A Novel Methodological Framework of Smart Project Delivery of Modular Integrated Construction

W. Pan[a], M. Pan[a] and Z.J. Zheng[a]

[a] Department of Civil Engineering, The University of Hong Kong, Hong Kong SAR, China
E-mail: wpan@hku.hk, panmi@connect.hku.hk, zhengzj@connect.hku.hk

Abstract –

Modular Integrated Construction (MiC) is an advanced type of modular construction focusing on addressing high-density high-rise buildings and is adopted as a new policy initiative in Hong Kong. Previous studies have examined the potential for using different methods and technologies to support project delivery in offsite and modular construction. However, there is a lack of systematic exploration and a paucity of examination of smart-tech solutions for MiC project delivery. This paper aims to develop a novel methodological framework of smart project delivery of MiC for achieving a better understanding of the complex process of MiC and ensuring the successful delivery of modular projects. This framework systematically structures the science, methods and technologies at four layers: sensor and data capturing, data storage and analysis, data visualization, and decision making. Drawing on the framework, key functions and technologies are explored through a systematic literature review, theoretical analysis and development, and focus group discussion with stakeholders. The framework provides a methodological basis for developing an integrative smart-tech platform for MiC project delivery. The findings of this paper are informative to practitioners and researchers for gaining a better understanding and implementation of MiC smart project delivery. The findings also contribute insights into the scientific methods and techniques of data capturing, analysis, visualization and use for dealing with complex and dynamic processes of modular building in high-density urban contexts.

Keywords –

Modular Construction; Modular Integrated Construction; Smart Technology; Project Delivery

1 Introduction

Modular construction (MC) has been adopted in many countries with demonstrated benefits including enhanced productivity and quality, improved health and safety, and minimized construction waste [1-3]. In Hong Kong, Modular Integrated Construction (MiC), an advanced type of the MC approach, focuses on addressing high-density high-rise buildings and has been developed as a game-changing approach to innovative building project delivery [4]. In MC and MiC, modules are produced in factories and then transported to sites for installation. It is critical to integrate real-time progress information from the factory production, module transportation and module installation on site, so that project delivery can be well monitored and controlled, achieving just-in-time delivery. However, there is still a lack of systematic exploration and a paucity of examination of smart-tech solutions for modular building project delivery.

This paper aims to develop a novel methodological framework of smart project delivery of MiC for achieving a better understanding of the complex process of MiC and ensuring the successful delivery of modular projects. This framework systematically structures the science, methods and technologies at four layers: sensor and data capturing, data storage and analysis, data visualization, and decision making. Drawing on the framework, key functions and technologies are explored through a systematic literature review, theoretical analysis and development, and focus group discussion with relevant academics and practitioners. The framework provides a basis for developing an integrative smart-tech platform for MiC project delivery. The findings of this paper are informative to practitioners and researchers for gaining a better understanding and implementation of MiC smart project delivery. The findings are also insightful in terms of the scientific methods and techniques of data capturing, analysis, visualization and use for dealing with complex and dynamic processes of modular building in high-density urban contexts.

2 Background

2.1 Modular construction in the world

Modular Construction (MC) is a novel approach to innovate building construction by using the Design for Manufacture and Assembly (DfMA) theory and advanced manufacturing and logistics technologies. A seminal definition of MC was provided by Gibb [5] as the building approach with three-dimensional (3D) units that enclose usable space and form part of the completed building or structure. MC has been adopted in countries including UK, US, Canada, Germany, Australia and Singapore, with demonstrated benefits including accelerated onsite construction, improved health and safety, enhanced productivity and quality, and minimized construction waste [1-3].

However, the adoption of MC has largely been for houses and low-rises, with only a small number of modular high-rises such as one of 44 floors using steel frame modules in London and another of 40 floors using concrete modules in Singapore [see 6]. There is yet little experience in and scarce knowledge of delivering modular tall buildings. For the small number of modular high-rises, reported benefits and challenges co-existed [1-2]. For example, the project Apex House, a 29-floor modular building in London, was found to have achieved the benefits: (1) 12-month saving in construction duration, (2) on-site waste minimized to 2%, (3) the number of on-site workers reduced to 40, but also encountered issues such as the need for (1) more training for workers in factory as well as on site, (2) enhancement of the capability of module supply chain, and (3) early logistics planning [1]. Another example is the 'B2 Tower' project, a 32-floor residential building in New York, which was completed with severe time and cost overrun and broken project partnership. Attributors to the failure were found to include absence of employee training, lack of a comprehensive plan, insufficient quality control, constraints from labor unions and limited supply chain capability [7].

