Digital twin-driven building projects: a new paradigm towards real-time information convergence throughout the building lifecycle

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Abstract

Influenced by the successful applications of emerging technologies, the manufacturing industry has entered the Industry 4.0 era, which highlights the trends of autonomous factories and smart production processes based on digital twin. In parallel, high-volume and multiple types of data streams have been widely established in the building and construction industry, which traditionally integrated in the building information modeling (BIM) platform. However, the effectiveness and reliability of cross-stage information transmission remain to be an obstacle in the development of BIM, reflected in the erroneous and inadequate information delivery, and thus impair the decision-making capacity of project participants. Here, we introduce a digital twin-driven paradigm as the new approach for automated and smart building workflow throughout building planning, design, construction and maintenance processes. Through the digital twin technology, interactions between physical and virtual world are operated and driven by a hybrid system comprised of big data, internet of things, and reverse engineering technologies. A small-scale model-making experiment and a gymnasium building case are conducted to demonstrate the digital twin framework. Overall, digital twins-driven building projects enable real-time data convergence accordingly to the time-based changes, making it possible to pursue the next stage of intelligent buildings and Industry 4.0.

1. Introduction

With the advent of Industry 4.0 era, the new technological evolution in the manufacturing industry, e.g., internet of things (IoT), cloud computing, big data and artificial intelligence has provided a promising future vision for a deep information transformation between physical and virtual world (Uhlemann et al. 2017). The implementation of the digital twin technology, in particular, puts forth a foundation for smart manufacturing systems that offer real-time respond to meet manufacturing assets, people, factories, and production networks demands (Lu et al. 2019). It is clear that the digital twin (DT), defined as a virtual mirror of the real world (Tao et al. 2018), is a core solution to support decision making at every stage of the manufacturing process and create quality of life products with high precision and efficiency.

Although the digital twin has brought out potential changes in manufacturing, healthcare, automobile, retail, and even smart cities fields (Mohammadi and Taylor 2017), it is rarely used in the building and construction industry. The similar requirement of real-time based processes to support intensive building information monitoring, delivering and optimization is pushing the limits of traditional building and construction industry facing the digital revolution. Existing method of building information modelling (BIM) has enabled an integrated platform of geometric models and other non-graphical information, comprising the design, construction, operation, management, and maintenance phases of construction projects (Jin et al. 2019). However, it remains a challenge of timely access to updated information not only among single process, such as the deviations in construction, but also across multiple processes from the as-planned states to the as-built state (Tuttas et al., 2015).

Accordingly, the emerging digital twin presents a powerful paradigm to build sustainable and intelligent building projects.

2. The Rationale for Digital Twin

2.1 Information transmission in the building lifecycle

In the traditional building and construction industry, artisans introduce language, graphics, text and models as the mediums for information transmission and expression throughout the construction activities. However, with the advent of computer technology, digital-based drawing rules ranging from 2D design to 3D modeling have rapidly become the major information carrier of contemporary architecture. This shift has revolutionized the connotation of building projects, leading to the dual fragmentation of physical and digital worlds. Besides, as with the long building lifecycle, participants in different stages tend to analyze and process building information independently, and thus resulting in redundancy, duplication or error data across multi-stages. Under the circumstance, it is essential to define building information and construct its mechanism in the building processes.

Existing Building Information Modeling (BIM) technology promotes the research of building information, allowing for collaborative management from all participants via building information model (Bryde et al. 2012). Although the integration mode of BIM enables design error decrease and productivity improvement, it is confronted with development problems, mainly in two aspects: 1) BIM-based building processes puts more focus on the data flow from digital to physical, rather than physical to digital. The lack of reverse feedback prevents parties in the previous phase from obtaining the updated building information. On the other hand, the absence of real-time interaction between physical and virtual models constantly impair the usability and validity of lifecycle information and decision-making. 2) On account of cognitive bias, the implementation of BIM is rarely applied to the phase of refurbishment, which is manifested as extended lifecycle and contains mass "as-built" information (Volk, Stengel and Schultmann 2014). Without the support of complete and up-to-date information, the value of BIM faces challenges.

In comparison, the advanced manufacturing industry has developed the concept of digital twin to cope the information obstacles so as to move forward the revolution of Industry 4.0. The real-time systems in manufacturing has more comprehensive representation, showing the potential ways to building and construction industry.

