Opportunities and Challenges of Digital Twin Applications in Modular Integrated Construction

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Abstract –

Digital twin (DT) is commonly known as a virtual model of a physical object, a process or a system. In order to create DT, the emphasis is on building a Cyber-Physical System (CPS), where information collected from physical processes is used for computation to generate a real-time monitoring cyber model. At the same time, changes of the cyber model will either be used for prediction or reflection in the physical system to achieve the control function. With the development of digital and information communication technologies, DT has been applied in various areas such as manufacturing and aerospace industries. However, studies on the application of DT in the building construction sector were limited. Such studies were particularly rare about volumetric modular building which has attracted a burgeoning interest in both academia and practice globally.

This paper aims to contribute a better understanding of integrating the use of DT for Modular Integrated Construction (MiC) by examining the opportunities and challenges. The paper first reviews the state-of-the-art DT applications across various industries, and then focuses on publications about DT applications in the building construction sector through conducting a systematic search of literature using Scopus. After review and analysis of the identified publications, the paper explores the opportunities and challenges of applying DT in MiC. The review results show that DT is often considered with other digital technologies for integration. A conceptual framework is developed for applying DT in module installation in MiC within the context of Hong Kong as a typical case of high-density cities. Promising opportunities with huge benefits are speculated from the application of DT in MiC, including enhanced coordination of logistics and construction management by using DT to monitor on-site progress during the module installation stage. Nevertheless, challenges are also identified, which exist in not only the sensing technology and cyber system, but also the social-political environment supporting innovation and regulation. The developed framework should provide a useful guide to address the challenges and shape future research on DT in MiC.

Keywords –

Digital Twin (DT); Cyber-Physical System (CPS); Modular Integrated Construction (MiC); Smart Construction

1 Introduction

The construction industry is on a pace from being low-tech towards being innovative, in order to address problems and challenges such as low productivity and profitability and skills shortages facing by the industry [1]. Digital twin (DT) as an emerging digital technology has obtained more and more attention across different industries, particularly in the manufacturing industry over the past few years [2], which can also be a possible solution for the construction industry.

It is acknowledged that the concept of DT was firstly introduced in a presentation by Dr Grieves in 2002, which contains four essential elements of the DT: real space, virtual space and dual links for data transmission between real space and virtual space [3]. After that, the name of DT was raised in a roadmap of National Aeronautics and Space Administration (NASA) to describe a virtual digital product of an aircraft's flight system [4] and has been used ever since. DT is defined as a real-time virtual representation of not only a system, but also a process [5] or a physical object [6].

With the development of digital and information communication technologies, DT has been applied in several industries with wide-ranging demonstrated benefits. For example, the use of DT in the aviation industry helps engineers to quickly find out critical weak spots and to predict the future state of the asset [7]. In the manufacturing industry, DT of a physical product enhances collaboration between customers and designers, where communications are faster and more transparent with the function of automatic real time data acquisition [8]. However, studies on the application of

DT in the building construction sector are limited. Such studies of DT are particularly rare about volumetric modular building construction which has attracted a burgeoning interest in both academia and practice globally. Therefore, this paper aims to achieve the following objectives:

1. Review and elicit the state-of-the-art DT applications particularly in the field of building construction sector;
2. Explore the opportunities and challenges to adopt DT in volumetric modular building construction through the analysis of reviewed publications;
3. Develop a conceptual framework for applying DT in Modular Integrated Construction (MiC) in the context of Hong Kong as a typical case; and
4. Identify current gaps and challenges for future research.

Following this introduction, Section 2 explains the background including the state-of-the-art DT applications across various industries, the context of Hong Kong and delimitation of research scope. Section 3 elaborates the methodological approach for the systematic review. Section 4 presents results of the review on the identified publications, and discusses the results from the perspectives of opportunities, challenges and current research limitations. Section 5 proposes a framework of applying DT in MiC considering the scenario of module installation. Section 6 draws conclusions, as well as recommends prospects for future research.

