system, high-rise commercial building	a) Reduced part count of the curtain wall system b) Reduced number of fasteners c) Using cost-effective materials d) Easy-handle components e) Reduced waste of materials
Gbadamosi et al. (2019) Gbadamosi et al. (2020)	Precast concrete wall, commercial building	a) Ease of assembly b) Ease of handling c) Speed of assembly d) Reduced waste of materials
Tan et al. (2020)	Prefabricated light steel frame, low-rise residential houses	a) Context-based design b) Technology-rationalised design c) Logistics-optimised design d) Component-integrated design e) Material-lightened design

These investigations adopted various principles of DfMA in construction projects, comprising infrastructure construction as well as building construction. However, the majority of DfMA principles were directly interpreted from the manufacturing lack of consideration of the characteristics of construction projects. Moreover, these developed DfMA guidelines provide common approaches but no specific details, such as a reduced number of components, which cannot be implemented on a project immediately. It is worth noting that all stated guidelines are not aimed at high-rise modular buildings. Representing the highest level of prefabrication, high-rise modular buildings have the most complex processes of manufacture and assembly, in which DfMA guidelines can release as much potential as possible. Therefore, it is important to develop a series of DfMA guidelines that include quantitative assessment criteria for high-rise modular buildings.

5.3 Developed DfMA-Based Design Guidelines for High-Rise Modular Buildings

This study, which develops design guidelines for high-rise modular buildings, focuses on three aspects related to the nature of the DfMA concept: manufacturability, transportability and assemblablity (see Figure 5.4).

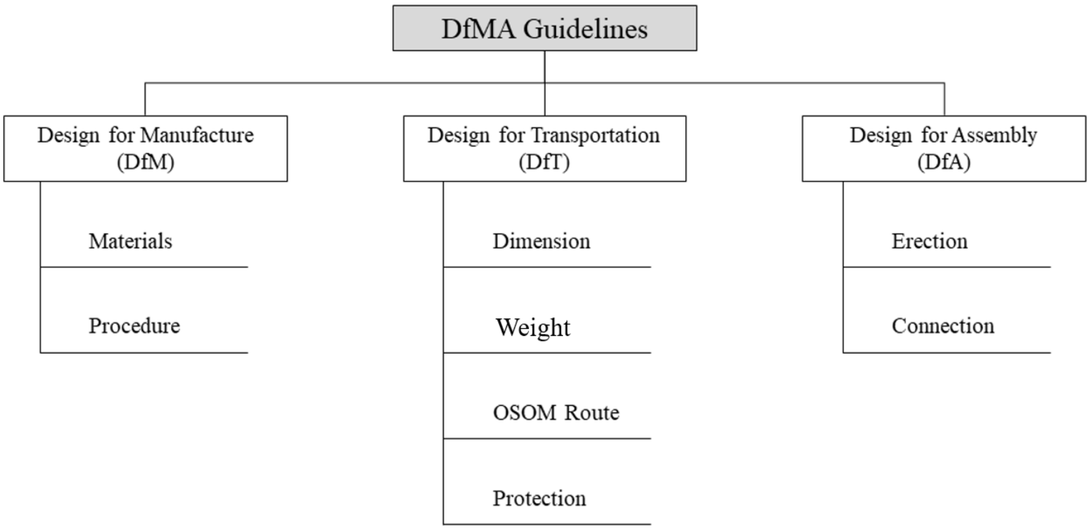


Figure 5.4 Draft DfMA guidelines proposed in this study

5.3.1 Design for Manufacture (DfM)

The primary factors considered in DfM focus on materials and procedure.

Materials

The primary materials of prefabricated pre-completed volumetric modules in high-rise modular buildings are steel and reinforced concrete (RC) (see Figure 5.5). Based on the materials' behaviour, two module forms are adopted for high-rise modular buildings: a load-bearing concrete module, in which loads are transferred through the side walls of the module; and a corner-supported steel module, in which loads are delivered through edge beams to corner columns (see Figures 5.6 and 5.7) (R. M. Lawson et al., 2012). In addition to the corner-supported module, steel modules have two more forms: light steel-framed modules and container modules. Although many studies have investigated light steel frame modules in modular construction (R. M. Lawson et al., 2008; R. M. Lawson et al., 2005; J. F. Zhang et al., 2020), the applications of this lightweight design are applicable for buildings under 10 storeys, given the structural stability and durability. Steel container modules are rarely used in high-rise modular buildings but are widely employed in large temporary projects because of their recyclability and easy transport—for instance, prefabricated container isolation-ward against COVID-19 in Singapore, and a reusable container stadium for the FIFA World Cup Qatar 2022 (K.-E. Hwang & Kim, 2022; Kucukvar et al., 2021; Wee et al., 2021).

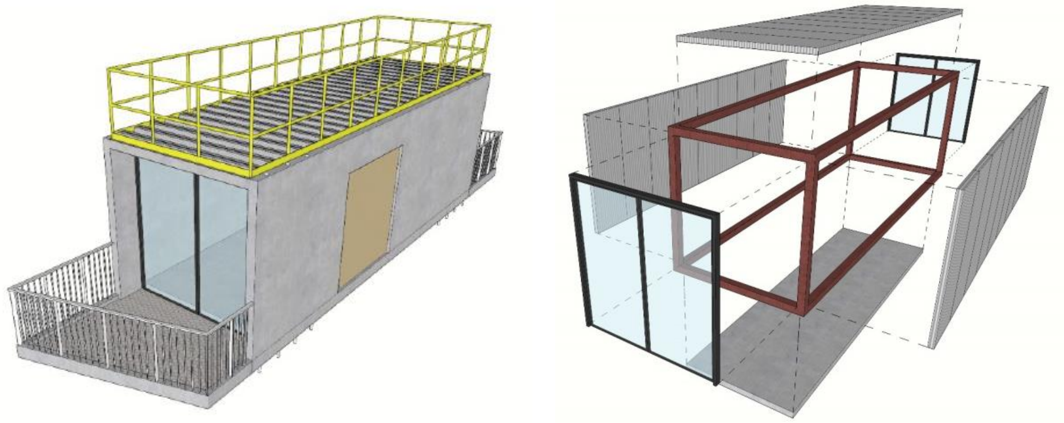


Figure 5.5 Reinforced concrete and steel modules in modular buildings (BCA, 2017)

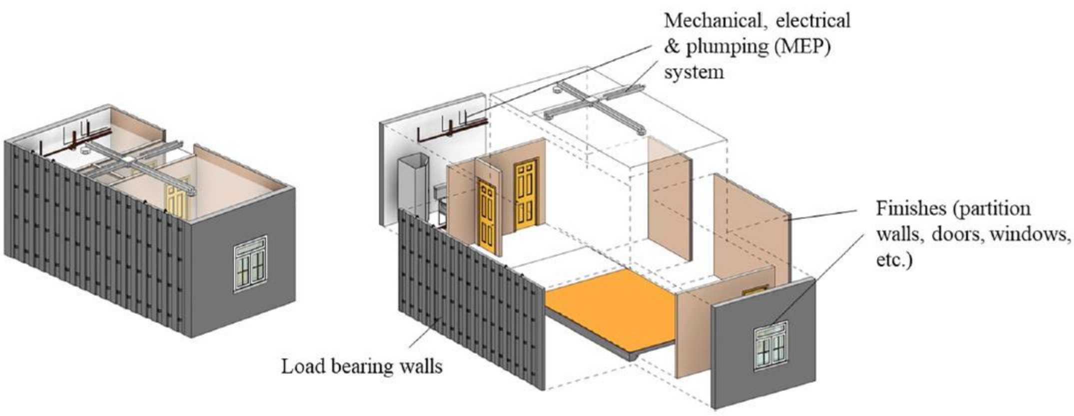


Figure 5.6 Load-bearing modular system (Liew et al., 2019)

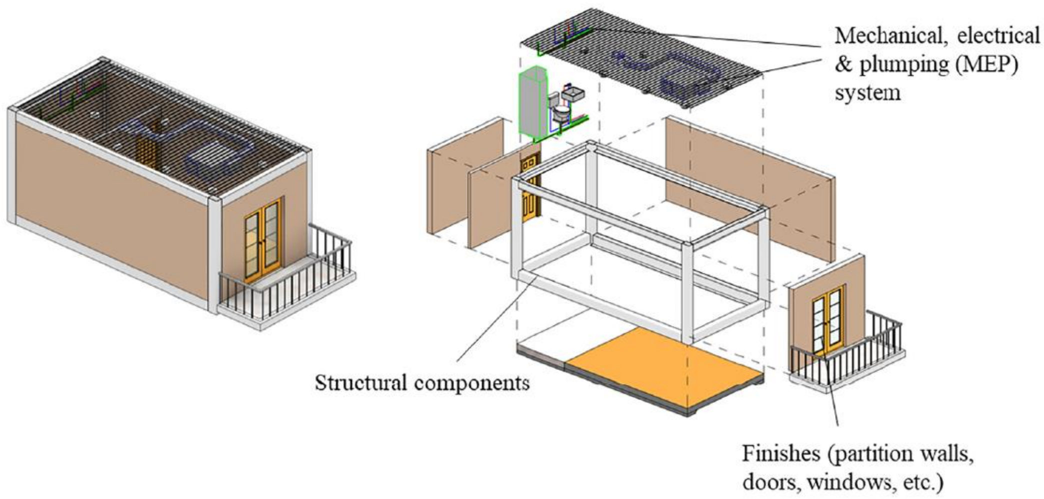


Figure 5.7 Corner-supported modular system (Liew et al., 2019)

After being produced at off-site factories, prefabricated modules are delivered to construction sites for installation. Therefore, the weight and size of the module are constrained by the limitation of transportation and lifting. To decrease the weight of the module, the lightweight module plays a key role in modular construction. Generally, the weight of an RC module is around 20–35 tonnes, and a steel module is approximately 15–20 tonnes, and more lightweight components are implemented. Given the load-bearing wall system, concrete is the dominant material of the RC module. By leveraging lightweight concrete on the floor, the weight of an RC module can be reduced by up to 40% (Liew et al., 2019). Steel modules can comprise more lightweight components. Manalo et al. (2017) proposed a fibre-reinforced polymer (FRP) sandwich system that has been used for roof, wall and floor components. Additionally, previous studies have developed various lightweight flooring systems in steel modules (Abeysinghe et al., 2013; Loss & Davison, 2017; Satasivam & Bai, 2016; Satasivam et al., 2014).

In addition to lighter weight, steel modules offer the design team more design flexibility because of the open space and larger module unit with a longer beam span ranging from 6 m to 12 m (M. Lawson et al., 2014). The modular building embedded with the long-span modules has fewer modules and inter-module connections, which reduces the period of installation. Using long-span steel modules, modular buildings can be used for commercial and industrial projects and are not restricted to residential buildings only (Liew et al., 2019).

Compared with the RC module, the steel module has higher requirements for fire resistance and corrosion. Fire performance is a major design consideration of high-rise modular buildings. Because of wide adoption of lightweight components involving lightweight concrete and composite materials floors, the likelihood of modular buildings being impacted by fire may increase. However, limited relevant studies have focused on the fire performance of modular structures. Ngo et al. (2016) conducted a numeric analysis method to explore the fire performance of a modular building using glass FRP composite components. Nguyen et al. (2016) proposed a new composite material—organoclay/glass fibre reinforced polymer laminates, which can effectively prevent the spread of fire and meet building fire requirements. To prevent personnel and property losses, fire engineering of modular buildings should consider the fire resistance of individual modules as well as the restraint of the spread of fire between modules. Thus, the design team should take into consideration the fire rating of the modular building and modular components, including wall, floor, façade and services equipment. Additionally, emergency equipment and means of escape should be considered at the design stage.

Corrosion is another challenge for high-rise modular buildings that consist primarily of steel modules. Corrosion is a kind of material degradation that affects the condition and performance of materials as well as structures. The structural connection is the most important location for corrosion monitoring and inspection, as investigated in some previous studies. For example, C. Wu et al. (2021) used steel-concrete composite internal joints for beam-to-column connection of steel modules, which improves corrosion resistance. In addition, designers should consider corrosive environments while preparing sufficient corrosion protection.

Last, all materials used in the manufacturing process should meet the specified quality. Regarding some safety-critical components—for instance, steel frame—more detailed tests and certifications should be provided to designers, such as sampling tests, initial tests and ongoing production tests (Murray-Parkes & Bai, 2017). Moreover, to promote productivity and supply chain management, designers should preferentially select raw material suppliers adjacent to the off-site manufacturing factory. Table 5.4 outlines the main characteristics of two types of modules adopted in high-rise modular buildings.

Table 5.4 Comparison of RC module and steel module in high-rise modular buildings (BCA, 2017)

	RC Module	Steel Module
Load path	Load-bearing module	Corner-supported module
Weight	20–35 tonnes	15–20 tonnes
Components	Wall: concrete Floor: concrete	Wall: lightweight wall Floor: concrete or

		lightweight flooring
Applications	Residential and hotel buildings	Student residence, residential and hotel buildings
Installation method	Stacking method	Stacking method
Hoisting method	Hoisting by crane	Hoisting by crane
Corrosion and fire protection	Similar to conventional construction	Need more monitoring and inspection

Procedure

The manufacturing procedure of prefabricated modules can be categorised into two approaches according to the primary materials of modules. Details of the procedure are presented below.