2.2 Digital twin and its applications

To date, the concept of digital twin as “a virtual representation of what has been produced” was firstly put forward in 2003 by Michael Grieves at University of Michigan (Grieves 2014). Taking account of the quality control of product lifecycle management (PLM), Grieves introduced a digital twin concept model with three critical parts, i.e., physical products, virtual parts and connections of data and information. While, further definition of digital twin was proposed by Glaessegen and Stargel (2012), regarding a digital twin as the mirror of life integrating multi-physics, multi-scale, and probabilistic simulation. Recent advance and explanations were summarized by Kritzinger et al. (2018) and a detailed classification of digital twin was introduced, which consisted of digital model, digital shadow and digital twin according to the different levels of data integration. Tao et al. (2018) summarized three characteristics of digital twin, namely real-time reflection, interaction and convergence, as well as self-evolution.

Until now, digital twin is mainly applied in manufacturing industry, and the field of aeronautics and astronautics (Lu et al. 2020). In order to analyze and separate digital twin from cyber physical system, Tao et al. (2019) compared the origin, development and practices between the two terms and provided an alter perspective. Besides, digital twin has been engaged in smart city, such as Virtual Singapore initiative, aiming at tackling live-ability issues. Nevertheless, in the building and construction industry, especially the architectural design field, there is rare literature research on digital twin. The concept of digital twin building has been mentioned in BIM conferences, for instance, 2018-2019 buildingSMART International (BSI) conference conducted a special technical workshop on BIM and digital twin. Some participants focus on the implementation of digital twin in the building operation phase, regarding the digital twin as an expression of "BIM+", rather than the definition of architectural digitalization from the perspective of the whole lifecycle and full-element of information.

In view of above mentioned, it is necessary for the building and construction industry to learn from the advanced experience of manufacturing in the development of information technology, establishing the digital twin theory applicable to the building projects. With the correspond of digital twin, existing BIM problems have the potential to be solved and achieve real-time building information systems.

3. Digital Twin-driven building projects

3.1 Conceptual framework of proposed approach

In allusion to the defective information transformation methods, a new integrating paradigm for complex building projects driven by digital twin is proposed. From a broader perspective, the concept of digital twin is a virtual representation that can simulate, predict and optimize multi-physics or multi-phase generated data over the entire building lifecycle. The core open database of digital twin, which serves as digital ecosystems, can enable the realization of interoperability across various information and platforms, including IoT sensors, operational hardware devices and software tools, as well as human-computer interfaces. With further integration and convergence between virtual world and physical world, the digital twin enhanced building projects evolve high-fidelity and real-time processes, creating an efficient and effectiveness building and construction workflow.

The general framework of digital twin is composed of three parts, namely：

1) the physical entities in real space；

2) the virtual models in virtual space；

3) the connected data and information that tie the physical and virtual space together (Tao et al. 2019).

Each part of digital twin involved in the building lifecycle stages starting from inception, brief, design to production, maintenance and deconstruction. The potential applications for a digital twin depend on what stage of the building lifecycle it models. Therefore, the implementation of digital twin is distributed in the four major stages as listed below, and then the digital twins in a narrow sense would be integrated together to achieve information fusion throughout the building lifecycle.

1. Digital twin-driven building planning. Planning is the initial step of building projects, information from the site, or clients can be driven by the digital twin and transfer to virtual data so that architects can fully understand the conditions of design. What's more, a digital twin could also represent as-built building information related to their physical entities, materials and geometry parts. If the preexisting digital information is available, the virtual part of digital twin only needs to be updated to capture building information. As digital twin is the mirror of physical world, it can perfectly guide the building project by making full use of previous design conditions.

2. Digital twin-driven building design. In conceptual design stage, the digital twin mode is established firstly, which represents the planning phase information, and then architects need to analyze and process to better understand the physical counterpart's performance characteristics. In order to define the concept and functions of the building project, digital parameters will be tested and physical prototypes could be simulated and verified before investing in the next phase of construction. Besides, the production plan and resource management for manufacturing needs to be transmitted and controlled by architects and other cooperated participants through the digital twin.

3. Digital twin-driven building construction. It is the key point in the construction stage to acquire the real-time data from the changing physical environment. Traditional information transmission of building lifecycle put emphasize on the information from design to construction, ignoring the feedback of the on-site circumstance. Only if multi-participants, for instance, architects, engineers, and constructors acquire the real-time data integrating physical and virtual information, the quality of building construction could be optimized. By incorporating effective techniques, the digital twin supports the entire interoperability of multi-phase data streams of construction state and help to make precise decisions.

