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Towards a Conceptual Framework of Using Technology to Support Smart Construction: The Case of Modular Integrated Construction (MiC)

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Abstract: Construction is a major source of carbon emissions. Moreover, it faces various other sustainability challenges, such as construction waste, construction noise, vehicular traffic near construction sites, dust and other air and water pollutants, and safety and well-being of construction workers. Poorly designed and constructed buildings will continue to affect the well-being of their occupants and overall energy efficiency throughout the building lifecycle. Hence, accelerating the transformation of the construction industry towards smart construction or Construction 4.0 is an important topic. The ways that technology can help to achieve smart construction, especially with the adoption of construction methods with increasing construction modularity, should be further explored. Focusing on modular integrated construction (MiC), this paper examines the following questions: (1) How has technology been applied to support MiC development and smart construction in Hong Kong? (2) What are the lessons learned? A case study approach of a building information model (BIM)-enabled multifunctional blockchain-based digital platform is adopted to allow us to systematically consider (1) the main objectives and scope, (2) the stakeholders involved, (3) the key outcomes and processes, (4) the applications of blockchain technology, and (5) the integration with other digital software and management platforms in practice. Drawing upon the experience, we propose a generic four-stage approach in understanding and facilitating the adoption of relevant technology towards smart construction. At Stage One, the technologies of BIM, RFID, and blockchain are applied to support the core elements of MiC production: just-in-time transportation and on-site installation. At Stage Two, the digital platform is extended to serve as an interface for third parties, notably government; monitoring, authentication, and certifications for information sharing; visualization; and real-time monitoring and updating of MiC projects. At Stage Three, the system focuses on people in the construction process, aiming to enhance the safety and well-being of workers and drivers throughout the construction process. Different Internet-of-Thing devices and sensors, construction robotics, closed-circuit television, dashboards, and cloud-based monitoring are deployed. At Stage Four, the full construction lifecycle is the focus, whereby a centralized smart command theatre is set up with multiple sources of data in a city information model.

Keywords: modular integrated construction (MiC); blockchain; building information modeling (BIM); smart construction

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1. Introduction

Smart cities have purposes [1,2]. With the use of technology (notably information and communications technology, ICT, and microelectronics) and its associated digital data, smart cities aim "to optimize resources, maintain sustainability, and improve people's quality of life" [3]. The concept of smart cities is, therefore, very broad, but it must involve the purposeful applications of technology in achieving goals related to better cities and people's life. Following Cohen's smart city wheel [4], the six components are as follows: (1) smart economy, (2) smart governance, (3) smart environment, (4) smart people,

(5) smart mobility, and (6) smart living. These six components are, in turn, related to urban policy, planning, and management. In particular, smart environment emphasizes that cities should pursue sustainability focusing on buildings, energy, and urban planning [3]. In cities, buildings form an essential part of the environment that no smart city initiatives can ignore.

Smart construction is also instrumental to the achievement of various Sustainable Development Goals (SDGs), notably those that are directly related to cities (SDG 11), manufacturing and innovations (SDGs 8 and 9), carbon emission reduction (SDGs 7 and 13), and people's health and well-being (SDG 3) [5]. Overall, construction is a major source of carbon emissions. Moreover, it faces various other sustainability challenges, such as construction waste, construction noise, vehicular traffic near construction sites, dust and other air and water pollutants, and safety and well-being of construction workers [6]. Poorly designed and constructed buildings will continue to affect the well-being of their occupants and overall energy efficiency throughout the building lifecycle [7]. Hence, accelerating the transformation of the construction industry towards smart construction is an important topic. Nonetheless, although there are suggestions and trials on the application of key technology, like blockchain, in the construction industry, they remain preliminary for full application. This paper aims to further explore the ways that technology can help to achieve smart construction, especially with the adoption of construction methods with increasing construction modularity.

2. Literature Review and Research Gap

2.1. Smart Construction and Modular Integrated Construction (MiC)

Smart construction is closely related to "lean construction", which was coined by Koskela [8] as a new production philosophy that focuses on the concepts, principles, and methodologies within the construction industry. Thus, construction is viewed no longer as simply converting materials into buildings (conversion process), but instead as a series of value-adding activities (flow process) that identify problems within the flow and provide solutions and improvements to such issues. Accompanying the transition of the construction industry from a conversion to a flow process is the evolution of construction methods from the conventional cast in situ method to various forms of precast and/or prefabricated construction methods, supported by Design for Manufacturing (DfM), Design for Assembly (DfA), and Design for Manufacturing and Assembly (DfMA) [6,9,10].

Industry 4.0 refers to the technological applications in network connection of embedded systems in Industry 3.0. The latter allows for the communication and interaction of intelligent objects through the Internet of Things (IoT) to provide data and services to end-users. With Construction 4.0 or smart construction, networked embedded systems together with cyber-physical systems (a virtual copy of the physical production system, i.e., digital twin) allow for other technological components to be built upon. The further inclusion of IoT provides information for business decision making [11]. The use of blockchain is a hallmark of Construction 4.0. X. Li et al. [12] developed a two-layer adaptive blockchain structure for off-site modular housing production, whereby the first layer is a private sidechain for participants to track and record transactions, and the second layer is the main blockchain for owner's communication and record of transactions with participants. For instance, material suppliers and manufacturers can upload, record, and track progress in the first layer. In the second layer, the owner controls the prior issue and possession of certificate authorities, publishes and subscribes of material and transaction records, and orders and verifies blocks through the signing of smart contracts. However, its applicability to other stakeholders, such as the monitoring authority, along the construction process is neglected. There is a need to further explore the applicability of blockchain specifically in modular integrated construction (MiC) projects for users alongside the construction process.