RC module

1. Mould preparation: Steel modules are fabricated first. These modules should be adjusted in three dimensions to produce different sizes of modules that meet designers' requirements.
2. Module shell works: Similar to traditional construction, the reinforcement cage is fabricated first, reserving MEP and other cast-in items, which should be highlighted on designers' drawings. All structural components (i.e. columns, beams, walls and slabs) can be identified as a complete module for concreting works to avoid construction joints. After concrete curing and demoulding, the RC module should be shifted to the installation works area.
3. Finishing and MEP works: The installation works should be conducted in a sheltered area by skilled specific trades. The designer may provide an in-process installation scheme of the finishing and MEP works. For example, installation works for RC modules can consist of the following steps: a) installation of lightweight panels, b) MEP installation, c) structural ponding and waterproof installation, d) floor screeding, e) windows and doors installation, f) wall tiles installation, g) plastering and skim coating, h) floor finishing, i) bathroom installation, j) wardrobe installation, k) railing installation, l) ceiling installation, m) painting works, n) protection and completion works. Figure 5.8 illustrates the main architectural and MEP installation works of RC modules.

Figure 5.8 Finishing and MEP works of RC module (BCA, 2017)

Steel module

In comparison with RC module production, steel module production can implement more innovative methods, such as robotic welding machines and 3D fabrication jigs that can enhance fabrication productivity at off-site factories. Furthermore, steel module production does not need any steel moulds for concrete components casting. The first step is steel shell assembly.

1. Module shell assembly: To ensure the material quality, validation of raw material should be administered associated with relevant certifications, including factory production certificate and mill cert. Then, designers should provide approved shop drawings for steel frame fabrication and assembly. During this step, some

associated tests should be highlighted by designers, including galvanised quality, welding quality and all components' dimensions.

2. Finishing and MEP works. Designers should prepare a specific installation plan with accurate information. There are several essential installation works: a) metal studs and side wallboard installation, b) mechanical and electrical piping and conduit installation, c) waterproofing and water ponding, d) tiles (floor and wall) and vinyl installation, e) false ceiling installation, f) doors and windows installation, g) external cladding and ledge installation, h) painting works, i) wardrobe installation, j) floor finish works, k) protection and completion works.

5.3.2 Design for Transportation (DfT)

Design considerations related to transportation focus on four aspects: dimension, load, OSOM route and protection.

Dimension

Modular construction may adopt different transportation modes, including shipping, road and rail, based on the locations of manufacturing factories and construction sites. When modules are produced at an offshore factory, these modules will employ international carriage to deliver to domestic ports for road or rail transport. Compared with rail and shipping, road transport is more limited by the dimension of modules. Road transport, as the last phase of any module delivery, is adopted most frequently in modular construction. Therefore, the design should consider road traffic limitations for module dimensions.

Road transport for modules from off-site factories to construction sites on road is restricted by local traffic regulations. The allowed dimensions of modules that can be transported on public roads are stipulated by relevant authorities. For example, in compliance with the dimension limitation issued by the Land Transport Authority of Singapore, the upper limits of height and width are 4.5 m and 3.4 m, respectively. This study investigates design considerations related to transportation based on Australian traffic rules.

Figure 5.9 indicates the dimension design process for high-rise modular buildings. The dimension limits for module transport have been set to secure safe movement across the network. If the dimension of the vehicle exceeds the dimension limits stipulated by the Australian Heavy Vehicle National Law and Regulations, it is compulsory to apply for an OSOM permit and meet pilot vehicle requirements. Therefore, to avoid these additional actions, the dimension of modules can be designed within 4.3 m, 2.5 m and 19 m (height, width, length). However, as mentioned in the DfM section, long-span modules can offer designers more design flexibility while reducing the number of connections. As a result, the use of large-sized modules promotes efficiency and productivity of transportation and assembly in modular construction. An OSOM permit is available for vehicles delivering a single module up to the laden vehicle dimension limits of 5.0 m, 5.0 m and 30.0 m (height, width, length). Designers should observe that these dimensions include external fittings such as guttering, lighting, plumbing and bay windows. Moreover, for transporting modules that are less than 12.5 m long, a rigid truck must be available. For a module longer than 12.5 metres, a semi-trailer, which can support the entire length of the module, is a feasible solution for module transport.

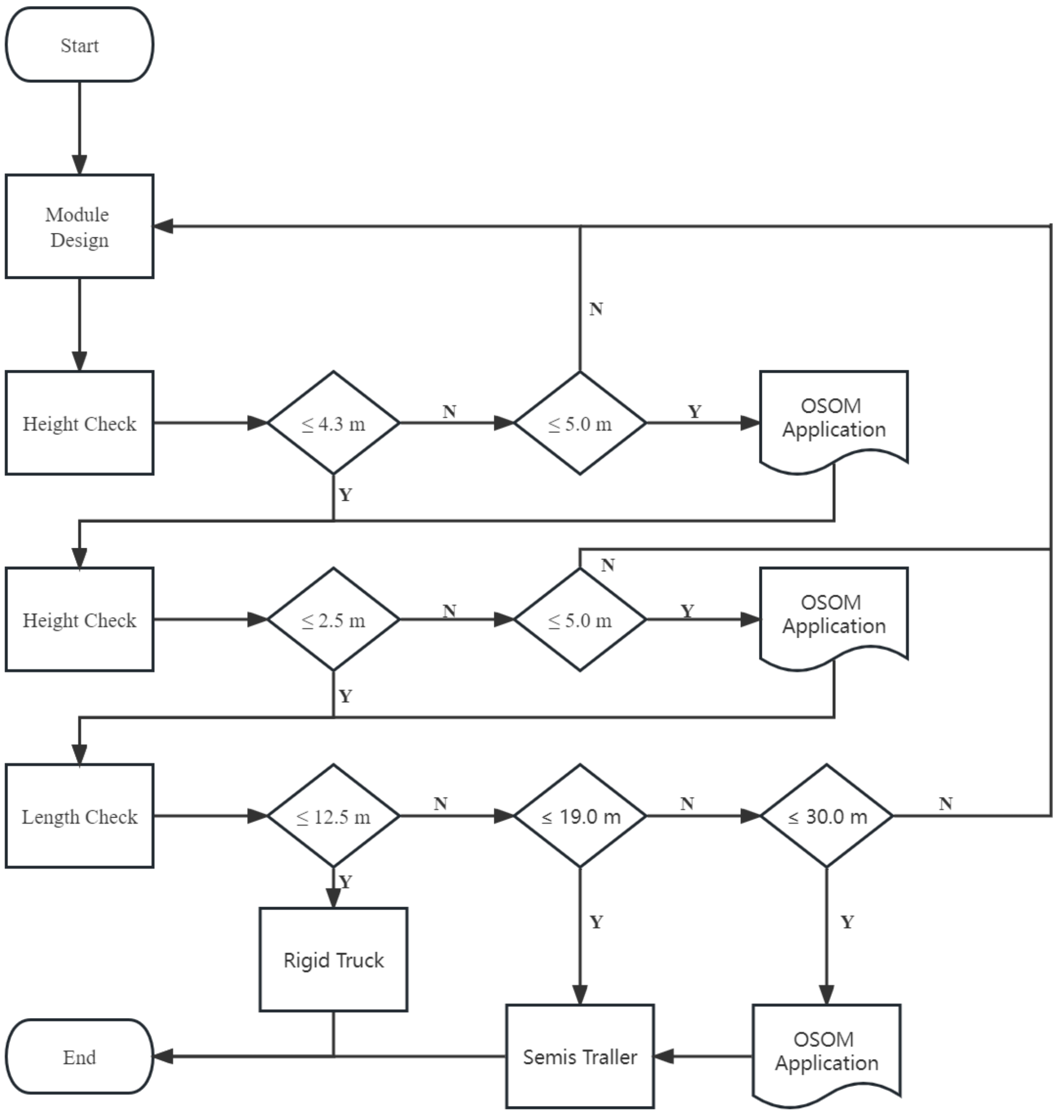


Figure 5.9 DfT-oriented dimension design process for modular buildings (Australian Heavy Vehicle National Law and Regulations)

Weight

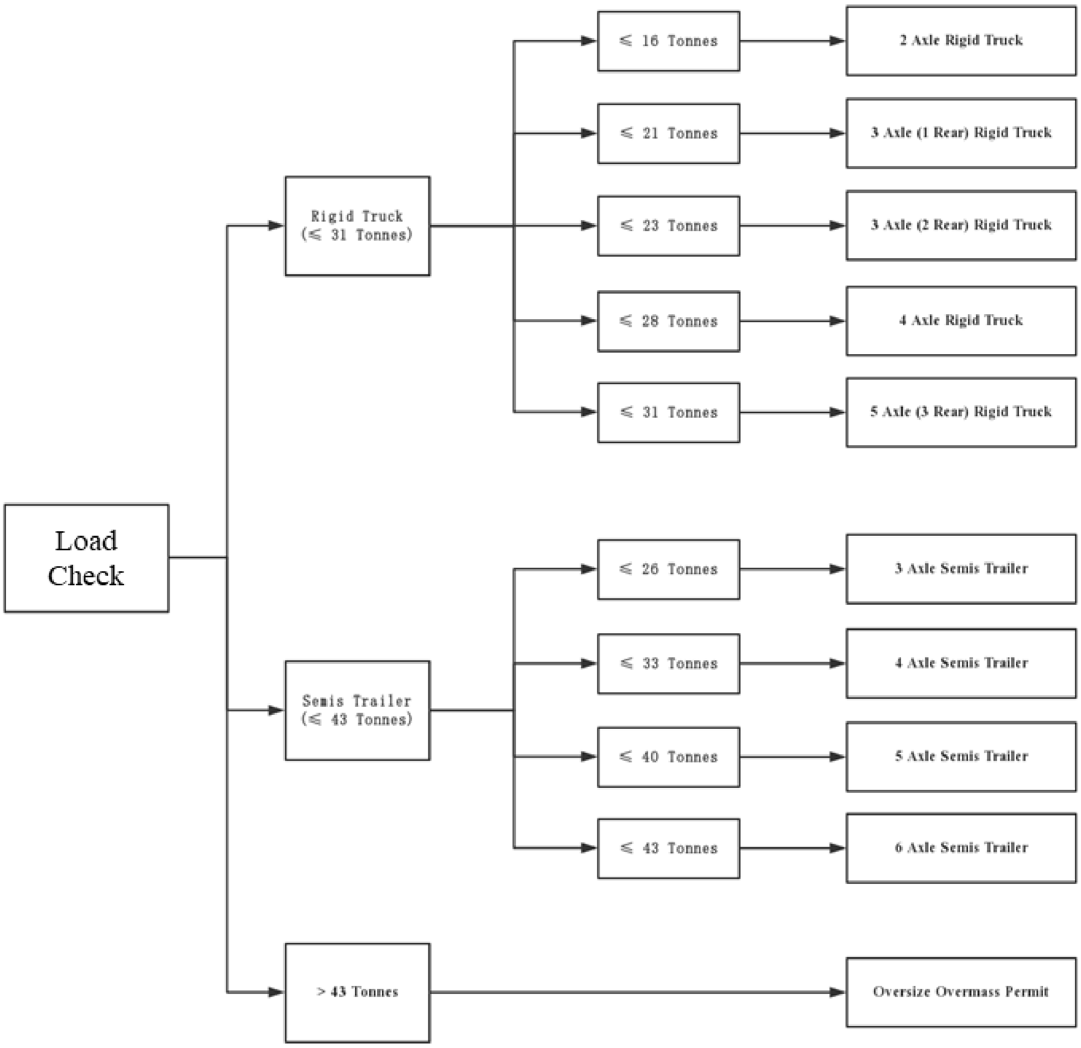


Figure 5.10 Transport vehicles for different weights of modules (Australian Heavy Vehicle National Law and Regulations)

Figure 5.10 presents the selection of transport vehicles for different weights of modules. Designers should understand the acceptable loading capacity of rigid trucks and semi-trailers before planning the transport of modules. Under normal conditions, an RC module is around 20–35 tonnes, and a steel module is around 15–20 tonnes. Based on the Australian National Heavy Vehicle Regulator, a 5-axle rigid truck is able to transport a module up to 31 tonnes. The loading capacity of a 6-axle semi-trailer can reach 43 tonnes. Therefore, designers should comprehensively consider the dimension and weight of all modules adopted in the project to determine the applicable transport vehicles and logistics team. If the proposed dimension and mass of the module coupled with the laden vehicle exceed local traffic limits, designers should cooperate with a logistics team that has the annual OSOM permit to plan transport routes and schedules.

Figure 5.11 Six-axle semi-trailer parking at factory

OSOM Routes

Designers should give priority to the logistics team applying for a Class 1 OSOM permit if the mass and dimension of the modules may excess the abovementioned limits. Furthermore, along with the logistics team and contractor, designers should plan the transport route and time at the design stage, considering the locations of the construction site, manufacturing factory and module storage area. The following several aspects will be highlighted in the transport management of modular construction.

1. Route

The laden vehicle can only travel on routes specified by local relevant authorities. For instance, in Victoria, Australia, the OSOM map is displayed on the VicRoads website. The roads in green (approved) and orange (approved with conditions) are allowed to be used for OSOM delivery. A separate permit is needed if other roads are designed as a transport route. Designers can find more details of routes involving areas of operation, exempted routes and prohibited routes in the Victorian OSOM route access lists (VicRoads, 2014).