4. Digital twin-driven building maintenance. Due to the entirely replicate of the physical

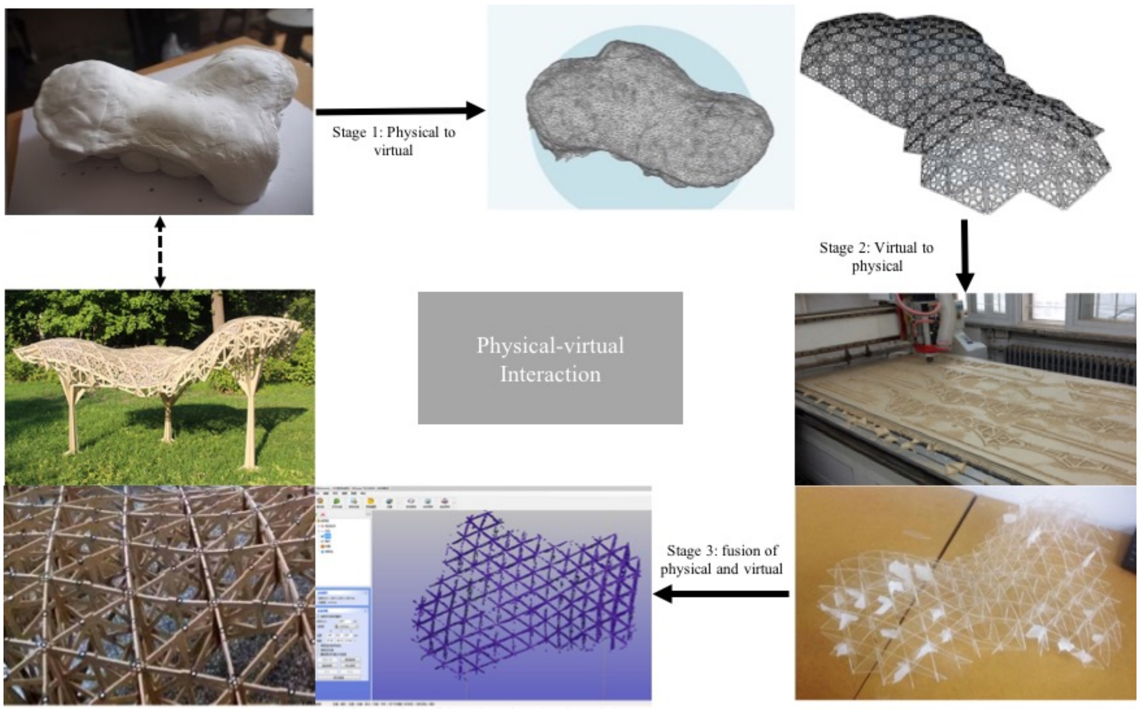

Figure 1. The workflow of the small-scale architectural model-making project

building, the virtual twin can reflect and correspond the lifecycle process of its origin building. No matter what happens to the building, such as retrofit, operation or deconstruction, with digital twin, architects could re-design the building with accurate information. It is less rework, reduced costs and improved quality.

The implementation and research approaches of digital twin will realize the entirely replicate of the physical world. Real-time data can be integrated to move forwards smart building and Industry 4.0. Nevertheless, it is worth noting that digital twin is not a fully new concept, it needs to combine the existing methods, such as BIM platform, algorithms to final accomplishment.

3.2 Key technologies of digital twin

In the digital twin-driven building planning, design, construction, and maintenance phases, the key technologies of digital twin can be classified to the following three aspects according to the data phase:

1. Data acquisition. Reverse engineering technologies, including LiDAR and IBMR could be adopted to acquire as-built information and upload to the virtual part of digital twin (Han et al. 2019). Internet of Things (IoT), cloud technology and big data are suitable for non-geometry information acquisition.

2. Data analytics. In terms of the point cloud data collected from reverse engineering technologies, some software like Geomagic Control X will be adopted to transfer and analyze the information. The platform of BIM is still usable for data processing and integrating. With the algorithm development through Dynamo, automated processes are implemented.

3. Data decisions. Under the combination of BIM and digital twin, a complete virtual picture is established of a building project. No matter it is new buildings or existing buildings, the digital copy of physical models will be integrated in the initial stage of design and thus architects can make precise decision. Also, real-time data can be tested, measured, and evaluated before any physical work is initiated.

In addition, it is still a great challenge to combine all these technologies and achieve ultra-high synchronization. Automated and real-time processes also need more time. This approach represents significant improvements, as many current projects are not fully commissioned. Therefore, uncover errors, redundancies, and incompatibilities can be reduced without the leak of building information.

