An i-Core and Smart Contracts-enabled Framework for Just-in-Time Delivery of Modular Integrated Construction Modules

Liupengfei Wu*, Weisheng Lu

Abstract

The construction industry faces significant sustainability challenges due to high energy and material consumption. Modular integrated construction (MiC) is a more sustainable alternative to traditional in-situ construction. It involves the fabrication of integrated modules in off-site controlled conditions and their transportation to construction sites for installation. MiC offers various social, economic, and environmental benefits, such as enhanced safety, increased productivity, and reduced waste. The success of MiC projects depends on efficient cross-border logistics, with Just-in-Time (JIT) deliveries being crucial. However, persistent problems related to JIT implementation still exist, even with the adoption of advanced project management software such as enterprise resource planning systems, building information modeling (BIM), and geographic information system (GIS) technologies. In this context, this paper proposes an i-Core and smart contracts-enabled framework for JIT deliveries of MiC modules. By addressing persistent problems related to JIT implementation, the proposed framework is expected to improve the overall efficiency and sustainability of MiC.

Keywords: Modular integrated construction, smart contracts, cross-border logistics, i-Core sensors

1. Introduction

Despite the construction industry's total receipts amounting to HKD 411.1 billion in 2022 (Census and Statistics Department, 2023), the construction industry in Hong Kong faces a wide array of problems. It suffers from (a) increasing construction costs, (2) declining productivity, and (3) a lack of a comprehensive approach (Wuni & Shen, 2020a). Hong Kong is ranked third in the globe in terms of construction cost in 2018, according to the surveys conducted by Arcadis (2018). In contrast to the increasing cost is the declining productivity. Notably, the industry faces a severe labor shortage and aging problems; the average age of skilled workers is 51 (Construction Industry

Council, 2024). Hong Kong also lacks a comprehensive approach to managing cost, enhancing project delivery capability, and accelerating the lead strategic development such as offsite construction to boost productivity and cost-effectiveness (Wuni & Shen, 2020).

The increasingly stringent problems have led to a re-emergence of Modular Integrated Construction (MiC). This construction approach produces standard three-dimensional (3D) volumetric units in an off-site factory and then transports the units to construction sites for assembly (Construction Industry Council, 2018). MiC, followed by pre-assembly and prefabrication, represents the highest level of off-site construction because most construction work (including full fixtures) is completed in the factory (Lu et al., 2018). As most works are carried out in a well-controlled environment, MiC is believed to be superior to its preceding cast-in-place construction approach in terms of productivity, quality, safety, and sustainability (Wuni & Shen, 2020b). A report by McKinsey indicated a 20~50% schedule compression and a cost saving of up to 20% if the modular approach is adopted compared with traditional construction (Bertram et al., 2019). Encouraged by the promising benefits, MiC is gaining considerable attention worldwide, especially in high-density places, e.g., Singapore, Hong Kong, and Japan, where housing supply cannot be met with traditional building approaches (Pan et al., 2023).

Since most of the work is outsourced to an offsite place, at the center of MiC is the construction logistics and supply chain management (CLSCM) (Wu et al., 2022). This is particularly true in the case of Hong Kong, where a large proportion of its MiC projects have their modules produced in nearby cities in the Greater Bay Area (GBA) in mainland China (Lu et al., 2022). With increasingly fierce competition in the global construction market, advanced project management software such as enterprise resource planning systems, building information modeling (BIM), and geographic information system (GIS) technologies have been adopted to facilitate information sharing and decision support in CLSCM (Darko et al., 2020). However, cross-border logistics and limited parking spaces at construction sites due to Hong Kong’s high-density development model complicate the implementation of just-in-time (JIT) delivery of MiC modules (Wu et al., 2024). Furthermore, current literature shows that existing transport frameworks mainly focus on on-time delivery of passengers via private cars, taxis, and buses. In contrast, an explicit theoretical framework for JIT delivery of MiC modules via trucks has received little attention.

Thus, this research aims to develop an i-core and smart contracts-enabled framework for JIT delivery of MiC modules. The research has three specific objectives: (1) to use i-Core to collect cross-border logistics data of MiC module deliveries; (2) to establish a MiC-focused estimated time of arrival (ETA) functional module for JIT delivery of MiC modules based on the collected data; and (3) to develop a JIT framework for MiC module deliveries using i-Cores and smart contracts. The rest of the paper is organized as follows. Section 2 provides the background. Section 3 explains our research method. Section 4 summarizes the results of data collection, proposes MiC-focused estimated time of arrival (ETA) functional module, and presents an i-core and smart contracts-enabled framework for JIT delivery of MiC modules. Section 5 discusses the novelty and limitations of the research, and a conclusion and future work are presented in Section 6.