MiC refers a construction mode based on the manufacturing process [13]. It is an innovative construction method that adopts the DfMA technology. Meanwhile, Multitradeintegrated mechanical, electrical, and plumbing (MiMEP) also adopts the DfMA technology. Functional building blocks are standardized into prefabricated modules and manufactured and produced offsite in factories before being transported to the construction sites for assembly [14]. In comparison, the conventional construction method of cast in situ was criticized for its negative environmental impact and higher carbon emissions compared to more modular methods [7,15]. With MiC, building components were fully manufactured and preassembled off-site. This latest modular construction method follows through the flow process of lean construction, where value-adding activities are required for overall improvements on construction quality [8,9]. With an in-depth analysis of 38 construction projects in Hong Kong spanning 20 years, Wong and Loo [6] found that higher construction modularity, in turn, is associated with more sustainable environmental indicators (notably lower carbon emissions and waste generation), economic indicators (notably lower project cost and time), and social indicators (namely lower human resource requirement and overall accident rate). Apart from building projects, DfMA, MiC, and MiMEP can also be adopted in infrastructure and engineering projects. Some examples are the adoption of DfMA in a 145-m-long footbridge connecting two major public housing estates in North West Kowloon, Hong Kong and a sewerage treatment plant using MiMEP in community isolation and treatment facilities in the Lok Ma Chau Loop, Hong Kong. Figure 1 shows a schematic representation of the sustainability impact of different construction methods [6,7,15]. Moreover, global cities like Singapore and London have encouraged modularized components in the construction of high-rise buildings, including the prefabrication of structural components, facades, and mechanical, electrical, and plumbing (MEP) systems [16–20].

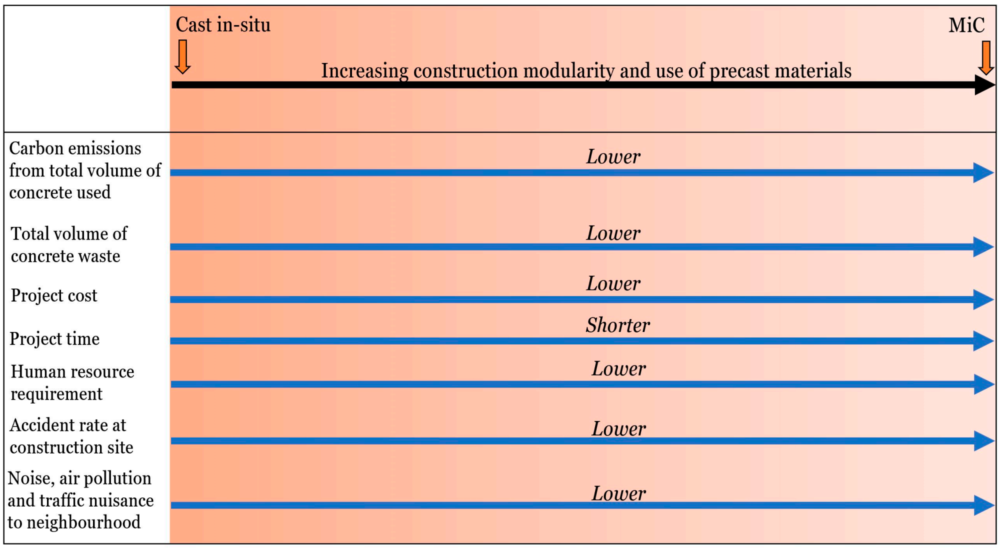

Figure 1. Comparison of Sustainability Impacts of Different Construction Methods.

2.2. *What Type of Technology?*

The use of technologies in the field of construction has not been new, Building Information Modelling (BIM), Geographic Information Systems (GIS), Global Positioning System (GPS), sensors, robotics, and cloud computing are useful tools in managing the construction lifecycle. In this paper, we only focus on their applications in MiC because the processes of design, manufacturing, transportation, and assembly of MiC require seamless and timely coordination among multiple stakeholders in multiple locations. To facilitate the readers to see the key applications (that is, “how to implement?”), the key benefits (that is, “why implement?”), and the major barriers for these technologies to be further applied (that is, “why not?”) in smart construction, Table 1 shows a brief comparison table of these aspects that are discussed below.

Table 1. A comparison table of smart technologies in MiC development.