2 Background

2.1 DT applications across industries

Researchers have contributed to the analysis of publications on DT applications across industries. Tao et al. [9] reviewed fifty papers in the manufacturing industry and found prognostics and health management (PHM) as the most popular application area. Enders and Hossbach [10] provided a cross-industry overview of DT applications, and classified ten industrial sectors where DT is applied, including manufacturing, aerospace, energy, automotive, marine, petroleum, agricultural, healthcare, public sector and mining (see Figure 1), where the manufacturing is the most popular industry applying DT. They also found that the applications of DT can be divided into three purposes including simulation, monitoring and control (see Figure 2).

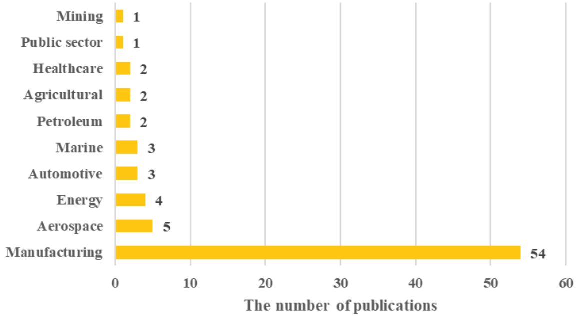

Figure 1. Distribution of relevant publications regarding DT applications across industries identified in the study of Enders and Hossbach [10]

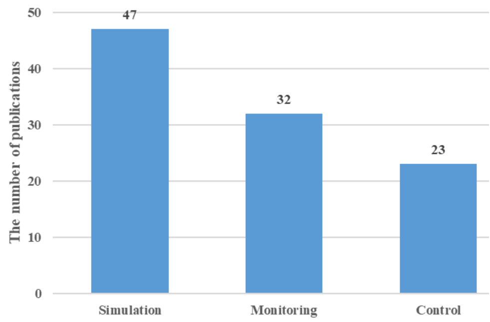

Figure 2. Distribution of relevant publications regarding purposes of DT applications identified in the study of Enders and Hossbach [10]

Even though some studies have been conducted on DT applications in the building sector, most of them focus on post-construction stage so that asset owners can better handle operation and maintenance works. For example, Khajavi et al. [11] established a DT of a building façade in order to collect environmental lighting, ambient temperature and relative humidity, which are used to reduce the overall management and operational cost. Lu et al. [12] developed a DT-enabled anomaly detection system for asset monitoring and validated it in a case study of the heating, ventilation and air-cooling (HVAC) system.

Nevertheless, studies on the application of DT in the building construction sector are limited. The potentials of DT application in MiC are still not clear. Therefore, literature review of relevant publications was carried out in this paper in order to explore opportunities and challenges of DT applications in MiC.

2.2 Hong Kong context

The construction industry in Hong Kong plays an important role in economic growth and social development, which contributed 4.5% of Gross

Domestic Product (GDP) in 2018 [13]. However, the Hong Kong construction industry is facing severe challenges including labour shortage, aging workforce and escalating cost [1]. In order to address these challenges, it was announced in the 2017 and 2018 Policy Address of the Government of the Hong Kong Special Administrative Region (HKSAR) that the Government should lead and promote the adoption of MiC in the construction industry [14, 15].

MiC represents the most advanced level of offsite construction [16], which is first defined by Pan and Hon [17] 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 realise enhanced quality, productivity, safety and sustainability*". MiC is a unique term used in Hong Kong, which belongs to volumetric modular building construction. Compared with conventional construction methods, MiC has distinct characteristics that the majority of on-site works are transferred to a factory for production of modules. In a factory, structural works, architectural works and building service works of modules were completed partially, and then following by transportation of modules to the construction site for installation and assembly. Several MiC pilot projects have been initiated in order to prompt its wide adoption in Hong Kong.

2.3 Delimitation of research scope

In this paper, Hong Kong is selected as a typical case of the high-density city to explore opportunities and develop the conceptual framework for applying DT in MiC. Regarding a building project adopting MiC, the construction lifecycle from offsite production of modules to onsite completion of construction works is the most concerned part, excluding design and operation and maintenance stages. This is because the most significant difference between MiC and conventional construction practices is the change of construction processes. As offsite production of modules in a factory is similar to works in the manufacturing industry, the research scope is limited to onsite works of a MiC project (i.e., module installation and other onsite building works).