2. Time

In addition to route restrictions, the transportation of OSOM modules is only allowed during specified times to prevent traffic jams. To achieve fast delivery, designers, contractors and logistics should arrange an appropriate time for delivering modules in accordance with local traffic regulations. For example, Table 5.5 shows time-of-day travel restrictions in

Victoria. Based on this table, designers can obtain accepted time information corresponding to varied routes and vehicles.

Table 5.5 Time-of-day travel restrictions for the laden vehicle in Victoria

Road or Area	**Day**	**Width ≤ 3.1 m** **Length ≤ 22.0 m**	**Width ≤ 3.5 m** **Length ≤ 26.0 m**	**Width > 3.5 m** **Length > 26 m**
Melbourne and Geelong urban areas, other than a major road	Monday to Saturday	At all times	9.00 am to 4.00 pm 12.00 midnight to 6.00 am	
	Sunday and public holidays	At all times	12.00 midnight to 4.00 pm	
Major road	Any day	At all times	6.00 am to 4.00 pm 1) No travel the day before a holiday period. 2) No travel the last day of a holiday period	
Rural Area	Any day	At all times	Sunrise to Sunset	
Freeway	Any day			Except for the day of a holiday period

Source: VicRoads (2018)

3. Pilot vehicle

Pilot vehicles are necessary if the dimensions of the laden vehicle exceed the limits stipulated by local regulations. Designers can examine the transportation plan and potential logistics team at the design stage. According to the width and length of the vehicle, different numbers of certified pilots should drive at the front or rear of the laden vehicle. Figure 5.12 illustrates the pilot requirements for OSOM transport in Victoria, Australia (VicRoads, 2017).

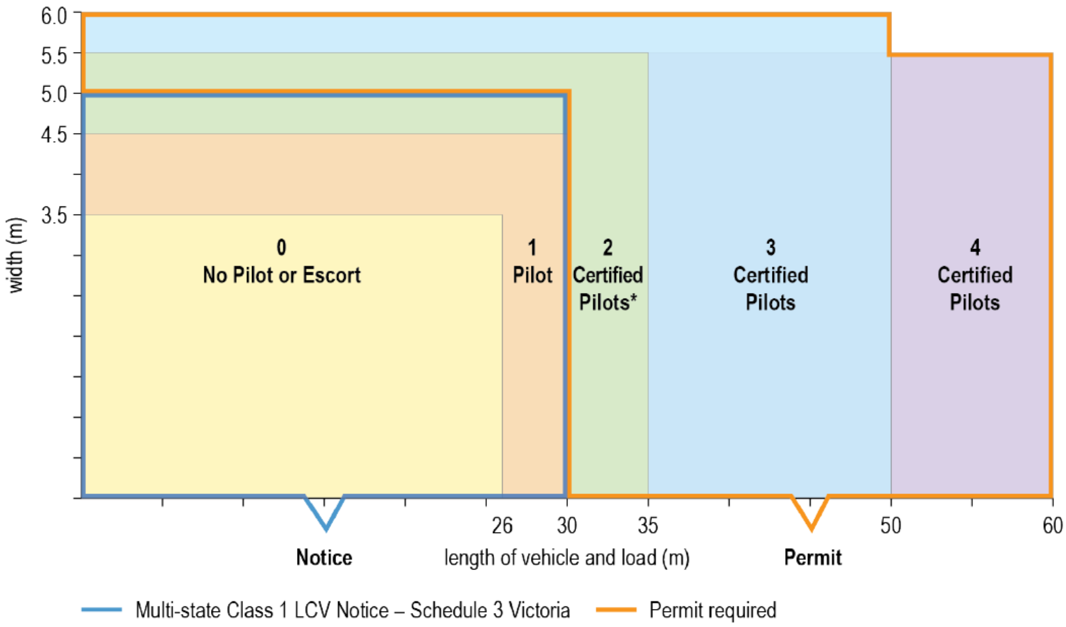


Figure 5.12 Pilot requirements for OSOM transport in Victoria (VicRoads, 2017)

4. Just-in-time (JIT) delivery

JIT delivery is highly recommended for high-rise modular buildings. Derived from the manufacturing industry, JIT is a lean construction approach adopted to decrease waste and improve efficiency and productivity (Hussein & Zayed, 2021b). It is applicable for each stage of modular construction, especially at the transportation and assembly stages. High-rise modular buildings are embedded with a large number of modules that are unable to be deposited at construction sites. Therefore, designers may explore more innovative technologies involving the global positioning system, the radio frequency identification device and Internet of Things to mitigate risks and improve the schedule performance of transportation and assembly (Hussein & Zayed, 2021b; C. Z. Li et al., 2016).

Protection

The protection of completed modules should be highlighted by designers focusing on preventing underlying damage, deformation and deterioration during module delivery (BCA, 2017). Repairing or dealing with these damaged components from transportation may result in construction delays and overrun costs (W. Lu & Yuan, 2013). Both internal finishes and external surfaces should be fixed and covered by a protection sheet before lifting the module onto the semi-trailer. Cover sheets, based on module size and design requirements, should be produced and temporarily or permanently placed on specified modules.

5.3.3 Design for Assembly (DfA)

There are two factors related to DfA: erection and connection.

Erection

Tower cranes play a key role in the erection of modules for high-rise modular buildings (Hussein & Zayed, 2021a). Given the height of buildings (10 storeys or higher) and a large number of module installations, tower cranes dominate site operations and affect construction performance (Pan & Hon, 2020). Consequently, tower crane planning, which incorporates crane selection and layout design, is a vital measure during the planning and design stage. It should involve consultation with all parties engaged in the project, including contractors, crane suppliers and designers.

Two main types of tower cranes are widely adopted for high-rise modular buildings: luffing and hammerhead tower cranes (see Figure 5.13). Designers should consider the advantages and disadvantages of each type of tower crane to determine the best crane type for the project. A luffing tower crane with a low slewing radius is a compact tower system that can be used in tight spaces such as downtown areas. However, compared with the hammerhead crane, the luffing tower crane generally has less lifting capacity and height, and the rental cost is higher. In contrast, as a result of greater equipment supply, hammerhead tower cranes have low rental costs and fast working speed (Hyun et al., 2021).

Figure 5.13 Luffing tower crane (L), and hammerhead tower crane ® (Workplace Health and Safety Queensland, 2017)

Unlike traditional construction, tower cranes operate during the entire period of module installation. Therefore, a crane's mechanical characteristics should be reviewed by designers associated with information on modules and buildings. For example, Table 5.6 presents some elemental specs of various types of luffing cranes used most in Australia. The lifting capacity and lifting height are related to weight of module and building height. In addition, crane layouts, such as locations and number of cranes, should be developed in reference to the site layout, construction program, installation cycle, number of modules and the crane's mechanical characteristics (Z. Zhang et al., 2022).

Table 5.6 Luffing HC-L crane models and specifications

Tower Crane	Max Lifting Capacity	Max Radius	Max Lifting Height	Max Tip Lifting Capacity
190 HC-L 8/16	16 tonnes	55 metres	47.9 metres	2.5 tonnes
0280 HC-L 12/24	24 tonnes	60 metres	64.9 metres	3.2 tonnes
357 HC-L 18/32	32 tonnes	60 metres	59.1 metres	4.1 tonnes
542 HC-L 18/36	36 tonnes	65 metres	53.3 metres	4.3 tonnes
710 HC-L 32/64	64 tonnes	65 metres	60.5 metres	7.2 tonnes

In addition to the selection of tower cranes, the design team should understand the sequence of lifting and installation works to provide adequate design details (e.g. lifting hook-ups, tag lines). The detailed sequence is outlined below:

1. The laden vehicle taking the prefabricated module should park at the launch area adjacent to the building receiving the module (see Figure 5.14).
2. The installation team should be separated into two groups: one group at ground level and the other group at the upper landing level. The two groups should have clear communication via walkie-talkies.
3. The lashings securing the module should be removed.

Figure 5.14 Arrival of the PPVC module at the launch area

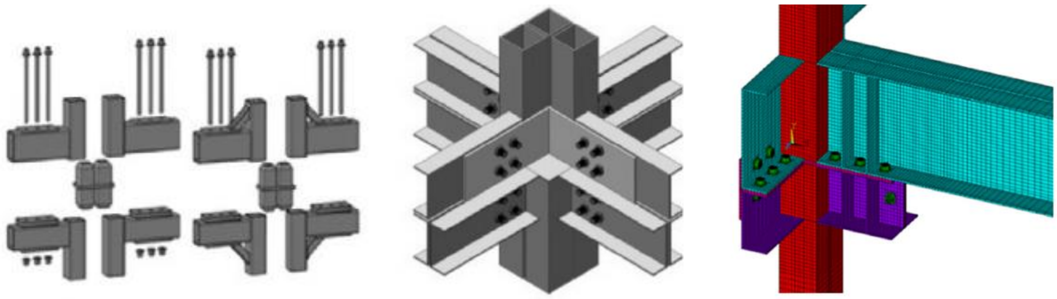
4. The centre vertical poles should be installed on the roof of the module using a ladder.
5. Workers on the roof of a module should be secured to 15 m self-retracting lifelines (SRLs) and then hook the lifting lines via tag lines onto the module lifting lugs.
6. Once lifting lugs are secured, workers should rig the lifting gear onto lugs and use chain blocks to level the module as the module will be unevenly loaded.
7. After workers descend from the module to the ground level, the chain blocks are adopted to take up the slack.
8. The laden vehicle can be driven off when the module is levelled off.
9. The installation team should have full sight of the module during the lifting, and the ground-level and upper-level signal people should maintain communication. Once over the landing site, the installation team should sight and locate the module over the locking points.
10. After the module has touched down, workers secured to SRL can remove the lifting lines from the lugs of the module and tie lashings around the roof perimeter of the module using installed vertical poles.

Connection

As a state-of-the-art construction approach, modular buildings are embraced by the construction industry because of their numerous benefits, especially decreased on-site construction time. Lego-like module installation significantly reduces construction activities' reliance on substantial connections, which can be categorised into three types: inter-module, intra-module and module-to-structures. Intra-module connections, such as beam-to-column joints for steel modules, are critical to secure the robustness and rigidness of the framework (Liew et al., 2019). This type of connection is provided during the manufacturing stage at the off-site factory. The other two types of connections, which are used in on-site module assembly, are considered by designers to facilitate a smooth installation process, as discussed below.

Inter-module

Inter-module connection consists of vertical modules connection and horizontal modules connection. The design consideration for these connections should focus on fast and easy installation first, while aiming to provide competent stiffness as well as resistance. For high-rise modular buildings, the vertical modules connection is crucial for the structural behaviour affecting building stiffness related to wind, seismic and lateral design (BCA, 2017). It consists of column–column connections and beam–beam connections that link an upper module to a lower module. The horizontal modules connections between adjacent modules forming the floor plan are also important for building stiffness. For steel modules, bolting and welding are the primary connection methods considered by designers. A bolted connection is preferred to achieve fast installation, especially for column–column joints. However, to execute bolt installation and inspection, it is necessary to leave access holes in floors, walls and ceilings at every corner of the module (Liew et al., 2019). Figure 5.15 illustrates three types of bolted connection systems. In comparison with a bolted connection, a welded connection avoids excessive access holes and reduces the risk of connection slip. Nevertheless, a welded connection requires skilled labour working in limited space, which consumes a significant amount of time and results in safety and fire risks. For the RC module, concrete or grout is poured in the gap between adjacent modules to form a traditional reinforcement concrete connection, which contributes to the impressive performance of strength and waterproofing. In addition, this connection produces a mass of construction site work and inseparable modules. Therefore, much more time and labour are required for module recycling or module removal. Moreover, designers should also be aware of the accumulative tolerance issue in module installation, which may cause bigger problems for high-rise modular buildings (ßee Figure 5.16) (Murray-Parkes & Bai, 2017). Thus, designers should provide tolerance limits for installation. For example, allowing a large tolerance for a bolted connection can reduce installation time. However, accumulative tolerance along with increasing storeys may result in weakness of lateral stability (Lacey et al., 2018). According to R. M. Lawson and Richards (2010), the total cumulative positional tolerance should not be greater than 40 mm for a 10-storey building.



a) b) c)

Figure 5.15 Various bolted connections: a) Z. Chen et al. (2017); b) K.-S. Park et al. (2016); c) Lee et al. (2017)