	Key Applications	Key Benefits	Key Barriers
Blockchain	Smart contracts; securities; digital currency; record keeping	Reduce transaction costs; facilitate document management; reduce risk	Lack of standards and protocols; cost of design, development, and deployment of specific blockchain system; lack of training
BIM	Core technology that can integrate with other technologies like CAD, laser scanning, GIS, and RFID; integration with open data	Visualize building models; commonly adopted in many developed countries at different levels; improve the accessibility, usability, management, and sustainability of digital data in the built asset industry	Upgrading from lower to higher levels of BIM for higher compatibility and integration with other technologies and data.
Laser scanning	Measurement and visualization of the environment; create as-built model	Reduce time and costs of measuring distance in three-dimensional manner	Cost; limited portability of equipment; large data size; lack of training in collecting and analyzing the LiDAR data
GPS, smart tags, sensors and CCTV	Location and object tracing; real-time environmental measurements	Facilitate supply-chain management; allow for real-time tracing and monitoring; early detection of environmental hazards	Cost of setting up the IoT technology; monitoring and analysis of the data collected
Construction robotics	Robot-oriented design; robotic industrialization; single-task construction robots; site automation; ambient robotics	Enhance productivity, safety, and efficiency	Cost; lack of off-the-shelf robotics suited to the needs of the construction industry
Cloud computing	Centralized computing to optimize production, transportation, and on-site assembly schedules in a collaborative manner	Facilitate and support other technologies, such as BIM; enhance data management and collaboration	Lack of awareness; lack of training
3D printing	Customized and flexible production	Reduce human labor; time savings; higher flexibility; higher degree of customization	Limited commercially available 3D printers suitable for the construction industry; further advancement of 3D-printing techniques and materials needed

2.2.1. Blockchain in MiC Development

Given that MiC requires transactions and tracing of process, as well as the fulfillment of contractual and statutory obligations among different stakeholders, blockchain is a key technology in MiC development. Generally, blockchain is a non-revocable distributed ledger system storing information in blocks connected by chains for better storage and management in multiple locations. Each block comprises of transaction data (information stored), a hash value, and a nounce value, ensuring the security of the information. The transaction data can be frequently traced back with no time and cost limitation as long as the nodes are operated. Blockchain can be divided into non-licensed and licensed types, and a consortium blockchain varies in openness of the network to participants [21]. Blockchain provides potential solutions to contemporary construction problems. Research from Leng et al. [22] has identified the benefits of blockchain-empowered sustainable manufacturing and lifecycle management for the development of Industry 4.0. Kim et al. [21] has discussed the potentials of adopting blockchain in the construction industry, concluding that this emerging technology has enhanced the efficiency in contract and cost data management. They also showed that smart contracts, securities, digital currency, and record keeping are considered to be popular blockchain technology applications in the construction industry, with smart contracts especially having the highest potentials. Badi et al. [23] reviewed the UK construction sector viewpoint towards smart contract adoption and found four factors—supply chain pressure, competitive pressure, top management support and observability—to be the most significant in explaining early adopters of smart contracts.

Due to the high volume of contracts, transactions, and parties involved, blockchain is deemed to be effective in monitoring the complex process as well as to reduce the transaction costs involved and to facilitate document management [14,24,25]. In the construction project lifecycle, "project cost/change management", "contract bidding and formation", and "procurement evaluation" are the three construction tasks with high applicability and impact of blockchain [21]. In the project execution areas, "procurement management" and "cost management" are identified as the main areas of applications. Hence, Kim et al. [21] concluded that "procurement", "contract", and "cost" are the areas that could begin with blockchain applications.

Dakhli, Lafhaj, and Mossman [26] demonstrated blockchain applicability specifically on the reduction of transaction cost. They referred to a 2017 report from the Infrastructure Client Group in the UK and reflected that transaction cost, although it may or may not create value to customers, can account for as high as 50% of the construction cost. Examples of the transaction cost incurred in a housing real estate program including the work contract and risk during construction, project management, and additional expenses throughout management, as well as marketing, commercial costs, and sales support during sales administration. By considering the impact on risk, project management, and sales support in the building of housing project, they revealed that an average of 8.3% of the total cost can be reduced by deploying blockchain in the process, with a standard deviation of 1.26% [26]. Hence, blockchain can also lower the cost in the construction process.

Despite the benefits of blockchain, there remains room for its full application. In particular, standards and protocols are required to ensure that data and information can be shared securely and reliably [27]. Alteration of features of blockchain will also be required to be included in the construction industry. The blockchain platform will also need to be altered to suit a specific enterprise system. However, a major challenge is the cost of implementing blockchain. Kang et al. [27] conducted a cost-benefit analysis and concluded that cost of the blockchain system and training for the use of blockchain are the two major barriers when applying blockchain. The design, development, and deployment of the blockchain system is expensive in both hardware and software, and there needs to be the provision of training for workers to adopt to the new process.