The merits of and challenges to adopting MC for high-rise buildings are not entirely understood by industry and public [3]. The design, production and construction of modules for high-rises face more technical challenges than for low to medium-rises [2]. The challenges are more significant in high-density maritime cities such as Hong Kong, Singapore, London, New York and Sydney where high-rise buildings are constrained by high-density urban environments and challenged by strong monsoons. However, there is a paucity of examination of MC tall buildings in high-density cities.

2.2 Modular integrated construction in Hong Kong

Modular Integrated Construction (MiC) is based on but advances the MC approach, and is first defined by Pan and Hon [4] as "*a game-changing disruptively-innovative approach to transforming fragmented site-based construction of buildings and facilities into integrated value-driven production and assembly of prefinished modules with the opportunity to realize enhanced quality, productivity, safety and sustainability*." It has recently been adopted as a new policy initiative as stated in the Policy Address 2017 of the Hong Kong Government [8].

The MiC initiative in Hong Kong was set in the Policy Address to mainly address two significant issues facing the construction industry: workforce shortage and very high construction cost. There are several ongoing high-rise MiC pilot projects, including two 17-storey blocks of student residence on a 3-storey podium at The University of Hong Kong and one 16-storey block of staff quarter on a 1-storey podium at The Hong Kong Science Park [9]. These projects adopt the MC systems available in the market within the existing planning and design process and practice. The benefits of MC demonstrated in other countries [1-3] are actually highly consistent and associated with time, cost, quality, safety, sustainability and productivity, and thus should also by large be achievable for MiC in Hong Kong. The potential of MiC to have a transformative impact on the construction industry is also recognized [10]. However, there is a lack of empirical evidence to support the advantageousness of MiC and clear knowledge to guide the successful project delivery that could thereby promote the wide uptake of MiC.

2.3 Previous research related to modular building project delivery

Previous studies investigated the challenges facing the delivery of MC building projects. For example, McGraw-Hill Construction [11] surveyed the American construction industry and their report revealed clients' major concerns such as the early commitment to design and engineering work, the higher requirements for transportation, and the constrained number of suppliers. Yang et al. [12] identified that MiC has many new challenges and more stringent requirements in project delivery than conventional construction methods and other types of offsite approaches. For example, onsite works for MiC depend heavily on integrated modules manufactured offsite, which implies that onsite works are especially vulnerable to poor quality control and delivery delays. There are difficulties identified in logistics control, especially when involving complicated and expensive cross-border transportation for overseas module supply [1]. Decisions to support the successful delivery of MiC projects with optimized performance in time, cost, quality and safety require a clear understanding of the complex process of MiC and leveraging of new technologies.

There have been attempts on the use of smart technologies to support project delivery in MC/MiC. Han et al. [13] integrated simulation models and post-simulation 3D-visualization techniques for MC to support project managers' precise planning of production process and construction operation. Ramaji and Memari [14] developed information delivery framework for standardizing information exchange mechanisms to facilitate Building Information Modeling (BIM) implementation in modular buildings. Li et al. [15] explored the integration of Radio Frequency Identification (RFID) with BIM in the precast concrete factory for scheduling and supply chain management. Niu et al. [16] examined the potential of integrating Geographic Information System (GIS) and BIM for MiC logistics management. These studies and technology applications are promising for tackling different delivery issues in MiC, but there is still a lack of systematic exploration of integrative smart-tech solutions for MiC project delivery.

3 Research Methods

This paper aims to develop a novel methodological framework of smart project delivery of MiC for achieving a better understanding of the complex process of MiC and ensuring the successful delivery of modular building projects.