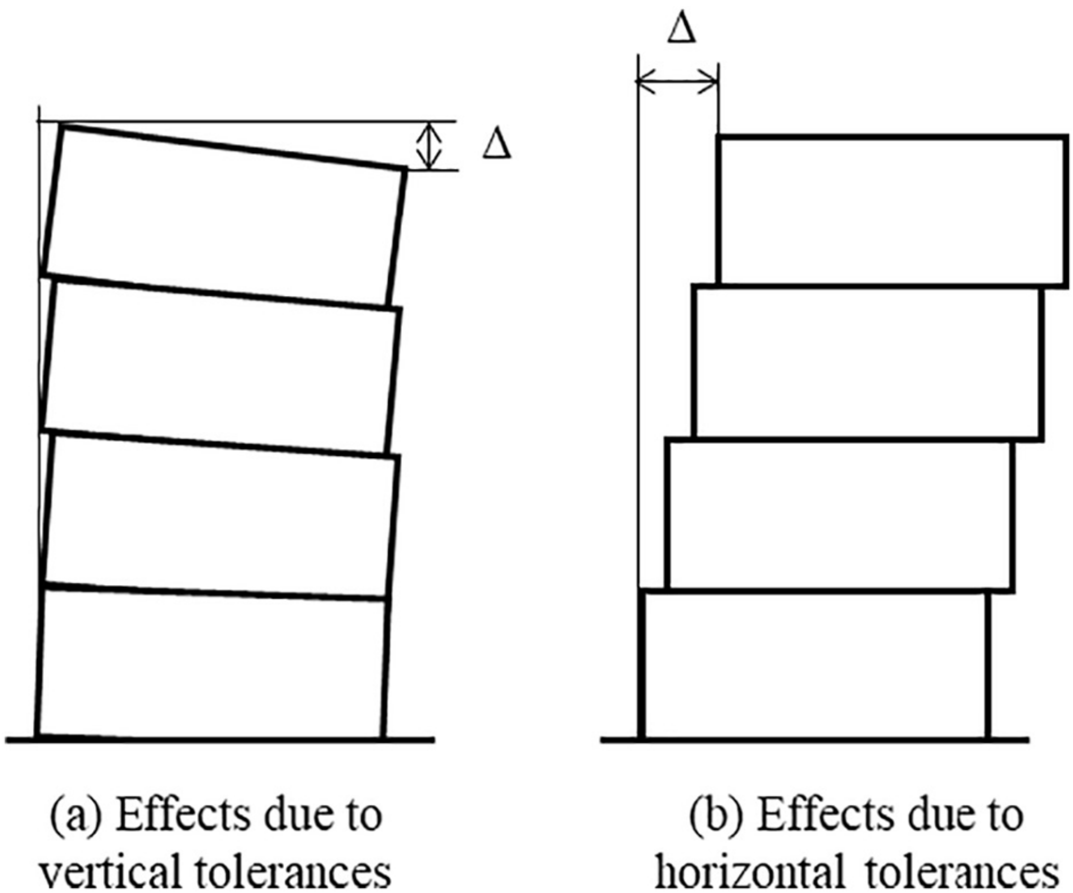


Figure 5.16 Accumulative tolerance error Δ during installation (M. Lawson et al., 2014)

Module-to-structure

In addition to connections used between adjacent modules, some connections link modules to foundations and structural cores—for example, concrete cores for lifts and stairs. For RC modules, the module-to-structure connections generally use the same approach—reinforcement concrete or concrete grout—to transfer the load through side load-bearing walls. In contrast, for corner-supported steel modules, steel end plates are fixed in the foundation or the surface of the concrete core using shear studs and concrete casting. Four columns of each steel module are then connected to the end plates by welding and bolting (K.-S. Park et al., 2016).

5.3.4 Interview

In an interview with eight experts from all stakeholder groups of modular construction, the proposed design guidelines were reviewed and discussed. Table 5.7 presents the profile of the experts, including job positions and working experience in high-rise modular buildings.

Table 5.7 Profile of experts in the interview

Role	Job Title	Years of Experience
Developer	Project manager	7
Contractor	Site manager	6
	Senior design coordinator	5
	Design coordinator	3
Consultant	Senior architect	6
	Architect	3
Manufacture	Assistant design manager	8
Logistics	Operations manager	5

The proposed design guidelines were provided to eight experts who each have at least three years of relevant working experience in modular buildings. Based on their working experience and knowledge, they scrutinised the details of the guidelines. Each part of the guidelines—DfM, DfT and DfA—gained widespread acceptance. In addition, the experts offered suggestions and doubts. Some concerns around the proposed guidelines were not closely related to design considerations. For instance, many interviewees mentioned that quality assurance (QA) and quality control (QC) checking is a significant step performed at the end of fabrication and installation that promotes quality as well as productivity. However, QA/QC checks focus on the completeness and accuracy of modules, not modular design. Therefore, the necessity and significance of QA/QC checks should be emphasised in the guidelines. The result of checking reveals the performance of each stage of modular construction while reflecting the outcomes of the design guidelines. Moreover, the developed guidelines should be appropriate for high-rise modular buildings involving different building types. As a result, some design considerations aimed at one specified type of building are not discussed in the guidelines.

5.4 Case Study

In the case study, two projects were selected to validate the proposed design guidelines. The design team carried out the modular design according to DfMA-based guidelines involving DfM, DfT and DfA. Relevant information related to the entire modular construction was collected and recorded. A quantitative analysis of the time reduction was then conducted.

5.4.1 Projects description

Project 1

Located in Singapore, the mixed development consists of around 60% residential and 40% shopping mall. There are three blocks of 9-storey residential buildings with a total of 216 units linked by three blocks of concrete cores, a 3-storey podium with commercial facilities, and a single level of the basement. These 216 units are composed of 756 PPVC steel modules and prefabricated bathroom units. The areas using the modular building approach of this project were over 16,000 m^2.

Project 2

An 18-storey Ibis Styles hotel, located in Perth, Australia, consists of 252 PPVM that provide 160 guest rooms, a lounge, a restaurant and bar, a meeting room, a business corner, and a gymnasium. All PPVM were fabricated at the factory and included full indoor decorations, MEP, bathroom, doors and furniture.

5.4.2 Planning and design stage

The developed DfMA-based design guidelines were provided to the design team at the early planning and design stage. All practitioners of design teams had at least two years of experience in OSC. However, because of the limited experience and knowledge of modular buildings—especially high-rise modular buildings—the design teams still attempted to design the buildings using the traditional design approach. Both design teams reported that, in previous OSC projects, many design issues were revealed during the downstream processes as a result of a lack of consideration of manufacturing, transportation and assembly. As a result, the author explained all details of the guidelines and discussed them with the entire design team until they understood the philosophy and method of these innovative design guidelines. After completing the preparation, the design teams cooperated with downstream practitioners and managed the modular design involving the architect, structure, MEP and façade system according to the DfMA-based guidelines. Figure 5.17 shows the BIM models developed in project 1. Figures 5.18 and 5.19 illustrate the typical module layout and floorplan in project 2. In addition, the time of the design stage was recorded to evaluate the efficiency of the guidelines' implementation.

Figure 5.17 BIM models of project 1, architect (L), structure (M) and MEP (R)

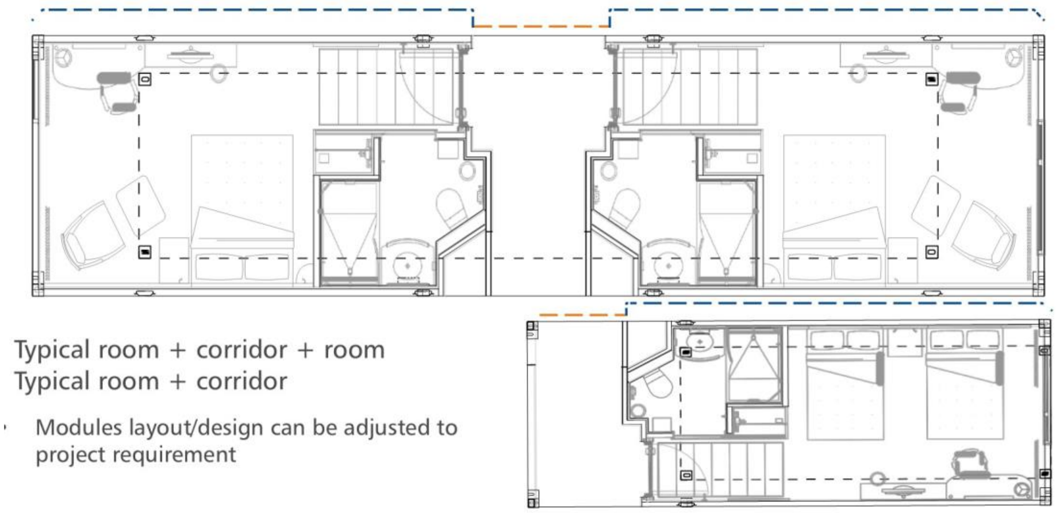


Figure 5.18 Typical module layout of project 2

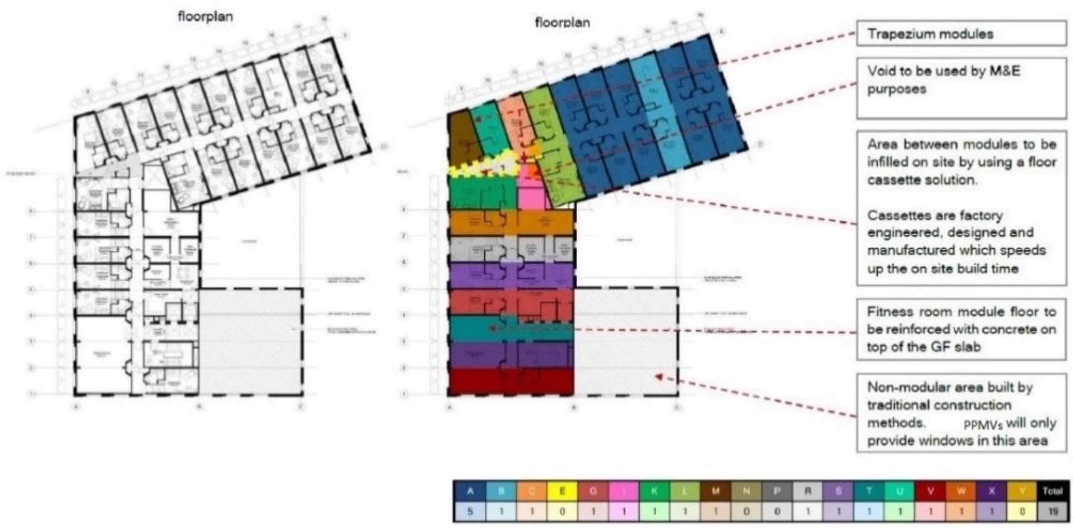


Figure 5.19 Module layout floorplan of project 2

5.4.3 Manufacturing stage

In this step, the detailed design drawings and BIM models, which meet the requirements of guidelines, were delivered to the manufacturers. As a result of the in-depth communication and consultation with the design teams, the manufacturers were able to optimise the original fabrication process and approach to complete the production of modules following the guidelines. As shown in the below photos (Figure 5.20 – 5.26), the steel modules of project 1 were produced at the manufacturing factory. As a result of the developed guidelines, the design teams suggested more efficient fabrication procedures to manufacturers to prevent defects and reworks. Furthermore, based on the guidelines, the design teams held discussions with the manufacturers regarding the materials and structures of the proposed modules at the design stage, which contributed to improving the supply-chain management of materials in the manufacturing stage.

Figure 5.20 Fireboard installation

Figure 5.21 Door installation

Figure 5.22 Window installation

Figure 5.23 Electrics installation

Figure 5.24 Tiling works

Figure 5.25 Painting works

Figure 5.26 Completed module at the warehouse

To identify the quality of fabrication and the efficiency of the design guidelines, QA/QC checks were performed at the factory. The checks were distributed into three levels: 1) sub-con QA/QC checks, 2) internal QA/QC checks and 3) third-party inspection checks. Figure 5.27 illustrates the entire framework of the quality checklist of project 1. Figures 5.28 and 5.29 present quality checklists of the specified works. Additionally, the cost consumed during the manufacturing was recorded. Documents and records related to modular design, such as RFIs, were also collected for further analysis.

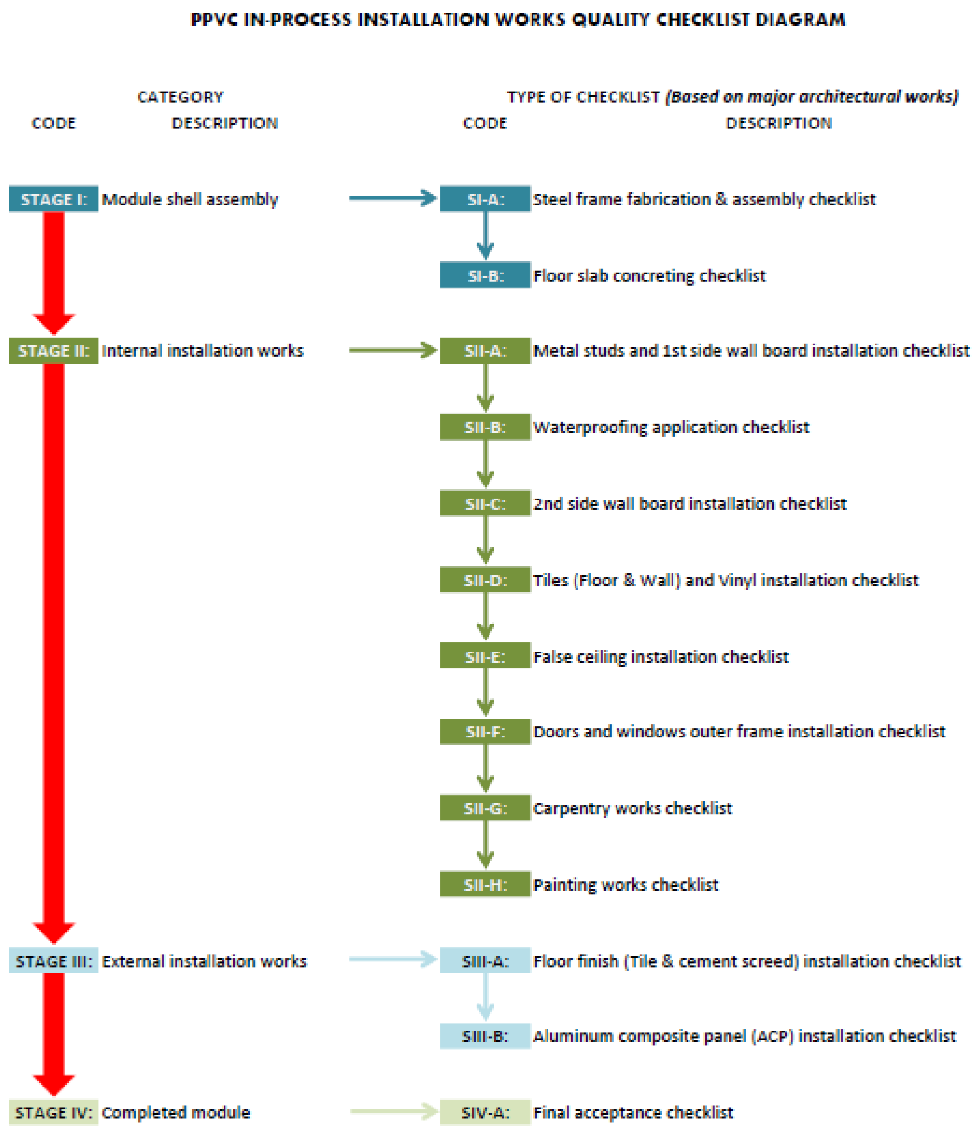


Figure 5.27 Manufacturing quality checklist diagram

	STEEL FRAME FABRICATION AND ASSEMBLY CHECKLIST *STAGE I: Module shell assembly*	Checklist Code: SI-A