2.2.2. Beyond Blockchains in MiC Development

BIM is a construction technology that can visualize building models with explicit details to enhance communication and collaboration between designers and builders for successful project delivery [28], and it can also allow for integration with other technologies, for instance, laser scanning, GIS, and RFID. BIM has been successfully implemented around the world. In HK, the government broadened BIM uses and requirements for public works. In 2017 and 2018, the Development Bureau. which oversees the planning, land, and building development, issued Technical Circulars (Works) No. 7/2017 and 18/2018 entitled "Adoption of Building Information Modelling for Capital Works Projects in Hong Kong" to highlight mandatory and optional BIM uses [29]. In Cheng and Das [28], a case study of a real-life project in Singapore's North Hill Student Residence Hall proved the usefulness and effectiveness of applying BIM in MiC. In the UK, the use of BIM has been mandatory for all public projects of five million pounds and over since 2016 [30]. Moreover, BIM applications have been classified into four levels, with Level 0 for two-dimensional (2D) computer-aided design (CAD) only without sharing, Level 1 with a combination of 2D and 3D CAD without sharing, Level 2 with the sharing of data between CAD and BIM in a common file format, and Level 3 with a shared BIM model by all parties. The "Digital Built Britain" agenda suggests that Level 3 is also targeted to include digital design for facility management [31]. Generally, there are already well-established BIM standards in Hong Kong, Singapore, the United Kingdom, and the United States that support open data [32,33]. OpenBIM further extends the benefits of BIM by improving the accessibility, usability, management, and sustainability of digital data in the built asset industry.

In addition, laser scanning is a surveying technology using laser light to measure distance based on the time required for the light to travel from the laser scanner to an object and back. It can scan the surrounding environment and generates 3D data points with high precision and efficiency. Related applications in construction include progress tracking, quality control, and assessment; structural health monitoring; and the development of as-built data [34]. Integrating the point cloud data with the as-built model and the BIM model can improve the efficiency, accuracy, and precision, which are essential to a successful MiC project. Using laser scanning in construction can provide timely information, improve accuracy and quality, and help cut costs since it is quicker than traditional mapping methods. Laser scanning also streamlines coordination on project sites, leading to better decision making. Currently, the Light Detection and Ranging (LiDAR) technology is still not very well adopted in the construction industry beyond specific applications like ground surface elevation and vegetation canopy surface height [35].

Furthermore, MiC projects can be greatly facilitated by IoT, which uses telecommnications to transmit real-time information collected through smart tags and sensors, such as GPS sensors, RFID tags, and NFC tags, as well as closed-circuit televisions [36,37]. IoT is recognized as one of the most important areas of future technology and is receiving a great deal of attention from industries [38] because it successfully addresses common project challenges including flat productivity, reduced margins, delayed schedule, and increased competition. In construction, IoT is not only implemented in early phases like design and construction, but also later during the operation of buildings [39]. With the combination of advanced IoT technology and BIM technology, an IoT-enabled BIM platform can be developed to overcome problems like inconvenient data collection, lack of automatic decision support, and incomplete information [40].

Moreover, construction robotics is perceived as an "emerging game-changing innovation" [41]. Its development is at the early stage but emerging as an important innovative building technology. Robots stand out for their great precision, speed, and efficiency in a variety of tasks, resulting in increased productivity when implemented in automated systems [39]. However, the study conducted by Pan and Pan [42] revealed that very few contractors have adopted construction robots in Hong Kong. Moving towards smart construction, there are five areas where robotics can be particularly helpful. They are robot-oriented design, robotic industrialization, single-task construction robots, site automation, and ambient robotics [41].

Furthermore, cloud computing is another core technology, which is a model for enabling convenient and on-demand network access to a shared pool of configurable computing resources that can be rapidly provisioned and released with minimal management effort or service provider interaction [43]. It is essential to the construction industry as intensive data are continuously generated during the project full lifecycle. A centralized BIM platform is an example of clouding computing that optimizes production, transportation, and on-site assembly schedules in a collaborative manner. It can overcome the shortages of a traditional BIM platform, where decisions at different stages are often isolated and only locally optimal [40]. On top of this, the cloud computer also provides increased efficiency and communication, real-time updates, safer workplaces, reduced waste and environmental impact, improved quality, easier collaboration, and time saving.

Besides, 3D printing is also one of the technologies that has become popular because of its flexible and transformative capabilities. It can replace human labor with automated production, thus allowing for significant time savings for customized and flexible production [44]. However, despite the improved techniques and materials, there are still many technical issues that restrict the implementation; for instance, large-scale models are unfeasible due to the limitations of commercially available 3D printers [44].

Construction industry has benefited from Industry 4.0 primarily based on the awareness of construction firms about the digitalization of the construction industry [45]. Digitalized technologies, as mentioned, enable construction companies to increase their productivity, quality, and buildability, as well as safety, and they help achieve the goals for a more sustainable building environment [46]. On top of that, smart construction can also benefit efficient energy consumption, cost-effective building maintenance and operation, job creation, health care management, real-time monitoring, and safety and security [47].

Regardless of the benefits, common barriers when adopting smart technologies are related to high implementation cost, lack of knowledge and skills, hardware limitations, interoperability issues, and network connectivity [48]. There are also some specific problems when adopting particular technologies; for instance, security and privacy issues, data acquisition and ownership, compliance, and regulations are some key issues when adopting big data [49]. All these challenges faced by practitioners hinder the adoption of smart construction.