3 Methodology

The research approach in this paper for searching and analysing relevant publications and exploring opportunities and challenges of DT applications in MiC, is adopted as proposed by Boje et al. [18]. The overall research methodology process including three steps is provided in Figure 3.

Firstly, publications related to the application of DT in the building construction sector were searched and identified. The search strategy included electronic databases of Scopus. The search terms "digital twin". "building" and "construction" were used to limit the scope. After the initial search, the literatures had to be published in a journal or a conference paper or as a book chapter. Title, keywords, abstract and main contents were then checked to see whether a publication is related to the field of building construction. Secondly, the filtered publications in the first step were reviewed and analysed from the perspectives of time, publication format, topic, consideration of other digital technologies, purpose and potential challenge of DT application in the building construction sector. Thirdly, based on results obtained from the previous two steps, we identified current research gaps, developed a conceptual framework for applying DT in MiC in the context of Hong Kong as a typical case, and explored opportunities and challenges for future research. The original research objectives were considered during each step [19].

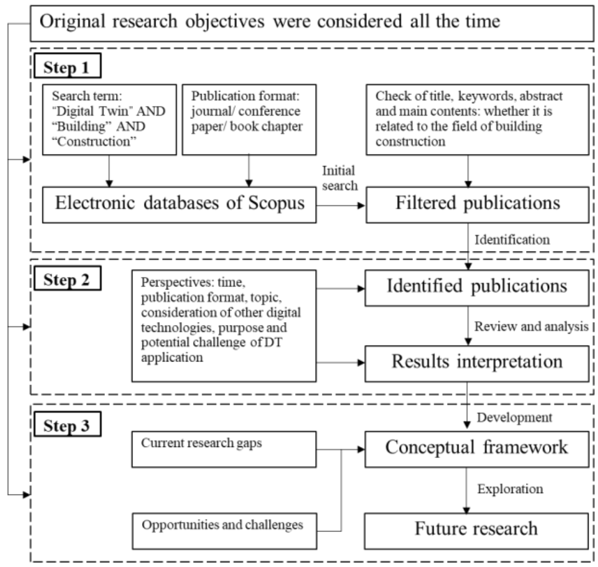

Figure 3. The overall research methodology process in this paper

4 DT applications in the building construction sector

4.1 Review of current practices

The latest search of publications through the electronic databases of Scopus was conducted in June 2020. The selection criteria as elaborated in Section 3 were applied to all papers in the initial search. 46 publications were filtered out for detailed analysis. After title, keywords, abstract and main contents of filtered publications were checked, there were in total 10 articles identified. All the identified publications are related to the application of DT in the building construction sector. The first related article was published in 2018. The identified publications were evenly split between journal articles and conference papers. Disturbance of publication time and format of the identified publications is provided in Figure 4.

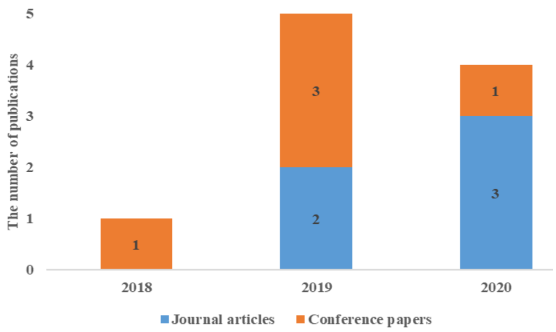

Figure 4. Distribution of publication time and types of the identified publications (as of June 2020)

Three of the identified publications considered the application of DT not only in the construction stage but also in the whole project lifecycle from the planning stage to the operation and maintenance stage [8, 20, 21]. Automated planning and scheduling of works is one of purposes of DT application [18, 22, 23]. Monitoring and assessment of construction performance is achievable with the aid of real-time data capturing from a construction site. One research developed DT of a type of machinery to prevent operation risks [25], while another one developed DT of a type of building material for simulation in order to reduce production time and cost [24]. A summary of different purposes of DT applications in the identified publications is provided in Figure 5.