Project Name :					
Unit No. :		Location / Work Area :		Inspection Ref. No. :	
Module No. :		Shop Drawing Ref.No.:		Inspection Date :	

ACTIVITIES		CONFORMITY (✓)			REASON FOR NON-CONFORMITY (If "NO" is marked)	CORRECTIVE ACTION TAKEN			
S/N	DESCRIPTION	Yes	No	N/A		DESCRIPTION	INSPECT'N. DATE	REMARKS (✓) COMPL'D.	SATISFY.
GENERAL:									
1	Provision of reference line markings:	√							
	a. 1 meter line from FFL								
	b. X & Y grid line								
2	Shop drawings approved for construction	√							
BEFORE AND DURING FABRICATION AND ASSEMBLY OF STEEL FRAME:									
1	Steel components as per drawing & specs.:								
	a. Column size and types	√							
	b. Beam size and types	√							
	c. Sub-frame size and types	√							
	d.Metal sheet paneling size and types	√							
	e.Bond deck size and types			√					
2	Setting out as per drawing:								
	a. Overall length clearance	√							
	b. Overall width clearance	√							
	c. Overall height clearance	√							
3	Alignment:								
	a. Verticality	√							
	b. Horizontaly	√							
4	Steel components assembly:								
	a. Welding joints as per drawing & specs.	√							
	b. Sub-frame distributed as per drawing & specs.	√							
	c. Provision of frame for fixing other services	√							
	d. Metal sheet paneling properly fixed	√							
	e. Bond deck properly fixed & as per drawing	√							
5	Sizes and location of openings (architectural):								
	a. Doors (clear opening)	√							
	b. Windows (clear opening)	√							
AFTER FABRICATION AND ASSEMBLY OF STEEL FRAME:									
1	Preparation of steel surface to receive finishes:								
	a. Excess welding components removed	√							
	b. Rusty surfaces removed	√							
	c. Decking surface free from any debris	√							
2	Painting of all steel components	√							

Inspected By : Name : Organisation : Date :	Confirmed By : Name : Organisation : Date :

Figure 5.28 Steel frame checklist

	PAINTING WORKS CHECKLIST *STAGE II: Internal installation works*	Checklist Code: SII-H

Project Name :					
Unit No. :		Location / Work Area :		Inspection Ref. No. :	
Module No. :		Shop Drawing Ref.No.:		Inspection Date :	

ACTIVITIES		CONFORMITY (✓)			REASON FOR NON-CONFORMITY (If "NO" is marked)	CORRECTIVE ACTION TAKEN			
S/N	DESCRIPTION	Yes	No	N/A		DESCRIPTION	INSPECT'N. DATE	REMARKS (✓) COMPL'D.	SATIS'FY.
COMPLETION OF PRECEDING ACTIVITIES:									
1	Puttying of wall & ceiling boreds:								
	a. Boards completely installed & good condition	√							
	b. Board joints installed w/ mesh & properly sealed	√							
	c. Screws sealed	√							
	d. Surface levelled and in proper alignment	√							
	e. Corner joints installed w/ beads & properly sealed	√							
	f. Surface clean & smooth	√							
BEFORE AND DURING APPLICATION OF PAINTS:									
1	Surface tested and complied for moisture content	√							
2	Materials to be used as per drawing & specs.:	√							
	a. Sealer paint type	√							
	b. Primer paint type	√							
	c. Final paint type	√							
	d. Final paint color	√							
3	Application of paints:								
	a. All surfaces not for painting are protected	√							
	b. Paints are mixed properly prior to application	√							
	c. Paint coats are applied evenly	√							
	d. Sealer paint completed & dry before primer coat	√							
	e. primer paint completed & dry before final coat	√							
AFTER APPLICATION OF PAINTS:									
1	All temporary protections are removed		√		Part of protection fixed				
2	Unwanted paints are removed & cleaned	√							
3	Damaged paint surfaces are being touch-up	√							
4	Final painted/coated surfaces are in good condition	√							
	-Free from scratches								
	-Free from dents								
	-Free from stains								

Inspected By :	____________	Confirmed By :	____________
Name :	____________	Name :	____________
Organisation :	____________	Organisation :	____________
Date :	____________	Date :	____________

Figure 5.29 Painting works checklist

5.4.4 Transportation stage

From the design and planning stage, there was constant communication and coordination between the design and logistics teams. The transportation plans, including the route, time, vehicles and schedule, were discussed and designed, taking into consideration the DfT in the guidelines. When prefabricated modules passed the QA/QC inspections in the manufacturing stage, the logistics teams, which owned the required semi-trailers, then carried out the designed delivery plans. Through the approved paths (see Figure 5.30), PPVC modules in project 1 were delivered to the construction site with a planned interval time, which considers the installation period to prevent the long vehicle parking at the narrow construction site. Figure 5.31 shows the PPVC module reaching the construction site. According to the requirement of DfT, the module was covered with a protective cover to decrease the risk of damage during transportation. To evaluate the effectiveness and efficiency of the guidelines, a quality inspection of the module was performed after it arrived at the site (see Figure 5.32). The time of the module transportation, including the module delivery period, vehicle parking period, etc. was registered for further discussion.

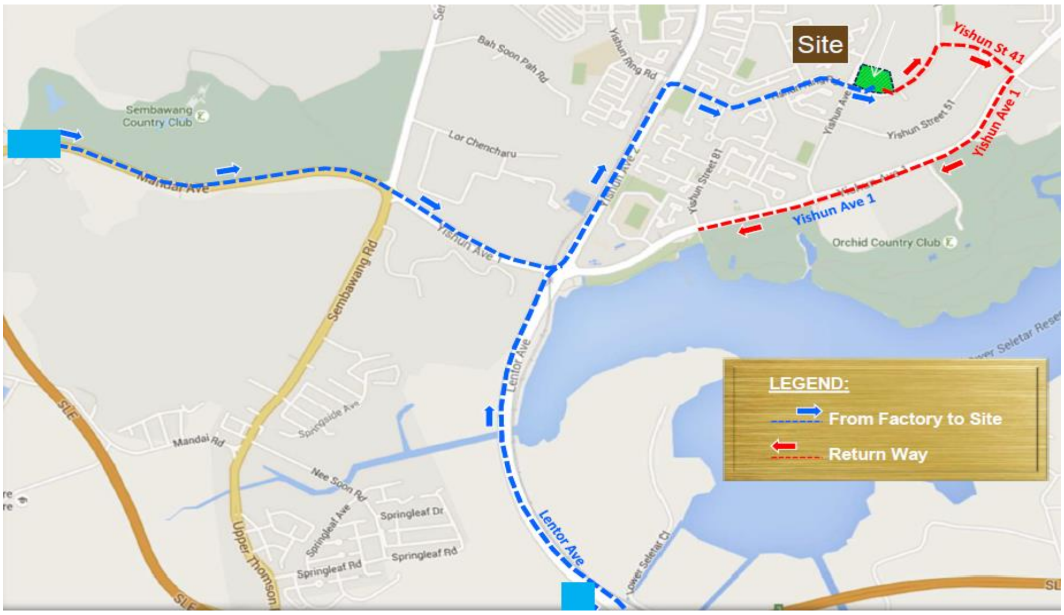


Figure 5.30 PPVC module delivery path

Figure 5.31 PPVC module at the construction site

	MODULE INSTALLATION CHECKLIST	Checklist Code:
	STAGE A: Module launching	**SA-01**

Project Name :					
Unit No. :		Location / Work Area :		Inspection Ref. No. :	
Module No. :		Shop Drawing Ref.No. :		Inspection Date :	

ACTIVITIES		CONFORMITY (✓)			REASON FOR NON-CONFORMITY (If "NO" is marked)	CORRECTIVE ACTION TAKEN			
S/N	DESCRIPTION	Yes	No	N/A		DESCRIPTION	INSPECT'N. DATE	REMARKS (✓) [illegible]	REMARKS (✓) [illegible]
GENERAL:									
1	PPVC module installation planning as per required:	√							
	a. Method & sequence of assembly & erection	√							
	b. Method of providing temporary supports	√							
	c. Provision for final structural connections & joint details	√							
	d. Unloading point is accessible	√							
	e. Unloading point is accessible	√							
PREPARATORY WORKS:									
1	Delivery of PPVC module as per required:								
	a. Site is accessible for delivery	√							
	b. Unloading point is accessible	√							
	c. Unloading / holding point based on "First In - First Out" principle according to the delivery schedule & erection sequence	√							
2	Delivery checklist as per launching schedule:								
	a. Correct type	√							
	b. Correct quantity	√							
	c. Correct module identification	√							
3	Hoisting of PPVC module as per required :								
	a. Adequate crane capacity	√							
	b. Adequate working clearance	√							
	c. Lifting inserts in proper location & good condition	√							
DURING MODULE INSTALLATION:									
1	Setting out:								
	a. Reference lines & offset lines accurately set	√							
	b. Concrete stump in proper position & alignment	√							
	c. Vertical or horizontal connectors in proper position & alignment	√							
	d. Dimensions & alignment as per specified tolerance	√							
	e. Internal tile alignment is achieved	√							
2	Lifting & installation:								
	a. Module is in good hoisting condition	√							
	b. Module is supported at more than two locations	√							
	c. Levelness in between modules are correct	√							
3	Joint connections of module to main RC structure:								
	a. Cast-in plate at RC beam installed as per design	√							
	b. Flushing composite completely installed	√							
4	Joint connections between modules:								
	a. Backer rod, modified PU sealant & waterproofing complete at ceiling beam joints (as per detail)	√							
	b. Backer rod, modified PU sealant complete at column / wall joints (as per detail)	√							
	c. Backer rod, non-shrink grout complete at floor beam joints (as per detail)	√							
AFTER MODULE INSTALLATION:									
1	M&E services installation in between modules:								
	a. GI conduit pipe completed & properly installed	√							
	b. P & S pipe completed & properly installed	√							
	c. Gas pipe completed & properly installed	√							

Inspected By :	____________	Confirmed By :	____________
Name :	____________	Name :	____________
Organisation :	____________	Organisation :	____________
Date :	____________	Date :	____________

Page 1 of 1

Figure 5.32 Module launching checklist

5.4.5 Assembly stage

In accordance with the developed design guidelines, the design teams assisted in selecting appropriate types and numbers of cranes. The crane layout was developed by the contractors and the design teams. Figure 5.33 illustrates the tower crane layout of project 1. Three hammerhead tower cranes were used, taking into account various factors mentioned in the guidelines in terms of the weight and dimension of modules, heights of buildings, lifting capacity, and height and radius of the cranes. In project 2, because of the restricted space, a luffing tower crane was the preferred solution. Following the evaluation index stated in the guidelines, the contractor and the design team selected a luffing tower crane with a lifting capacity of 32 tonnes and 59.1 m lifting height (see Figure 5.34).