Given the substantial benefits of smart construction, this study examines two major research questions:

1. How has technology been applied to support MiC development and smart construction in Hong Kong?
2. What are the lessons learned? In particular, given the preliminary stage of MiC development and its potential sustainability gains, are there step-by-step guides for the gradual application and extension of smart technology to better support MiC development? Generally, the investment required is huge and a phased introduction will help to facilitate the early adoption of relevant technology towards smart construction.

3. Methodology

Similar to Kang et al. [27], we adopt a case study approach. We believe that real-life case studies and the actual workflows are important in analyzing the applications of technology to the MiC process. In this paper, we examine BEANiE, a BIM and Blockchain-Enabled Multifunctional Digital Platform, which has been developed and used by a construction company in Hong Kong to support smart construction and MiC since December 2019. Applying the philosophy of Common Data Environment (CDE) and City Information Modeling (CIM), the platform was designed to improve the supply chain in terms of traceability with the applications of RFID, BIM, and blockchain technologies for data information processing in tracking and monitoring from manufacturing, delivery, and installation to the handover of MiC. As the building process is no longer a simple conversion of materials, value-adding activities are included in the flow. Quality control is added for the assurance of material stability and durability, while inspections are added to storage and assembly work to ensure construction and building safety.

Hence, we shall carefully trace and analyze the development of BEANiE. With three years of applications and development, BEANiE has been enhanced to Version 6.0. Moreover, it has already been applied in the management of 13 MiC projects with diverse building functions, ranging from demountable transitional housing, a community health center, a primary school, and a government complex to high-rise public housing and government staff quarters. In the analysis of the development and functions of BEANiE, we shall systematically consider (1) the main objective and scope; (2) the stakeholders involved and their interests and concerns; (3) the key outcomes and processes; (4) the applications of blockchain technology; and (5) the integration with other digital, Artificial Intelligence (AI), and IoT devices' software and management platforms. Through learning from the case study, we suggest a conceptual framework for similar platforms in smart construction. It is important to emphasize that the framework is generic, and it aims to guide and facilitate the applications of smart technologies in MiC development.

4. Results

4.1. BEANiE 1.0

The quality assurance (QA) and quality control (QC) system for the production of MiC modules in factory is obviously one of the greatest challenges that brings most of the subsequent trades of work to the upfront production stage. Therefore, for MiC to work, quality tests and control procedures are needed for all critical and detailed sequence from production to installation.

In addition, a large number of MiC modules are being delivered to the construction site on a daily basis in accordance with the construction cycle. Since typical construction sites in Hong Kong are with very limited storage area, the just-in-time (JiT) delivery strategy is important to maintain the site's smooth logistics and at the same time to feed the construction workfront with the required quantity of MiC modules every day. As a result, a highly secured multifunctional platform to provide the most efficient way for the whole project team to communicate seamlessly without geographical limits is necessary to ensure the productivity and avoid additional costs for double handling and extra storage.

Quality and time and cost, of MiC production were the primary focus areas of BEANiE 1.0. Hence, this earliest version has the following primary features [50].

1. Properly record, register, file, or upload the test and/or inspection data to the platform for real-time tracking and monitoring of the status of every single MiC module at each step of production by adopting RFID, a MiC Progress Monitoring eForm System, a BIM-integrated viewer, and a blockchain browser.
2. Enable any authorized personnel at any time to access and track any piece of MiC module to verify its completion and quality checking status through remote joint inspection. Without physically travelling to the factory in China or other locations especially when there is travel limitation like during the COVID-19 pandemic, end users can arrange remote joint inspection, and the inspection data can be securely recorded on the conventional database, while the BIM database and critical checkpoints could be additionally logged to a blockchain server to ensure that the data transactions are securely stored and digitally ledged. In addition, a mobile BIM viewer with a color-coded system provided in the platform enables offsite management to instantly understand the current MiC progress.

4.2. BEANiE 2.0

The Digital Works Supervision Systems (DWSS) initiative was launched by the Hong Kong Special Administrative Region (SAR) government on 1 April 2020 in Technical Circular (Works) No. 3/2020 issued by the Development Bureau [51]. It sets out the policy and requirements on the adoption of DWSS as a technical requirement in capital works project of 300 million Hong Kong dollars or above. DWSS includes the Request for Inspection/Survey Check (RISC) form and site diary among other key construction workflows. These workflows have been incorporated in BEANiE 2.0, fulfilling the government's requests for information about materials, contractors, and subcontractors; construction programs; project management; early warnings; payment records; and BIM workflows. In Kang et al. [27], they used the Shek Wu Hui Sewage Treatment project as a case study.

DWSS is essentially a web-based centralized portal of collecting construction works information and managing the workflows of site activities to enhance efficiency, safety, and quality performance. It is also a workflow-enabled application system that consists of the following five mandatory modules to facilitate the digital processing of required forms and records with one centralized database system covering the following:

1. RISC form;
2. Site diary/site record book;
3. Site safety inspection records;
4. Cleansing inspection checklists; and
5. Labor return record.