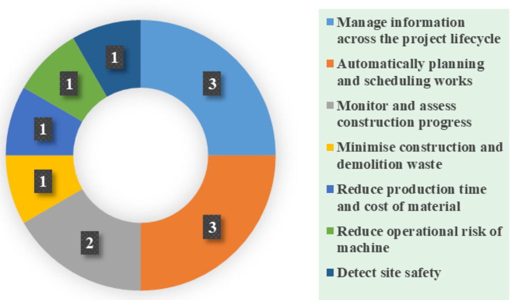

Figure 5. Summary of opportunities of DT applications in the identified publications
Note: numbers in the figure refer to the number of publications

Regarding consideration of other digital technologies, nine publications mentioned about "Building Information Modelling (BIM)", where seven of them considered DT as an evolutional representation of BIM, while the remaining two treated BIM system as a DT [22, 23]. Seven publications [8, 18, 20, 22, 24, 25, 26] included "Internet-of-Things (IoT)" together with sensor in order to collect data from the physical space, but only one of them considered the application of "Wireless Sensor Network (WSN)" for real-time data transmission [25]. Three publications [8, 20, 25] mentioned "cloud platform" when considering storage, analysis, processing and integration of captured data. The concept of "machine learning" was mentioned in three publications [18, 22, 25] so that a self-learning DT can be created. Bevilacqua [20] stated that both Augmented Reality (AR) and Virtual Reality (VR) can benefit from the implementation of DT, as they provide users a more immersed platform to view historical and real-time data. The frequency of other digital technologies, including BIM, IoT/sensor, WSN, cloud platform, machine learning, AR and VR, mentioned in the identified publications is provided in Figure 6.

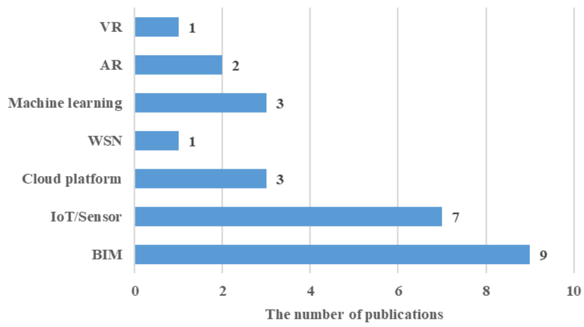

Figure 6. The frequency of other digital technologies mentioned in the identified publications
Notes: VR: Virtual Reality; AR: Augmented Reality; WSN: Wireless Sensor Network; IoT: Internet-of-Things; BIM: Building Information Modelling

Three publications discussed the potential challenges of DT application in the building construction sector [8, 18, 25]. They all mentioned the technology complexity, particularly in the field of sensing technology to gather data on construction site, with the proper consideration of installation and maintenance as well. Development of structuring methods and computing algorithms on the overwhelming amounts of data was also regarded as a common challenge to ensure the high-efficient of data processing. Other potential challenges in terms of the technical level and the social-political level were also raised as below.

- Lack of sensors with comprehensive capabilities (e.g. integrated measuring distance, temperature, humidity, air quality, etc.) [18];
- Complexity of integration of sensors with different reading frequencies and accuracies (i.e. interoperability) [18];
- Development of reliable and efficient data transmission methods to ensure data connectivity and reduce time delay for further processing [18, 25];
- The existing complex social system [25];
- The dynamic of human interactions with construction activities [25];
- Data privacy (e.g. the sharing of data may need to follow relevant regulations on data privacy) [25]; and
- Data security (e.g. confidential project data needs to be protected during data transmission between real and virtual spaces) [25].

4.2 Opportunities, challenges and limitations

Results of the review on publications related to the application of DT in the building construction sector revealed that relevant researches have been conducted, due to the development of digital and information technologies and demonstration of benefits brought by DT applications across industries. However, only a few researches were conducted in a systematic manner with developed frameworks for DT applications in the building construction sector. Management of information across the whole project lifecycle and automatic planning and scheduling of works are the two most mentioned purposes of applying DT in the building construction sector. The concept of DT was not considered alone, but integrating with at least one existing digital technology. For example, BIM is commonly used as the data model of a building, providing a fundamental basis to develop a DT. Comparatively, DT has extra characteristics of real-time data acquisition through integrating IoT and WSN technologies. Application of DT in the building construction sector has promising benefits such as automated monitoring of site progress and reduced operational risk of machine. However, there are technical and social-political challenges to be addressed including interoperability of various sensors, development of optimised data processing algorithms and data privacy and security issues.