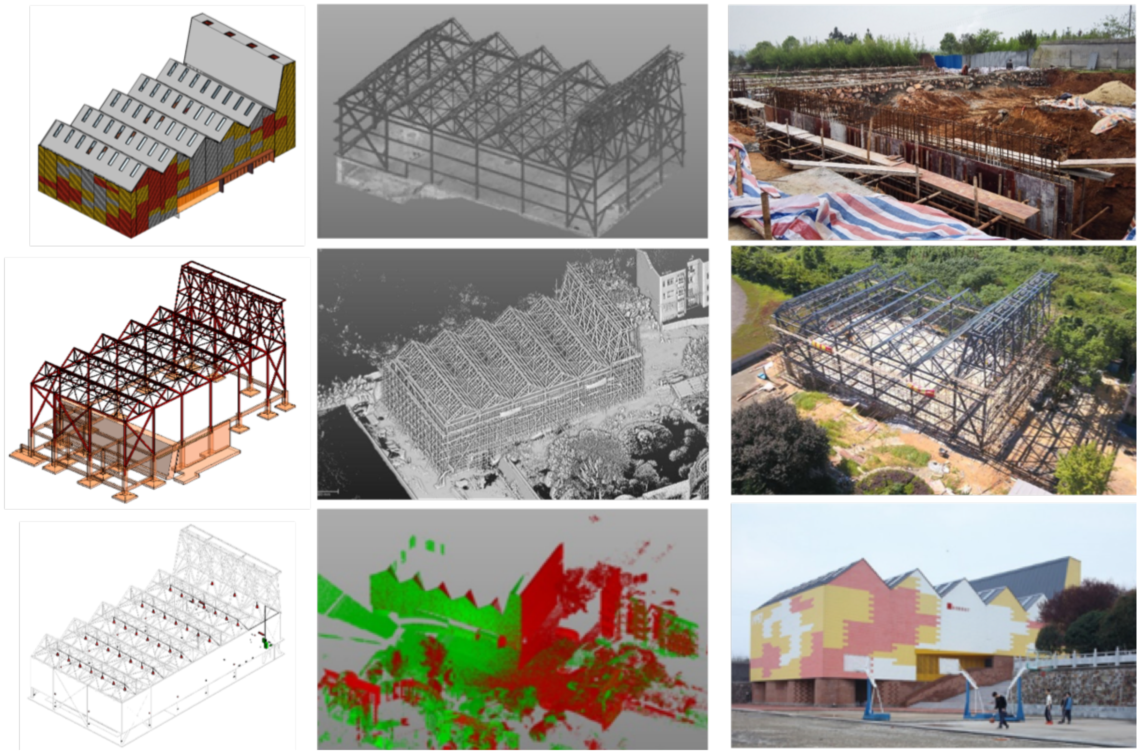

Figure 2. Reverse engineering applications in stages of digital twins

4. Case Study

4.1 A case of small-scale architectural model-making project

The model-making project is an experiment that merely involves design and construction phases, which is used as an example to demonstrate the necessity of physical-virtual interaction, and to illustrate the future advantages of bringing digital twin into building processes. According to the transmission directions of flow data, the project is particularly divided into three stages.

The first stage is the process of mapping a manual model to its digital mirror, using a Canon M6 camera and Autodesk Remake software. This process not only enables architects to make full use of their inspiration, but also provides a basis for detailed design. After optimizing the primary mesh model to parametric model, the analytic digital structure and surface components are prepared for construction. In the second stage, the manufacturing information is transferred from Autodesk Revit to CNC machines. Due to the influence of wood thickness and mechanical errors, model prototypes need to be tested constantly to achieve a deep fusion of digital and physical worlds like the function of a digital twin. The last stage and also the most neglected stage is a second reverse process from physical entities to digital models. Through the adoption of 3D laser scanning, deviation values in real construction can be detected and fed back to the design phase. Under the cross-comparison of physical-virtual information, a wood-made fabrication with a maximum deviation of 4mm is accomplished.

As shown in Fig.1, the convergence of cross-stage and cross-dimensional information makes it possible to precisely construct the architects' inspiration. In the face of complicated building projects, real-time information systems driven by digital twin will play a more fundamental role over the lifecycle of buildings.