In addition, DWSS is highly industry-specific for local practices and provides end-to-end solutions to all stages of the construction progress, from design through procurement, construction, and maintenance. To cater for this technical requirement, BEANiE 2.0, both in mobile and web-based platforms, was rolled out in March 2021. It is equipped with DWSS and is developed specially for the construction industry with the following new features:

1. Collect and centralize all construction inspection data;
2. Two-factor authentication;
3. Mobile device management (MDM);
4. Fulfill OGCIO Regulations (ISPG-SM04 Practices Guide for Cloud Computing Security and ISPG-SM01 Practice Guide for Security Risk Assessment and Audit);
5. Workflow process enabled;
6. Approval process embedded;
7. Report and dashboard management; and
8. BIM compatibility.

4.3. BEANiE 3.0

Precast and MiC elements are manufactured off-site and delivered to the construction site. The Fleet Management Module was added in BEANiE 3.0, released in October 2021, to monitor the fleet to ensure JiT delivery and installation. With the use of 4G/5G/NB-IoT connectivity, cross-border driving and the driver's well-being can be monitored. Drivers can also be advised on better logistics routes by sending the GPS location to the cloud platform on a mobile to monitor the journey on-the-go, and each MiC location can be easily tracked by adopting a cloud-based monitoring platform. Remote operators can also communicate with the drivers to remind them to rest and ensure safe journeys on delivery. Besides, an indoor air quality (IAQ) sensor is also installed to monitor the air quality to provide an adequate working environment for drivers involved in cross-border transporting of the MiC modules. Personal text messages remind drivers to take rest and have some more fresh air intake to ensure safe journeys on delivery and, hence, workers' well-being can also be enhanced.

4.4. BEANiE 4.0

The manufacturing process in the off-site factory is difficult to monitor all the time. In order to enhance the monitoring during the manufacturing for precast and MiC elements, BEANiE 4.0 rolled out in September 2022, whereby a Closed-Circuit Television (CCTV) System is linked with a dashboard for live viewing. The live video is uploaded to BEANiE with blockchain. The inspector can login to the dashboard and very easily monitor the factory situation and the recorded video when necessary. This additional functionality greatly facilitates real-time monitoring in a cross-border manner between the MiC factory and the construction company.

4.5. BEANiE 5.0

With the primary aim of enhancing the safety and traceability for safety zone control in MiC projects, BEANiE 5.0 was introduced in late December 2022. Workers are required to wear a high visibility safety vest, safety elastic vest, safety helmet, or wristband with an embedded Bluetooth token for identification, and a robot, namely MobiLog, can authorize workers and at the same time alert the site management staff when an unauthorized worker trespasses a restricted area. Figure 2 shows examples of the technology. Besides, if a worker falls down, this can also be detected, and the management staff can remotely monitor and take immediate action when necessary. Such a Bluetooth token can also be used as an emergency alarm system, commonly known as the safety bell, to allow workers to assert an emergency condition and raise a direct alarm for the awareness of system administrators.

(**a**) (**b**)

Figure 2. Use of Smart Technology in Enhancing Safety and Traceability at MiC Construction Sites (BEANiE 5.0). (**a**) High visibility safety vest, safety elastic vest, safety helmet or wristband with Bluetooth token; (**b**) MobiLog in operation.

4.6. BEANiE 6.0

BEANiE 6.0 is now under development. It can further expedite progress and increase efficiency, productivity, and quality. Applying the philosophy of digital twin, independent project information of selected sites and metadata will be collected via 5G, sensors and IoT and transmitted to a cloud server to directly display these real-time data in a Smart Command Theatre in a designated location to monitor and enhance productivity, site safety, workers' activities, logistics, fleet management, smart mobility (e.g., autonomous vehicles), environmental index, and other related infrastructure performance at a corporate level to facilitate predictive measures. Clients can also be invited to access the Smart Command Theatre when necessary.

Furthermore, BEANiE 6.0 will make use of even more data, notably open data from the government (such as weather, traffic incidents, and air quality), to improve real-time responses during the MiC process. In recent years, the Hong Kong Government has pledged to open up more data from both public and private organizations through a one-stop platform on the public sector information (PSI) portal "www.data.gov.hk (accessed on 9 December 2022)"). The portal releases free access of information from government departments and public and private organizations aiming to facilitate smart city development. The electronic identify (eID) for citizens allows them to access government services and electronic forms digitally through a single, personalized interface. It also aims at providing end user services to both public and private sectors, especially smaller enterprises to achieve synergy and avoid the use of excessive resources [52]. While the open data development in Hong Kong is still faced with many barriers and challenges [53], the ultimate aim is to fully incorporate different stakeholders and to make full use of relevant data in enabling smart decision making, ultimately working towards the implementation of smart city. BEANiE 6.0 is expected to be released in December 2023.

Subject to the project owners' requirements, BEANiE, equipped with BIM technology and other add-on software, can be enhanced to be applied to any stage of a construction project. For instance, an energy simulation software that allows users to perform reliable dynamic energy evaluation of the BIM model has been added to perform facility management. In the future, BEANiE can cover the full project lifecycle including design, production, architecture, facility management, and asset management.