The framework was developed through an iterative process including literature review, theoretical analysis and development, and focus group discussion with relevant academics and practitioners. The research process is illustrated in Figure 1. First, the 1st round literature review was done on research works regarding MC/MiC, project delivery frameworks, and relevant smart technologies. Second, by integrating literature review results with theoretical analysis, an initial framework of smart project delivery of MiC was developed. Third, drawing on the initial framework, key functions and technologies were explored through a 2nd round literature review, through which the framework was concretized and refined. Fourth, focus group discussion was conducted with relevant academics and practitioners to verify and further refine the methodological framework with embedded functions and technologies. The details of focus group participants are presented in Table 1. Purposeful sampling was used to select focus group participants to cover MiC clients, contractors, suppliers, relevant government departments, as well as academic and professional bodies who have responsibility for MiC research and consultancy.

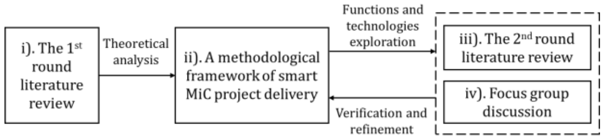

Figure 1. Research process of developing the methodological framework of MiC smart project delivery

Table 1. Participants in focus group discussion

Item	Description	Number
Primary area of practice	Contractor (with ongoing MiC project)	3
	MiC supplier	3
	Client (with ongoing MiC project)	4
	Government and its agencies	3
	Universities and professional bodies	10
Years of experience	6-9	4
	10-19	5
	More than 20 years	14
Total		23

4 A Methodological Framework of Smart Project Delivery of MiC

Successful delivery of construction projects heavily requires the reliable monitoring and control of project performance in terms of cost, time, quality, safety, and environment to satisfy stakeholder requirements via effective communication [17]. While existing literature [17-19] has addressed decision making issues of what and how performance should be measured, this present paper aims to provide a fundamental exploration of the underlying methods and technologies to support decision making in project delivery intelligently.

The proposed methodological framework of smart project delivery of MiC is illustrated in Figure 2, which systematically structures the science and methods at four layers: sensor and data capturing, data storage and analysis, data visualization, and decision making. The key scientific questions to address include:

- What types of information are needed for MiC smart project delivery?
- How such information can be represented and exchanged in various computing models with accuracy to suit different project stages?
- How such information can be analyzed and visualized for decision support?

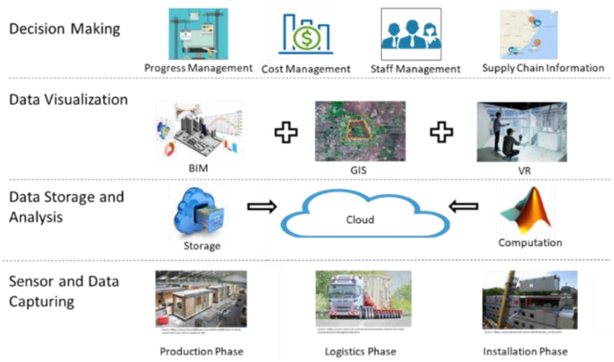

Figure 2. A novel methodological framework of smart project delivery of MiC

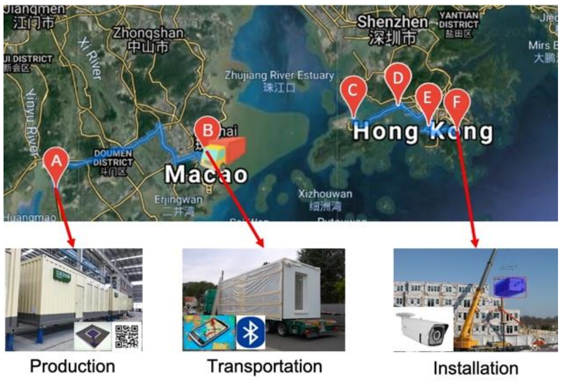

Figure 3. Examples of sensors used for MiC smart project delivery in the Greater Bay Area

4.1 Sensor and data capturing

The fundamental layer is sensor and data capturing, which is related to the collection of different types of information during different phases (see Figure 3) to effectively record and track relevant types of information, thereby supporting MiC project delivery.

During the production phase, tagging technologies, such as barcode [20], RFID [20], or Near-field communication (NFC) [21], can be fixed to individual modules for recording production information, e.g. module weight and dimensions, material sources, producers, quality checking and testing records. During the logistics phase, Global Position System (GPS)-based [22] and Bluetooth-based sensors [23] can be used for real-time tracking and tracing of module locations, which can further provide useful information for logistics coordination. During the on-site construction phase, images can be taken by site cameras and drones [24] to capture real-time information on module delivery and installation for efficient site planning and progress monitoring. Besides, different physiological sensors integrated into wearables [25] can be used to monitor fatigue and working conditions of workers for occupational safety and health management, such as electrocardiogram (ECG/EKG) sensors for heart monitoring, electromyography (EMG) sensors for muscle monitoring, and electroencephalography (EEG) sensors for brain monitoring.