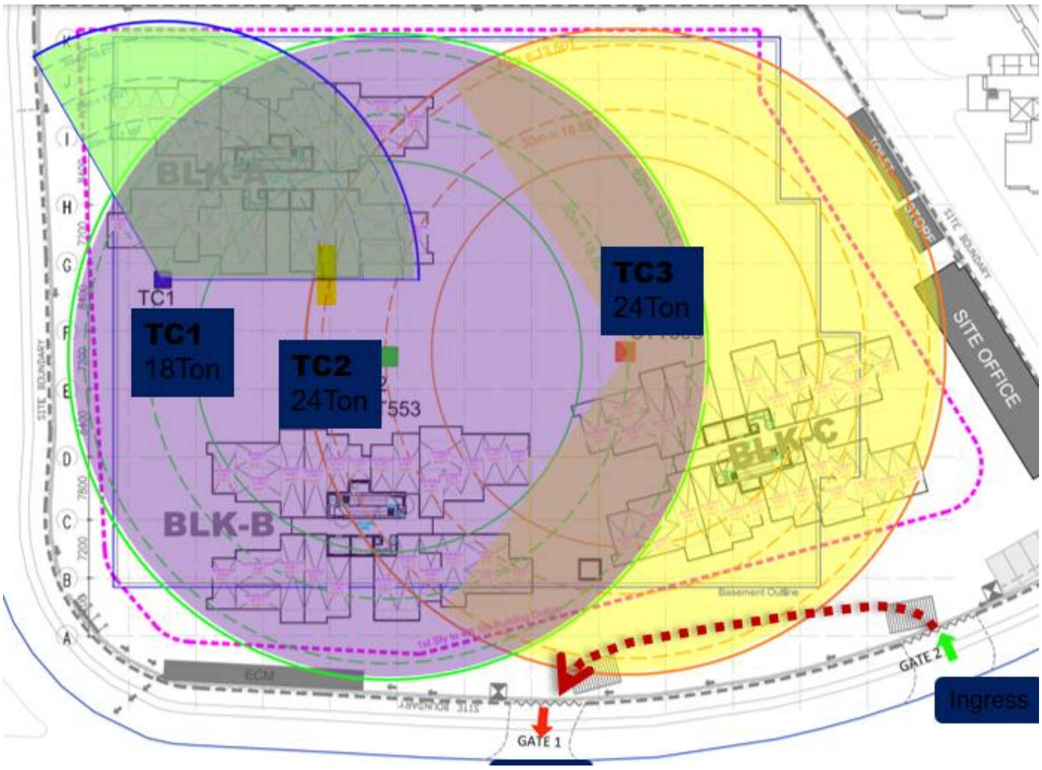


Figure 5.33 Tower crane layout

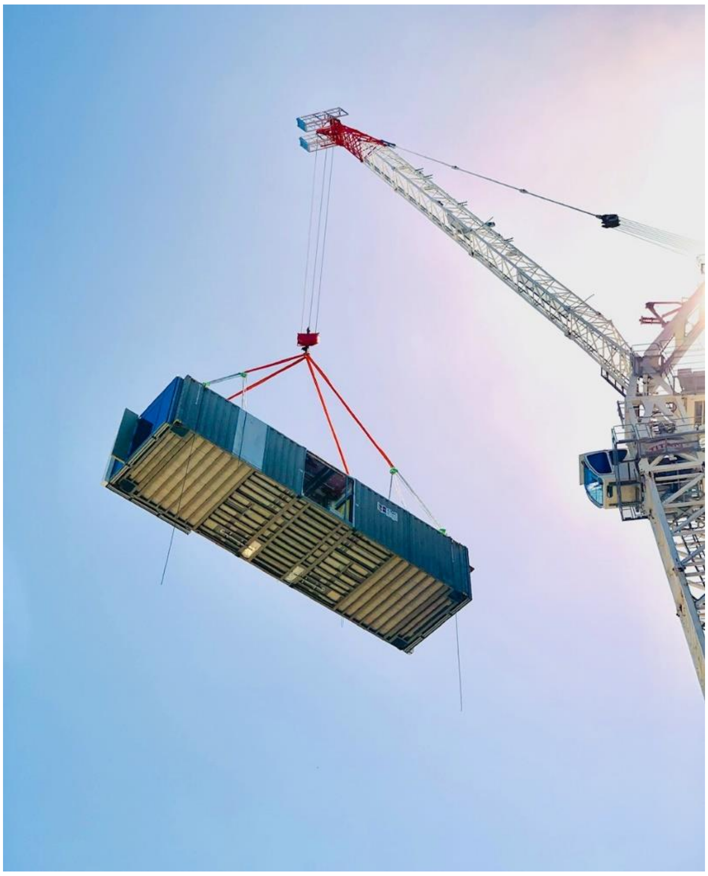


Figure 5.34 Luffing tower crane in project 2

The prompt completion of the module installation can be attributed to the prudent design concerning connections. Leveraging the optimal types of connections slashed the installation period of prefabricated modules as well as the risk of working at heights. Figure 5.35 shows the steel plate fixed to the concrete podium. Based on the guidelines, the design team proposed these precast plates at accurate locations that can be directly connected to modules connections. In addition, the design team considered the feasibility of maintenance and the aesthetics of the building. The installation and inspection holes were provided along the corridor and were covered by carpet (see Figure 5.36). For analysis of time reductions, relevant information and documents were collected in relation to module installation (e.g. installation floor cycle). The remaining and finished fit-out installation checklists were also recorded to identify the quality and performance of module installation (see Figures 5.37 and 5.38).

Figure 5.35 Module-to-structure connection

Figure 5.36 Installation and inspection hole for inter-module connection

	REMAINING FALSE CEILING INSTALLATION CHECKLIST	Checklist Code:
	STAGE B: Remaining fit-out installation works	**SB-02**

Project Name :					
Unit No. :		Location / Work Area :		Inspection Ref. No. :	
Module No. :		Shop Drawing Ref.No.:		Inspection Date :	

ACTIVITIES		CONFORMITY (✓)			REASON FOR NON-CONFORMITY (If "NO" is marked)	CORRECTIVE ACTION TAKEN			
S/N	DESCRIPTION	Yes	No	N/A		DESCRIPTION	INSPECT'N. DATE	REMARKS (✓)	
								[illegible]	[illegible]
COMPLETION OF PRECEDING ACTIVITIES:									
1	Fire compartment boards complete & good condition:								
	a. Putty / skimming	√							
	b. Painting	√							
2	Connection of concealed M&E services:								
	a. Electrical	√							
	-Cable tray								
	-Concealed pipes								
	-Lightning conductor								
	b. Plumbing and Sanitary	√							
	c. ACMV	√							
	-Duct								
	-Cable tray								
	-Refrigeration pipes								
3	M&E services testing completed and cleared:								
	a. Electrical Resistance test	√							
	b. Drain pipe flow test	√							
	c. Water pressure test	√							
BEFORE AND DURING INSTALLATION OF FALSE CEILING:									
1	Metal frame to be used as per drawing & specs.								
2	Ceiling boards to be used as per drawing & specs.:								
	a. boards types	√							
	b. board thickness	√							
3	Setting out as per drawing & as per existing (Installed at yard:								
	a. Alignment	√							
	b. Level Height (finishing level)	√							
4	Metal frame installations:								
	a. Sufficiently anchored in the ceiling / wall	√							
	b. Frame equally distributed	√							
	c. Provision of frame for access panels	√							
	d. Provision of frame for fixing other services	√							
5	Board installations:								
	a. Type of boards installed as per location	√							
	b. Even distribution of screws for board fixing	√							
6	Provision of access openings as per drawing:								
	a.Location	√							
	b. Sizes	√							
7	M&E services openings as per drawing:								
	a.Location	√							
	b. Sizes	√							
AFTER INSTALLATION OF OF FALSE CEILING:									
1	Preparation of ceiling surface to receive finishes:								
	a. Board joints properly sealed	√							
	b. Screws sealed	√							
	c. Surface levelled and in proper alignment	√							

Inspected By :	____________	Confirmed By :	____________
Name :	____________	Name :	____________
Organisation :	____________	Organisation :	____________
Date :	____________	Date :	____________

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Figure 5.37 Remaining fit-out installation checklists

	CHECKLIST FOR INTERNAL WALLS	Checklist Code:
	STAGE C: Finished fit-out quality checks	**SC-02**

Project Name :					
Unit No. :		Location / Work Area :		Inspection Ref. No. :	
Module No. :		Shop Drawing Ref.No.:		Inspection Date :	

ACTIVITIES		CONFORMITY (✓)			REASON FOR NON-CONFORMITY (If "NO" is marked)	CORRECTIVE ACTION TAKEN		REMARKS (✓)	
S/N	DESCRIPTION	Yes	No	N/A		DESCRIPTION	INSPECT'N. DATE	COMPLT'D.	SATIS'FY.
FINISHING:									
1	No stain marks	√							
2	Consistent color tone	√							
3	No rough / patch surface	√							
ALIGNMENT & EVENNESS:									
1	Surface even (Not more than 5mm per 1.2m)	√							
2	Verticality of wall (Not more than 5mm per meter)	√							
3	Walls meet at right angles (Not more than 4mm over 300mm)	√							
4	Edges (wall to wall) to appear straight & aligned	√							
CRACK / DAMAGE:									
1	No visible damage / defects	√							
HOLLOWNESS / DELAMINATION:									
1	No hollow sound when tapped with tapping rod	√							
2	No sign of delamination	√							
JOINTING:									
1	Straightness of corners & joints	√							
PLASTER FINISH:									
1	Surface even	√							
2	No hollow sound when tapped with tapping rod	√							
3	Surface shouls have no brush / trowel marks	√							
TILE FINISH:									
1	Tile joints aligned & with consistent joint size	√							
2	No hollow sound when tapped with tapping rod	√							
3	Consistent color & neat pointing	√							
4	Lippage bet. 2 tiles should not be more than 0.5mm	√							
PAINTING:									
1	Surface are evenly painted	√							
2	Good opacity, no patchiness resulted from touch-up works	√							
3	Free from peeling, blister and chalkiness	√							
4	No discoloration and fading	√							

Inspected By : ______________________
Date : ______________________
Verified/Closed By : ______________________
Date : ______________________

Rectified By : ______________________
Date : ______________________

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Figure 5.38 Finished fit-out checklist

5.4.6 Results and discussions

To evaluate the efficiency and effectiveness of the developed guidelines, the time reduction was measured by comparing the practitioners' previous projects of a similar scale. In addition to the time and cost reductions, other contributions were discussed based on the responses from all stakeholders.

A quantitative analysis focusing on time reductions is difficult because the results should be compared with data that do not use the developed design guidelines. Therefore, in this study, the actual data were compared with the scheduled plan. Moreover, the corresponding practitioners provided associated information based on their previous similar-sized projects as a benchmark.

Compared with the planned design period, the actual design period was 105 days, which was a 12.5% decrease (see Figure 5.39). As shown in Figure 5.40, the actual design period of project 2 was 88 days—much less than that of the initial schedule and the design period of a previous 10-storey hotel located in Singapore that adopted PPVC technology. Compared with the initial plan, the actual design period saved 12 days. The design team explained that they had a clear understanding of the entire modular construction because of the design guidelines. As a result, the design team improved their communication and coordination with other parties, which significantly reduced the design time. Moreover, by understanding the requirements of downstream processes, the design team was able to provide optimal design solutions while preventing additional time on design modification. According to the records of design modification, including RFIs and updated drawings, the design issues decreased significantly. For project 1, the design issues detected during the entire modular construction were 70–80% of previous similar projects. In project 2, compared with a past hotel modular building, the design issues decreased by over 40% according to the design team.