4.2 A case of gymnasium building project

The gymnasium of No.3 Middle School in Yueyang, China is taken as an example to explain the workflow of digital twin-driven building projects. As illustrated in Fig. 2, the digital twin prototype presents three parts, including construction on-site, virtual entities and the convergence between physical and virtual worlds. The digital twin framework and reverse engineering technology based on cloud-point models take effect throughout the entire process. Through the application of 3D laser scanning devices and analyzing software, the errors in construction phase are easily found out, as the red part representing the divergence between design and construction models. With the integration, adequate data could be provided to the builders and thus promote the smart control of the project. The processes is similar with the first case, but due to the longer period lifecycle of real-scale building construction, this case still needed to be examined in the future to verify the digital twin system.

5. Conclusion

This study provides a comprehensive approach to bridge the gap between physical and virtual environment in building planning, design, construction and maintenance processes. Digital twin-driven building projects are expected to provide real-time accurate data steam attributed to the efficiency and precision improvement. Future work will focus on the collaboration of multiple techniques and automated database, such as sensors, IoT devices, GIS applications in supporting the realization of digital twin. Despite the challenges, the benefits of digital twin buildings can be foreseen.

Endnotes

1. Bryde, David, Martí Broquetas, and Jürgen Marc Volm. “The Project Benefits of Building Information Modelling (BIM).” International Journal of Project Management 31, no. 7 (2013): 971–980.
2. Glaessgen, E, D. Stargel. "The digital twin paradigm for future NASA and US Air Force vehicles." in 53rd AIAA/ASME/ASCE/ AHS/ASC Structures, Structural Dynamics and Materials Conference 20th AIAA/ASME/AHS Adaptive Structures Conference 14th AIAA, (2012): 1818.
3. Grieves, M. "Digital Twin: Manufacturing Excellence through Virtual Factory Replication." (2014): 1e7. https://www.researchgate.net/publication/275211047_Digital_Twin_Manufacturing_Excellence_through_Virtual_Factory_Replication
4. Han, Dongchen, Hong Zhang, Weiwen Cui, and Huang Jie. "Towards To A Hybrid Model-Making Method Based On Translations Between Physical And Digital Models." in Intelligent and Informed-Proceedings of the 24th International Conference on Computer-Aided Architectural Design Research in Asia, volume 2, ed. Matthias Hank Haeusler et al. (Wellington: CAADRIA, 2019), 561-570.
5. Jin, Ruoyu, et al. “Integrating BIM with Building Performance Analysis in Project Life-Cycle.” Automation in Construction 106, (2019):102861.
6. Kritzinger, Werner, Matthias Karner, Georg Traar, Jan Henjes, and Wilfried Sihn. "Digital Twin In Manufacturing: A Categorical Literature Review And Classification." International Federation of Automatic Control-PapersOnline 51, no.11 (2018): 1016-1022.
7. Lu, Yuqian, Chao Liu, Kevin I-Kai Wang, Huiyue Huang, and Xun Xu. “Digital Twin-Driven Smart Manufacturing: Connotation, Reference Model, Applications And Research Issues.” Robotics and Computer-Integrated Manufacturing 61, (2020): 101837.
8. Mohammadi, Neda, and John E. Taylor. “Smart City Digital Twins.” 2017 IEEE Symposium Series on Computational Intelligence (SSCI), (2017).
9. Tao, Fei, Jiangfeng Cheng, Qinglin Qi, Meng Zhang, He Zhang, and Fangyuan Sui. "Digital Twin-Driven Product Design, Manufacturing And Service With Big Data." The International Journal of Advanced Manufacturing Technology 94, (2018): 3563-3576.
10. Tao, Fei, Qinglin Qi, Lihui Wang, A.Y.C. Nee. "Digital Twins And Cyber–Physical Systems Toward Smart Manufacturing And Industry 4.0: Correlation And Comparison." Engineering 5, no.4 (2019): 653-661.
11. Tuttas, S., A. Braun, A. Borrmann, and U. Stilla. “Validation Of Bim Components By Photogrammetric Point Clouds For Construction Site Monitoring.” ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences II-3/W4, (Nov 2015): 231–37.
12. Uhlemann, Thomas H.-J., et al. “The Digital Twin: Demonstrating the Potential of Real Time Data Acquisition in Production Systems.” Procedia Manufacturing 9, (2017): 113–120.
13. Volk, Rebekka, Julian Stengel, and Frank Schultmann. "Building Information Modeling (BIM) For Existing Buildings — Literature Review And Future Needs." Automation In Construction 38, (2014): 109-127.