Useful insights were obtained through the focus group discussion. Several professionals raised the concern of accuracy requirement (e.g. tracing the module in the factory to the exact on-site location) for selecting suitable sensors. Besides, some participants suggested a life-cycle management perspective that covers the stages from planning through operation and maintenance. In this regard, temperature, humidity, light and pressure sensors can be adopted to monitor the built environment; strain gauges can be used to measure strain on the module structure, thereby monitoring the health condition of the modular building.

4.2 Data storage and analysis

The second layer is data storage and analysis, through which the collected data from using smart sensors can be processed with a cloud-frog-edge computing integrated strategy (see Figure 4).

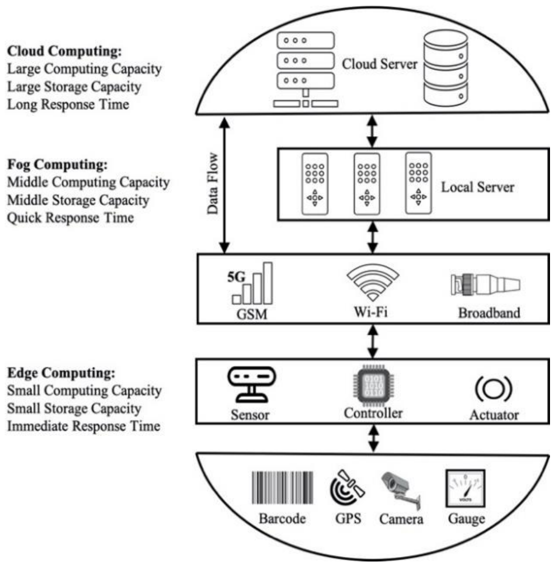

Figure 4. Cloud-frog-edge computing strategy for data storage and analysis

Cloud computing [26], and its extension, fog computing [27] and edge computing [28] can be used for dealing with different data and tasks of MiC. In general, cloud computing [26] is used for tasks that require large computing capacity but allow longer response time; frog computing [26] can be used for tasks that require a middle level of capacity; edge computing [28] is used for tasks that require immediate responses and small computing capacity. For example, in the case of onsite module installation using computer vision to detect the status of the modules, the monitoring task requires immediate responses from video streams and do not require a very large scale of computing compacity, edge computing should therefore be considered. While if the task is like logistic planning that requires large computing compacity on route selection but does not require immediate response, cloud computing should be adopted.

Based on such a data storage and analysis platform, real-time progress monitoring and control function can be developed for MiC projects to achieve just-in-time delivery. Machine learning algorithms can be integrated to predict potential progress delays and risks for better decision making. The concern of platform robustness was also discussed during the focus group meeting, in terms of how to integrate different data sources and extract information for different functions and how to manage and secure big data effectively. It is therefore important to consider information compatibility and design the information exchange schemes.

4.3 Data visualization

The third layer is data visualization, where BIM is the core technique that provides the interface for professionals to access data for project delivery.

The integration of GIS with BIM [16] is recognized as critical in digitalizing the logistics process for logistics planning and decision making. The integration is achievable through building geometry data communication between BIM (e.g. Revit) and GIS (e.g. ArcGIS) platforms for concurrent modelling of buildings. An example is given in Figure 5. Based on the BIM-GIS integration, the transportation and installation status of all modules can be visualized with their location and broader environment information for better logistics management. In addition, augmented reality and virtual reality (AR and VR) [29-31] can be used to enhance BIM for supporting effective execution of construction activities. For example, AR can provide workers with installation details of each type of module in a 3D view, from which workers can easily understand where and how to install a module.