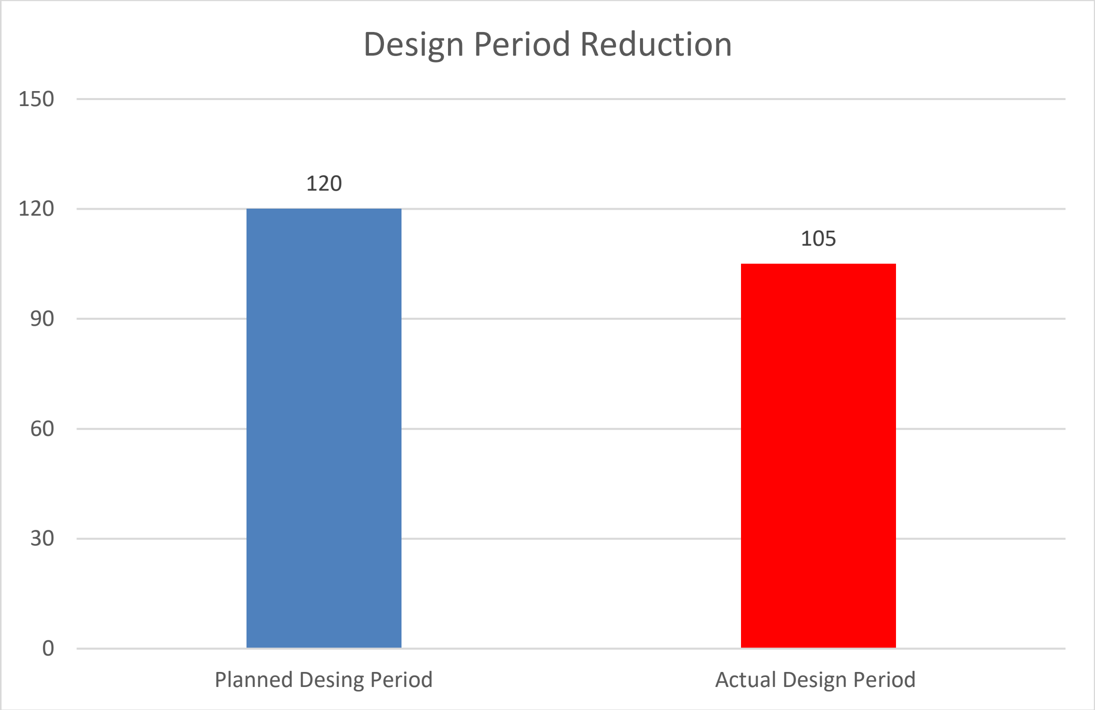

Figure 5.39 Design period reduction analysis of project 1

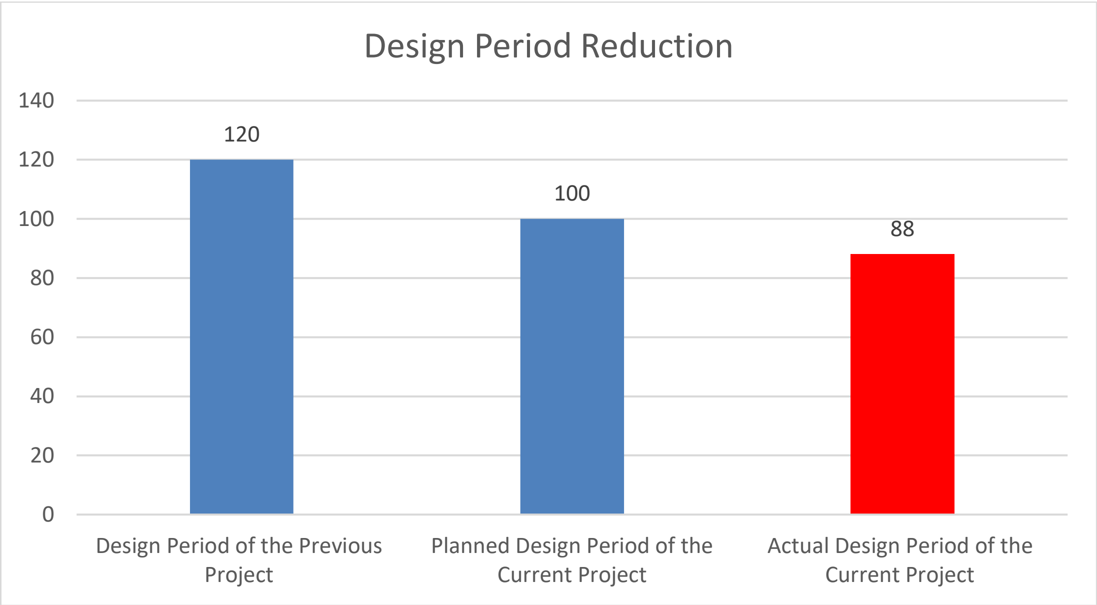

Figure 5.40 Design period reduction analysis of project 2

In relation to the manufacturing process, the comparison of the module fabrication time of different projects is not convincing because the numbers and types of modules are distinct, and the labour involved in each project is not the same. To identify the promotion of manufacturing, the actual fabrication time was compared with the initial plan. For project 1, as a result of the developed guidelines, the fabrication time saved around 30 days compared with the initial plan (see Figure 5.41). As shown in Figure 5.42, the actual fabrication work was completed 32 days before the planned schedule, which reduced around 18% of the total manufacturing time. Because of the guidelines, the design teams developed the drawings comprising the selection and procedures of the materials for manufacturing, which were beneficial for modular fabrication. The manufacturers highlighted the importance of the developed guidelines; they had spent a large amount of time and effort on coordination with design teams in previous projects because the drawings lacked sufficient fabrication information and were based on traditional construction methods. Moreover, based on the records of quality checklists, the quality of fabrication was enhanced. According to the records of the manufacturer in project 2, the defect rate had a 24% decrease compared with previous similar projects. The manufacturers explained that module drawings based on the design guidelines clarified the detailed approach and procedure of manufacture and helped reduce defects and reworks.

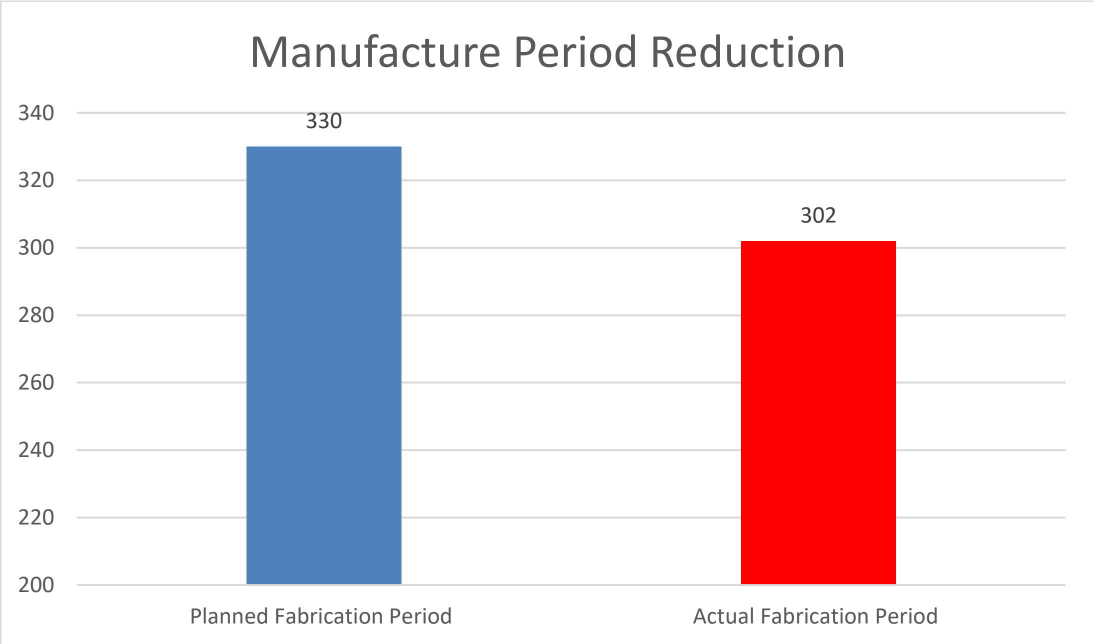

Figure 5.41 Manufacture period reduction analysis of project 1

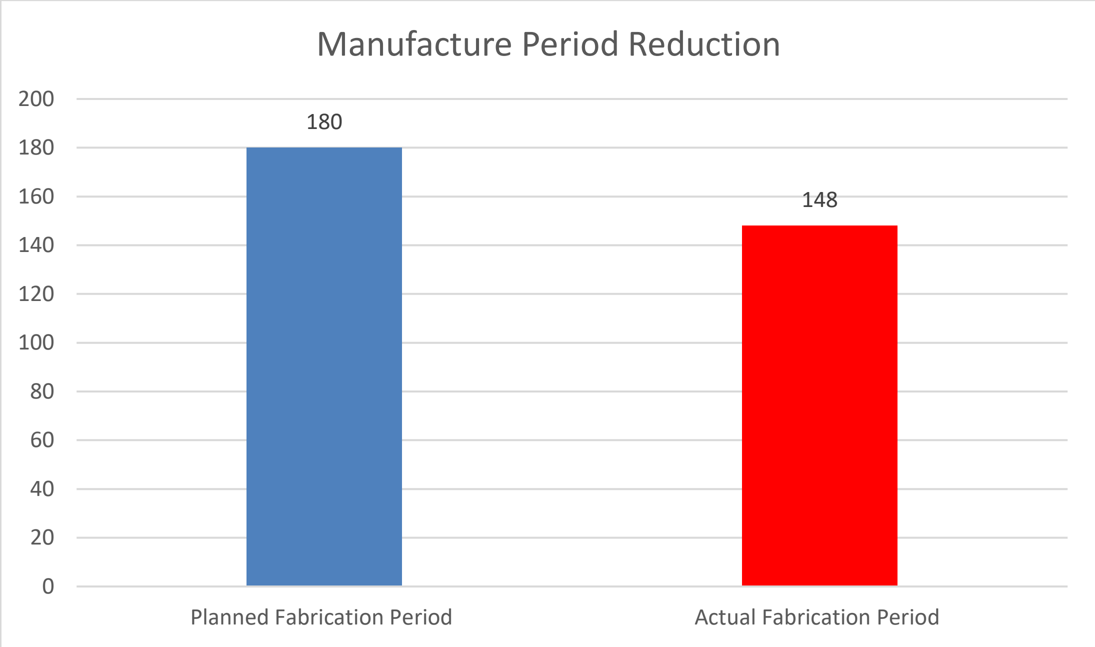

Figure 5.42 Manufacture period reduction analysis of project 2

Regarding the transportation stage, because the manufacturing factory of project 2 was overseas, PPVMs were transported to the domestic port by international carriage. It took around one month with two shipments to deliver all 252 PPVMs and 11 roof modules. The modules were then transported to the local storage warehouse. Based on the developed guidelines, the design teams assisted the logistics teams to obtain approval for OSOM transport. Aligned with the installation plans, the prefabricated modules were delivered to construction sites at specified intervals, which guaranteed a steady installation processes. Moreover, both projects adopted adequate transportation protection in accordance with the requirements of the design guidelines. As a result, damage to the modules caused by transport was restricted. In project 2, of a total of 252 modules, only two modules were damaged during the delivery based on the result of module launching checklists. This is much better than any other project using PPVM, according to the design team.

The assembly processes of the two projects also improved. From the planning and design stage, the design teams following the developed guidelines provided contractors with a feasible proposal related to the tower crane layout, which was the foundation of the installation works (Z. Zhang et al., 2022). The design guidelines described the erection and installation procedure, which promoted the efficiency of installation and increased construction safety. In addition, the fast installation of the modules can be attributed to the complex application of various types of connections. Figures 5.43 and 5.44 highlight the installation period reduction of the two projects. The actual installation time of project 1 was 242 days, with a rate of five days per floor cycle, which saved around 60 days in total, compared with the initial plan. In addition, according to the records of the installation works checklist, the defect rate was reduced to 82% of the average rate of previous projects. regarding project 2, because of the main road access limitations and the requirements of the OSOM permit, the modules could only be transported to the construction site during weekday off-peak hours. Furthermore, the extreme weather, including strong winds and hail, affected the installation schedule. In this case, the installation team, according to the developed guidelines, optimised installation methods and procedures to install 10 modules per day. The total installation was approximately 5 months.

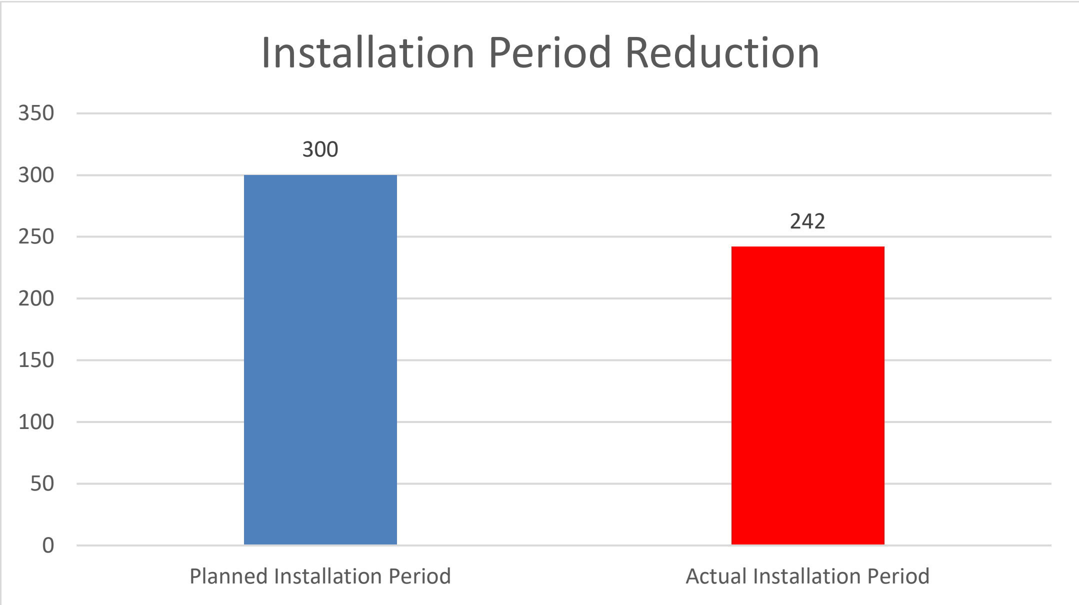

Figure 5.43 Installation period reduction analysis of project 1

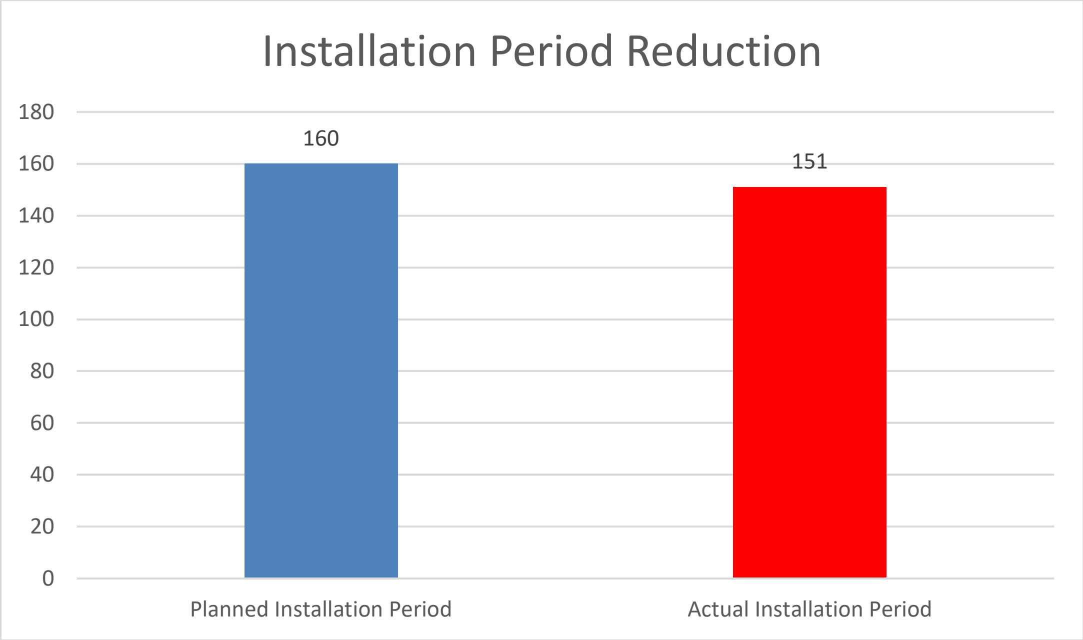

Figure 5.44 Installation period reduction analysis of project 2

Compared with the analysis of time reduction, it is more difficult to measure and analyse the cost reduction during each stage of modular buildings. Contracts for different work packages had been signed before the commencement of these works. From the perspectives of developers and main contractors, it is impossible to quantify the specific cost reduction resulting from the implementation of the design guidelines. However, the practitioners from all stakeholder groups were in broad agreement on cost reduction in each stage of modular construction. The cost reduction can be attributed to the time reduction and improved quality. As a result of the time reduction in each stage, some corresponding costs (e.g. labour and equipment costs) also decreased. In addition, because of the guidelines, the enhanced quality and performance of construction reduced the costs of reworks and defects.