5. Lessons Learned: A Four-Stage Approach

Based on the development of BEANiE and the theoretical understanding of smart construction, we can answer research question 2. The lessons learned are conceptualized as the development towards smart construction involving MiC in four major stages. Figure 3 is a schematic diagram of the development stages. The top of each box describes the main objective and scope. The bottom of each box describes the stakeholders involved. The center part summarizes the key outcomes and processes of each box. On the left-hand side are the applications of blockchain technology. On the right-hand side is the integration with other digital software and management platforms. The two strands of technologies can be applied alone or together. For instance, Kim et al. [21] suggested that smart contracts and construction Bitcoins are more widely adopted in the planning phase of construction project, whilst blockchain-based BIM management platforms are promising for the design phase. The integration of blockchain with IoT is more active in the construction and operation or maintenance phase. ISO19650, on the other hand, allows for information on the whole lifecycle of the building asset to be managed under a standardized framework. In the meantime, the open platform, CDE, CIM, and Application Programming Interface (API) (e.g., green assessment add-on), allows for information to be used by all parties at each stage. Furthermore, a white-label platform is also available to be used by external parties for adaptation and application.

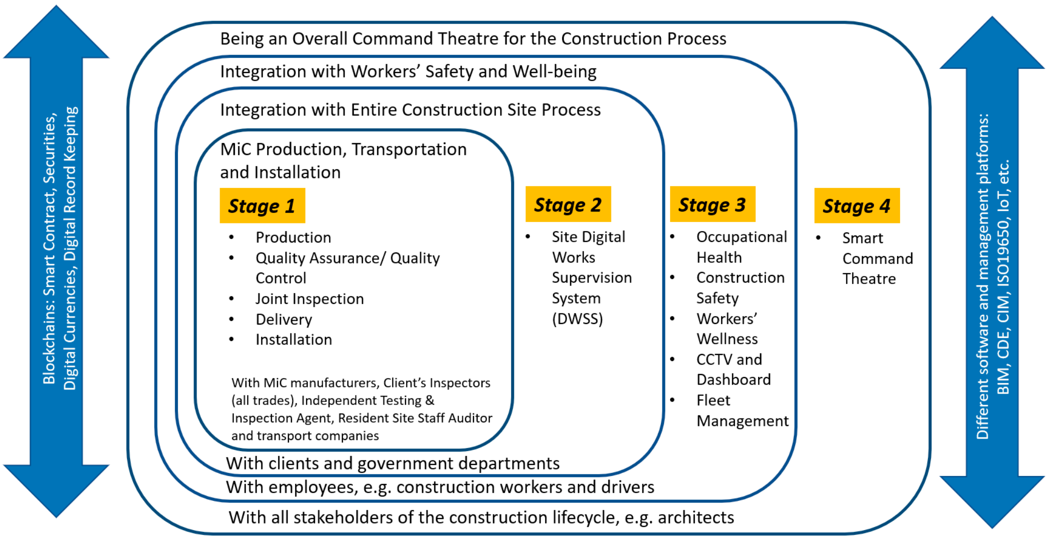

Figure 3. A Conceptual Framework of Smart Construction: The Case of MiC.

5.1. Stage One

MiC production, JiT transportation, and on-site installation are the core elements of Stage One. MiC manufacturers and transport companies are the key stakeholders to be engaged with the construction company. The three parties adopt RFID technologies to monitor the management of MiC production, QA/QC, delivery, and installation. This captures the key characteristics of BEANiE 1.0. The shared ledger on blockchain-based platform facilitates users to store data safely and reliably [27]. The key technologies used include RFID, custom-made eForms, the BIM database, a mobile BIM integrated viewer, and the blockchain browser. The organization of the open platform also enhances data accuracy, transparency, and traceability, allowing for better monitoring of the construction progress.

However, the platform is not user-friendly for the checking, updating, and modification of information and authority. Papers are still used in the workflow. Hence, the process is prone to errors and requires data validation. Therefore, although the blockchain benefits the construction process at this stage, the use of blockchain cannot be fully utilized. The platform primarily serves the construction company's internal process of monitoring the quality and other aspects of business obligations of other parties involved in the production, transportation, and installation of MiC for relevant construction projects.

5.2. Stage Two

Integrating Stage One with the entire construction site process is classified as Stage Two. Designated staff of a construction company who are involved in the construction site processes are to adopt the blockchain-enabled technologies to monitor the DWSS workflow, as in BEANiE 2.0. This stage is seen to be triggered by government requirements on digitalization of construction projects in the society and the corresponding digitalization of its monitoring and regulatory regime [54]. In other words, this is closely associated with government initiatives towards smart cities in general and smart construction specifically. To the private construction industry, this sends a strong signal of accelerating the application of technology to take advantage of a centralized official portal and to minimize the transactions cost of dealing with different government departments in a decentralized manner.

Accordingly, a key feature of Stage Two is that the blockchain multifunctional platform no longer only serves to facilitate private sector transactions and ensure quality and timely delivery/completion of business obligations but to serve as an interface for third-party services, notably government, monitoring, authentication, and certifications. The secured construction works information and workflows of site activities are shared with the monitoring authority to fulfill various technical requirements. In Hong Kong, DWSS encompasses the RISC form, site diary/site record book, site safety/inspection records, cleansing inspection checklists, and labor return record. Hence, BEANiE 2.0 also extends to different stages of construction, from procurement to construction to maintenance. The key functions of Stage Two include inspection, authentication, management, regulation compliance, report, and approval. The key technologies also extend to dashboard management, which enables a visualization of the process and the participation of multiple parties in monitoring and updating (e.g., in authenticating and giving approval) the real-time status of relevant MiC projects. Data transparency is enhanced at this stage.