The current research gaps identified from the review are summarised as below for future research.

- The definitions of DT and BIM used in some publications remain identical, which are inaccurate, so a clearer and more uniform definition of DT is needed;
- There is a lack of study on the application of DT in the volumetric modular building construction; and
- There is a lack of empirical evidence to prove benefits of DT application in the building construction sector.

5 A framework of DT application in MiC

In order to apply DT in MiC, the emphasis is on building a Cyber-Physical System (CPS), where information collected from the real space is used for computation to generate a real-time monitoring cyber model. In the meantime, changes of the cyber model will either be used for prediction or reflect in the real space to achieve the control function.

Based on findings in Section 4, a framework of applying DT in MiC is provide in Figure 7. The framework was built in the context of module installation, as it is a unique onsite construction activity compared with conventional construction practices. Interpretation of the framework is provided as below.

1. Firstly, IoT technology is applied on real-time data capturing from labour who is responsible for module installation works, material (i.e. module to be installed) and machinery (i.e. crane) (Sensors supporting wireless transmission of data are required)
2. If BIM containing planning and scheduling of module installation works is available, it will be considered as an input of data source, which is of benefit to enhance logistics coordination
3. WSN or the 5th generation mobile network (5G) is used to ensure transmission and connectivity between the physical space and the cloud platform for storage
4. Computing algorithms are applied for processing data stored in the cloud platform in order to generate real-time DT of module installation process
5. AR, VR and web portal provide construction mangers a user interface to visualize the DT
6. The real-time DT of module installation process has the potentials to provide basic functions including labour safety detection, installation progress monitoring and prediction of required module installation time.
7. The advanced functions may allow construction managers to exert influence on the real space by controlling the DT, through control sensors and a rapid data transmission network. Control sensors include types of buzzing, flashing and vibrating.

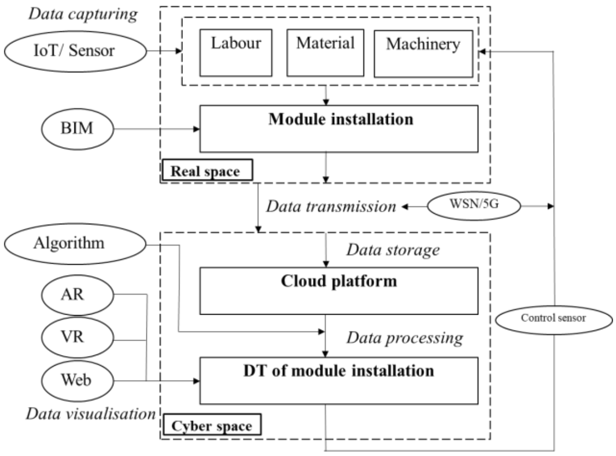

Figure 7. The proposed framework of DT application in module installation of MiC

6 Conclusions

This paper provides an overview of academic publications related to DT applications across industries, particularly in the building industry. The purposes of this paper are to provide a systematic review of application of DT in the building construction sector and to explore opportunities and challenges of applying DT in MiC within the context of Hong Kong as a typical case of high-density cities. Through literature review and analysis of ten publications related to DT applications in the building construction sector, the primary findings are as below.

- Management of information across the whole project lifecycle and automatic planning and scheduling of works are the two most mentioned purposes;
- DT is always integrated with other digital technologies;
- Theoretically, automated monitoring of site progress and reduced operational risk of machine are achievable benefits by adopting of DT; and
- There are technical and social-political challenges to be addressed before adoption of DT.

The framework considering the application of DT in the case of module installation process was proposed based on the findings. Through integrating with other digital technologies in the framework, the DT has potential functions of monitoring, predication and control. In addition to the current generic research gaps for the building construction sector mentioned in Section 5, future research is proposed to explore the following directions about DT applications in MiC:

1. Further literature review and meta-analysis of publications on DT applications in the building construction sector using more electronic databases; and
2. Interviews and focus group discussions with academics and practitioners in the areas of DT and modular building (covering different groups of stakeholders, e.g. client, consultant, contractor) to verify and refine the developed framework.

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