5.4.7 Application of design guidelines

According to two case studies, the method and progress of implementing developed design guidelines can be concluded as follow. First, all stakeholders including designers, manufacturers, logistics, and contractors should involve at the beginning of the design and planning stage. Designers should take into account the constructability (e.g. manufacturability, transportability, and assemblability) of high-rise modular buildings based on coordination and communication with corresponding stakeholders, respectively. Second, designers should provide detailed modular design following the requirements of DfMA-based design guidelines. The detailed design should consist of the following information in relation to the constructability of modular buildings:

1) Manufacturability (see section 5.3.1)

Based on building types and height, the modular design should consider,

- Selection of module`s material (Steel module or RC module)
- Specific manufacturing processes

2) Transportability (see section 5.3.2)

Based on local traffic regulations, the modular design should consider,

- Limit of dimensions
- Limit of weight
- Plan and schedule of OSOM route
- Method and process of protection

3) Assemblability (see section 5.3.3)

Based on site conditions and module types, the modular design should consider,

- Selection and layout of tower crane
- Type of module connections

Last, the downstream stakeholders should conduct activities in accordance with the requirements of design guidelines. For example, fabrication processes developed by manufacturers and installation processes developed by contractors (see sections 5.4.3 & 5.4.5) should be consistent with the design guidelines and be scrutinised by designers.

5.4.8 Conclusion and limitations

The developed design guidelines were implemented for two projects in two case studies. From the early planning and design stage, the design teams maintained good coordination and communication with all stakeholders. By taking into consideration the downstream processes (i.e. manufacture, transportation and assembly), the design teams were able to provide comprehensive solutions based on the proposed guidelines for high-rise modular buildings. As a result, the following processes were improved according to the drawings and models embodying the requirements and approaches of the guidelines. To evaluate the efficiency of the developed guidelines, the time reduction in each stage of the two projects was analysed and discussed. Because of the proposed guidelines, the construction periods of the two projects were reduced considerably. Furthermore, the good records of quality checklists for different specific works identified the importance of the proposed design guidelines.

However, there are a few limitations in this study. First, both projects adopted steel modules only. No RC modules were investigated in the case studies. Second, as a result of the COVID-19 restrictions, only two projects were selected in this study. Third, it was difficult to collect some confidential information involving the detailed costs of the specific work package.

5.5 Summary

This chapter demonstrated the development and verification of DfMA-based design guidelines for high-rise modular buildings. The DfMA concept derives from the manufacturing industry and has been embraced by the construction industry in recent years. By considering the downstream processes (i.e. manufacture, transportation and assembly), the DfMA concept plays a crucial role in the design stage of OSC. However, the application of DfMA for high-rise modular buildings comprising a large number of PPVC or PPVM modules is limited. In Chapter 4, the constraints hindering the development of high-rise modular buildings revealed that 'lack of design standards and guidelines' is one of the primary problems affecting the entire life cycle of modular construction. Therefore, developing DFMA-based design guidelines is important in facilitating the development and progress of high-rise modular buildings.

First, to understand the existing implementation of DfMA in the construction industry, a comprehensive literature review was conducted. Because this innovative method was first adopted in manufacturing, relevant design guidelines for the manufacturing industry were investigated. However, it is difficult to use these descriptive and qualitative guidelines in the construction industry because of the difference between manufacturing and construction. Some countries and regions have published DfMA guidelines for construction, and some previous studies have applied various principles of DfMA in practical construction projects. However, current guidelines provide common approaches but no specific details, and these guidelines are not aimed at high-rise modular buildings. As a result, it is important to develop a series of DfMA guidelines for high-rise modular buildings.

Second, the DfMA-based guidelines were developed considering the primary stages of modular construction in terms of manufacture, transportation and assembly. From the perspective of the design team, the guidelines focused on the downstream processes and provided quantitative criteria and detailed procedures for all practitioners involved in modular buildings. The guidelines consist of three main categories: DfM, DfT and DfA. The DfM compared two primary materials of prefabricated modules: steel modules and RC modules. In addition, the specific procedures of manufacture for both steel and RC modules were explained. Concerning DfT, all requirements related to module delivery, including dimension, weight, OSOM route and protection, were presented. For the last part, DfA introduced the procedure of module installation and different types of connections.

Last, the developed guidelines were implemented in two high-rise modular buildings. To validate the efficiency and effectiveness of the guidelines, all practitioners from different parties were requested to follow the requirements of the guidelines. From the planning and design stage, the design teams maintained good communication and coordination with all parties and provided drawings and models in accordance with the guidelines. The practitioners, including manufacturers, logistics teams and contractors, then completed the projects accordingly. The time and quality checklists of each stage were recorded to evaluate efficiency and performance. The final results showed that the implementation of the developed guidelines reduces the entire construction time while also promoting the quality of construction.

CHAPTER 6: Conclusions, Contribution and Future Recommendations

Conclusions, Contribution and Future Recommendations

6.1 Introduction

This chapter summarises the research findings for each objective in Section 6.2. Section 6.3 presents the theoretical and practical contributions of this study. The last section discusses the research limitations and future studies.

6.2 Conclusion

6.2.1 Research findings for Objective 1

Objective 1: To obtain a comprehensive understanding of modular buildings.

This objective has been achieved. The findings are outlined below.

a) A comprehensive literature review related to modular buildings was conducted:

- The definition of modular buildings in OSC was presented as 'pre-assembled units formed a building with fully internal finishing'.
- The benefits of modular buildings were revealed, including reduced construction period, decreased wastage and safety risk, and improved quality.
- The challenges of modular buildings were disclosed.

b) The ranking of 27 primary constraints hindering the development of high-rise modular buildings was identified:

- According to a focus group and questionnaires, 'lack of coordination and communication among stakeholders', 'higher cost', 'lack of government support', 'lack of experience and expertise', 'lack of standards and guidelines', 'poor supply chain integration' and 'complexity of connection' were recognised as the foremost challenges.
- The improvement of modular design is the key to the development of high-rise modular buildings. The DfMA is a potential solution to optimise the design of high-rise modular buildings.

6.2.2 Research findings for Objective 2

Objective 2: To develop a design guideline for high-rise modular buildings based on DfMA theory.

This objective has been achieved. The findings are outlined below.

a) An in-depth literature review related to DfMA-based design guidelines was conducted:

- The DfMA principles are derived from manufacturing and have been adopted in the construction industry. Benefits include a reduced number of components, reduced materials wastage, reduced on-site activities, standardisation of elements and materials, and increased prefabricated elements and modules.

b) DfMA-based design guidelines for high-rise modular buildings were developed:

- DfM provided comparison information of steel and RC modules. Moreover, DfM indicated the entire manufacturing procedures of steel and RC modules.
- DfT illustrated key design considerations in relation to module transport, including dimension, weight, OSOM route and protection.
- DfA manifested the details of erection and connection during the assembly stage. Erection explained tower crane selection and the detailed installation procedure. Connection introduced the different types of connections used in high-rise modular buildings.
- Compared with previous studies, the developed guidelines with a focus on high-rise modular buildings provided practical quantitative criteria that can be employed directly by all stakeholders.

6.2.3 Research findings for Objective 3

Objective 3: To validate DfMA-based design guidelines for high-rise modular buildings.

This objective has been achieved. The findings are outlined below.

a) The developed guidelines were adopted by all stakeholders of a project with three blocks of 9-storey residential buildings located in Singapore. Significant improvements were achieved:

- The design period was reduced from 120 days to 105 days—a time reduction of 12.5% compared with the initial schedule. The design issues detected throughout the entire construction were reduced by around 20–30% compared with previous projects of a similar scale. The design team had an in-depth and comprehensive understanding of high-rise modular buildings, including manufacture, transportation and assembly.

- The manufacturing period was reduced from 330 days to 302 days, which was a decrease of 8%.
- A steady module transport process was performed because of the advanced application of OSOM and the protection of the modules.
- Compared with the initial schedule, the installation period was 242 days, with a rate of five days per floor cycle, which saved around 60 days in total. The defect rate of installation works was reduced to 82% of the average rate of previous projects.

b) An 18-storey hotel, located in Perth, Australia, consisting of 252 PPVM, implemented the developed guidelines. Significant improvements were achieved:

- The actual design period was 88 days, with a 12% reduction in comparison with the schedule. In addition, the design quality increased, and there was a 40% decrease in design issues.
- The actual fabrication work was completed 32 days before the planned schedule, which was an 18% reduction in the planned manufacturing time. The quality of manufacture also improved. The defect rate decreased by 24% compared with previous similar projects.
- A total of 252 PPVMs were transported from the overseas factory. Module protection was conducted according to the guidelines. As a result, only two modules were damaged during the transport.
- The installation period saved 9 days, achieving 10 modules installed per day.

6.3 Contributions

This study is motivated by leveraging the DfMA philosophy to improve productivity and the quality of the entire life cycle of modular construction and trigger the widespread application of high-rise modular buildings. The primary contributions consist of the following two aspects.

1. Theoretical connections between the DfMA philosophy and the constructability of high-rise modular buildings.

DfMA, combined with DfM and DfA, is an innovative design method as well as a design philosophy. Stemming from the manufacturing industry, DfMA has been widely adopted in numerous manufacturing companies (Bogue, 2012). Previous studies have provided various design principles in relation to manufacture and assembly to improve the efficiency and quality of production. Meanwhile, considering the difference between manufacturing and construction, some studies provided relevant principles of DfMA, which were adopted in many empirical construction projects (W. Lu et al., 2020). However, the previous proposed guidelines were not closely related to high-rise modular buildings, although high-rise modular buildings have the most complex processes of manufacture and assembly. This study contributes to interpreting the DfMA philosophy into practical design guidelines with quantitative criteria for high-rise modular buildings. In comparison with the constructability of traditional construction, this study integrates the DfMA methodology to interpret the constructability of modular buildings into manufacturability, transportability and assemblability. These three factors represent the nature of the DfMA philosophy while establishing evaluation criteria for the entire life cycle of modular construction. The contribution of this study is linking the DfMA philosophy and concept to the specific constructability of high-rise modular buildings. In contrast to previous studies, the DfMA philosophy in this research expanded the design consideration for transportation, DfT, and merged into DfMA, considering the heavy workload of module transport.

2. Innovative DfMA-based design guidelines for high-rise modular buildings.

Many previous studies have explored the development and progress of DfMA integrated with theory and practice, and identified its motivations, prospects and challenges in construction. Limited studies have provided a quantitative evaluation criterion of DfMA that transforms abstract design philosophy into a concrete numerical value to offer direction for architects and engineers in the design stage. The contribution of this study is developing a series of DfMA guidelines involving quantitative assessment criteria for high-rise modular buildings. It included three parts: DfM, DfT and DfA. DfM presented the holistic comparison between steel and RC modules and specific manufacturing procedures for two types of modules. DfT highlighted the limitations of module transport related to traffic regulations, including dimension, weight and OSOM route. Additionally, the details of module protection during the transport were presented. Last, DfA provided consideration related to tower cranes and detailed installation procedures. Moreover, the different types of connections adopted in high-rise modular buildings were explained. Therefore, the developed design guidelines can be implemented directly by all stakeholders of high-rise modular buildings. In accordance with the design considerations stated in the guidelines, design teams can reduce the design period and improve the design quality. All practitioners can engage in good communication and coordination based on the guidelines. Two case studies validated the efficiency and effectiveness of the guidelines. The time reduction and improved quality were displayed throughout the entire modular construction.

6.4 Limitations and Future Research

First, only two case studies validated the developed guidelines. As a result of COVID-19 restrictions, cross-border site and factory visits were restricted. Only two projects using steel modules consented to data collection, even though the manufacture and installation procedures of concrete modules were demonstrated in the guidelines. Therefore, it is recommended that more projects comprising RC modules be investigated in future research to comprehensively identify the efficiency of the guidelines.

Second, details of developed guidelines can be improved by adding content related to distinct high-rise modular buildings in different countries and regions. For example, DfT claims that the design team should consider the dimension and size of modules, which are restricted by local traffic rules and regulations. However, the limitations of laden vehicles on roads vary in different countries and regions. Therefore, more specific requirements can be indicated in the guidelines in future research for widespread adoption in projects.

Third, although the benefits and value were demonstrated by all stakeholders of the two projects, design teams still have to spend time and effort to manually check the detailed requirements. Thus, future research could focus on enhancing the efficiency of the application of the guidelines by providing automated rule-based checking in BIM models.

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