5.3. Stage Three

Integrating Stages One and Two with the safety and well-being of workers and drivers is classified as Stage Three. At this stage, the employer adopts blockchain, IoT, and 4G/5G/NB-IoT technologies to monitor the occupational health, construction safety, and worker's/drivers' wellness through CCTV, dashboard, and Bluetooth technologies. This stage generally encompasses BEANiE 3.0, 4.0, and 5.0.

A key new feature of Stage Three is that the system now focuses on people in the construction process. The safety and well-being of construction workers and drivers transporting MiC over long distances are covered in the process of smart construction. In particular, the Bluetooth technology is used in high visibility safety vests, safety elastic vests, safety helmets, or wristbands to trace whether construction workers are in hazardous zones or are having no movement at unusual locations so that immediate actions can be taken to handle the situation and to minimize harm to workers [55]. Similarly, the focus on long-distance transportation of MiC is no longer only put on the JiT delivery, but also on the occupational safety of cross-border drivers with IAQ sensors as IoT for communicating advice on safety (such as taking rests) and route choice. Moreover, with 4G/5G connectivity, live video streaming through CCTV at various MiC checkpoints, including within the MiC factories, is possible on dashboard. Linking the permissioned IoT-BIM platform for off-site production management has moved to a more advanced and real-time stage [56]. Moreover, on-site safety, including the inspection of tower cranes used for MiC installation, can be enhanced at this stage [57]. Last but not least, the use construction robotics is also integrated (such as with MobiLog in BEANiE 5.0) with cloud-based computing (such as with best logistics route based on traffic situations) to support smart construction with MiC.

5.4. Stage Four

Having an overall command theatre for the entire construction process will be classified as Stage Four. All stakeholders of the construction lifecycle are invited to adopt blockchain technologies to monitor not only the processes mentioned in Stages One, Two, and Three, but also the full construction lifecycle via a Smart Command Theatre and CIM, where data collected from a variety of sources can be put all together as a support decision tool for the planning and management of MiC projects. This is the stage that BEANiE 6.0 is working towards.

At this stage, the requirements of cloud-based computing and the integration of multi-sourced data, including LiDAR, data collected from the construction robotics (such as MobiLog), and data from other open sources, are high. Hence, at Stage Four, the platform aims to extend to include all stakeholders of the construction lifecycle, for example, architects, to facilitate smart construction. Furthermore, Stage Four integrates the platform with other relevant open data from multiple sources. Governments' open data platforms allow for API and AI to be applied based on the shared data. As such, smart construction can be achieved with an overall command theatre for the construction process, encompassing all relevant technologies and updated information, such as weather conditions and air quality. International standards (such as ISO 9650) are adopted to allow for the best practices to be shared across the industry. As the platform extends and serves multiple purposes, the challenges of reducing information redundancy and ensuring efficiency are also key at this stage [58].

There is room for the conceptual, technological, and application development of BEANiE by extending the CIM concept to include cross-project dynamic data in the smart command theatre. Some promising areas include real-time traffic, autonomous vehicles, environmental conditions, waste management, operational cost, etc. All these data can support more in-depth analysis on particular aspects of the construction process when required. Furthermore, the smart command theatre can provide a responsive simulation platform for planning and design and help manage smart construction projects for improving the overall operation and maintenance at the corporate level.

6. Conclusions

This paper reviews the adoption of smart technology in MiC development of the construction industry. A case study of BEANiE is conducted. The lessons learned are being conceptualized as four stages that provide benchmarks and lessons for other cities, where construction with MiC can yield substantial sustainability benefits and the progress towards a smart city is substantial.

In the future, the challenges of smart construction will continue to loom large, especially in compact cities where negative environmental impacts (including construction waste, noise, and air pollution) are generated close to people's major residential and activity centers. There is a dire need to use smart technology to minimize the negative externalities associated with construction activities and to maximize the benefits that buildings can bring to the urban population. In particular, the speed of construction is a major consideration for situations like urban renewal, war rehabilitation, and other situations like fulfilling the housing needs of a large number of vulnerable low-income and/or migrant populations and ensuring their welfare.

As a result, smart construction will continue to revolutionize the industry. Smart sensors, machine learning, and AI-based analytics are expected to be widely adopted to capture real-time data and provide valuable insights for better decision making. There will also be more accurate predictions about future outcomes. Overall project sustainability performance can be improved with resources more optimized, costs reduced, and safety enhanced. Most importantly, sustainability, energy, and technologies with environmental, social, and governance (ESG) elements can also be enhanced to bring a better future to the society. While some experiences in developed countries (notably Singapore, the UK, and the US) have been included in this paper, future research work on a deeper and focused analysis of smart construction practices among the G7 countries will provide further insights for promoting smart construction.

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