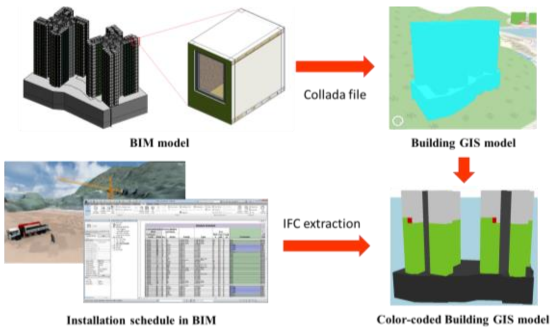

Figure 5. An example of BIM-GIS integration (after [16])

4.4 Decision making

The top layer is decision making, which deals with the managerial issues of how the analyzed and visualized information can be used for data-driven decision support in MiC project delivery. Technically, this layer should involve the design and development of desktop software (e.g. [17]) and mobile application to provide user friendly interfaces for decision making.

From a top-down perspective, identifying key areas of decision making [32, 33] is a preliminary task to support technical design of lower layers. By defining decision criteria and decision making rules, automated monitoring and control can also be achieved.

From a bottom-up view, data visualization can support decision making of stakeholders in an easily understandable manner and provide actionable insights for project delivery. First, decision makers can easily and quickly assess project delivery progress based on visualized data, thereby making timely and informed adjustments. For example, the real-time progress for module delivery can be visualized and compared with the scheduled time to support logistic planning and coordination. Second, different stakeholders can effectively communicate with each other based on data visualization for making joint decisions easier, and also can track the works of other stakeholders to make self-adjustment. Third, alternative plans or different remedial actions for identified issues can be clearly evaluated through data visualization to support decision making.

5 Discussions

The successful delivery of MiC building projects requires accurate and reliable monitoring and control to unleash the full benefits of this “factory assembly followed by on-site installation” [7] construction method for achieving its advantageousness. There are a variety of intelligent methods and technologies available to support MiC smart project delivery. However, how to effectively integrate various methods and technologies to provide different functions and fulfill stakeholder requirements is still a challenging issue. The developed methodological framework in this paper should address this knowledge gap by providing a systematic approach for understanding many methods and technologies and establishing technical plans for MiC smart project delivery. Table 2 summarizes the examples of methods and technologies with different functions for achieving MiC smart project delivery.

MiC is a very new concept and its feasibility of adoption for high-rise buildings still remains unclear [1]. More research is needed to discover the full potential of MiC and how successful implementation can be achieved. In this regard, the developed methodological framework should support the exploration and examination of best practice for the successful delivery of MiC projects. It provides a benchmarking tool for analyzing different technologies and their integrations to best orchestrate the complex process of MiC project delivery.

From a practical perspective, the developed methodological framework should support the establishment of a workable platform, which could allow optimization for achieving MiC smart project delivery and visualization of the whole process to project stakeholders for better engagement and continuous improvement.

Table 2. Examples of methods and technologies for MiC smart project delivery

Layer	Method and technology	Function
Sensor and data capturing	Barcode, RFID, NFC	Record production information
	GPS, BLE	Track module location
	Camera	Track onsite installation progress
	Physiological sensors	Monitor fatigue and working conditions of workers
	Temperature, humidity, light and pressure sensors	Monitor the built environment
Data storage and analysis	Cloud computing, frog computing, edge computing	Preprocess raw data, match computation tasks with suitable computing capacity, and data storage
Data visualization	BIM	Data manage and exchange center
	GIS	Provide intuitive logistic information
	AR/VR	Assist construction activities
Decision making	Desktop Software, Mobile Application	Interfaces for decision making

6 Conclusions

Modular Integrated Construction (MiC) is an advanced modular construction approach by particularly addressing complex and dynamic high-rise building in high-density urban contexts. It has shown a great potential for the betterment of building construction, but there is still a lack of systematic exploration of how successful project delivery of MiC can be achieved. This paper has developed a novel methodological framework of smart project delivery of MiC. The developed framework systematically structures the science, methods and technologies at four layers: sensor and data capturing, data storage and analysis, data visualization, and decision making. Drawing on the framework, key functions and technologies were explored through a systematic literature review, theoretical analysis and development, and focus group discussion.

The framework provides a basis for understanding different technologies and methods for MiC project delivery. The findings contribute insights into the scientific methods and techniques of data capturing, analysis, visualization and use for dealing with the complex and dynamic processes of modular building in high-density urban contexts. Future study will establish an integrative smart-tech platform based on the developed framework to support project delivery of MiC using real-life projects.

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