2. Background

2.1 Cross-border MiC logistics

The global procurement landscape is characterized by the involvement of cross-border logistics in MiC. In recent years, many countries and cities have seized the opportunity presented by these supply chains to seek cost-effective labor, materials, and space for offsite or offshore MiC production (Lu et al., 2022a). For instance, Hong Kong has relocated its MiC factories to Mainland China's Pearl River Delta region for this purpose (Lu et al., 2022a). According to the Observatory of Economic Complexity (OEC, 2023), prefabricated modules ranked as the 340th most traded product globally in 2020, accounting for 0.052% of total world trade. OEC (2023) reports that Germany ($1.08 billion), the United States ($493 million), France ($438 million), Norway ($414 million), and the United Kingdom ($381 million) were the top importers of prefabricated modules in 2020. In the same year, China ($1.66 billion), the Netherlands ($554 million), Czechia ($450 million), Estonia ($443 million), and the United States ($397 million) were the leading exporters. Given the significant volume of import and export activities in the MiC industry, the importance of efficient cross-border MiC logistics cannot be overstated.

MiC cross-border logistics has three sub-phases: transportation preparation, execution, and completion (Wu et al., 2022a). The researchers have identified the key elements within the scope of cross-border MiC logistics as follows: (1) The production manager must sign the transportation bills to initiate the delivery tasks as an entry criterion. (2) The loading lists and relevant module details serve as inputs for the cross-border transportation tasks. (3) The exit criteria involve the vehicle driver or captain returning the signed transportation dockets to the manufacturer. (4) The outputs of this logistics process are the quality assured modules. Specifically, during the transportation preparation phase, the manufacturer needs to make customs declarations in advance. Subsequently, the logistics provider can load the modules onto trailers or barges. In the execution phase, the vehicle driver or barge captain is responsible for delivering the modules to the inspection site to facilitate customs clearance. At this stage, the modules may be temporarily stored at a designated storage site or directly delivered to the construction site, depending on availability. The contractors' operators then assess the condition and status of the modules. Once approved, the operators sign the delivery dockets, and the drivers or captains complete the transportation tasks by returning the signed delivery dockets to the manufacturer.

2.2 Current technologies for cross-border MiC logistics

Existing technologies adopted in the cross-border MiC logistics are reviewed in this section. Tables 1 summarizes 15 major technologies currently employed for different uses of cross-border MiC logistics. However, the implementation of JIT deliveries for cross-border MiC need to be further studied and resolved.

Table 1. Current technologies for cross-border MiC logistics

Technology	Uses
1. IoT (Ali et al., 2020)	-Spatial-temporal information collection -Decision support
2. BIM (Magill et al., 2022)	-Process visualization -Process tracking -Resource and materials management -Information exchange -Quality management -Planning -Scheduling - Transportation route simulation -Decision support
3. ERP (Irizarry et al., 2013)	-Information sharing -Decision support
4. SCO	-Information sharing

(Niu et al., 2017a)	-Process visualization
5. Robotics (Luo et al., 2023)	-Material handling
6. Laser scanning (Aryan et al., 2021)	-Visualization -Quality inspection -Planning -Progress tracking
7. AI (Pan and Zhang, 2021)	-Planning -Scheduling -Inspection -Real-time project information query and notification
8. UAV (Dupont et al., 2017)	-Module transportation -Inspection -Progress tracking
9. Big data (Yu et al., 2020)	-Decision support
10. Could computing (Abedi et al., 2015)	-Data storage
11. AR (Kolaei et al., 2022)	-Inspection -Progress monitoring
12. GIS (Irizarry et al., 2013)	-Transportation planning -Transportation simulation -Transportation visualization -Process tracking -Resource and materials management
13. VR (Davila et al., 2022)	-Planning -Process simulation
14. 3D printing (Ramani and Garcia de Soto, 2020)	-Component production
15. 5G (Mendoza et al., 2021)	-Fast communication

2.3 i-Core and smart contracts

i-Core refers to an independent, programmable, and adaptable integrated chip that can be embedded into construction machinery, devices, and materials, as discussed by Niu et al. (2017a). Similar to a computer's central processing unit, i-Core has the capability to transform inert modules into intelligent construction objects known as smart construction objects (SCOs), enabling JIT deliveries of MiC modules. To facilitate JIT deliveries of MiC modules, i-Core can be equipped with a range of components that can be integrated based on specific requirements. The customization of i-Core is particularly challenging due to the diverse nature of real-life construction practices, which are often unique to specific procedures, projects, and companies.

Thus, the components of i-Core are designed to be flexible and can be tailored on a case-by-case basis, as depicted in Figure 1. For instance, i-Core can be configured with features such as a global positioning system (GPS), a timer, an inertial measurement unit (IMU), 4G network connectivity, Wi-Fi, and a thermometer.

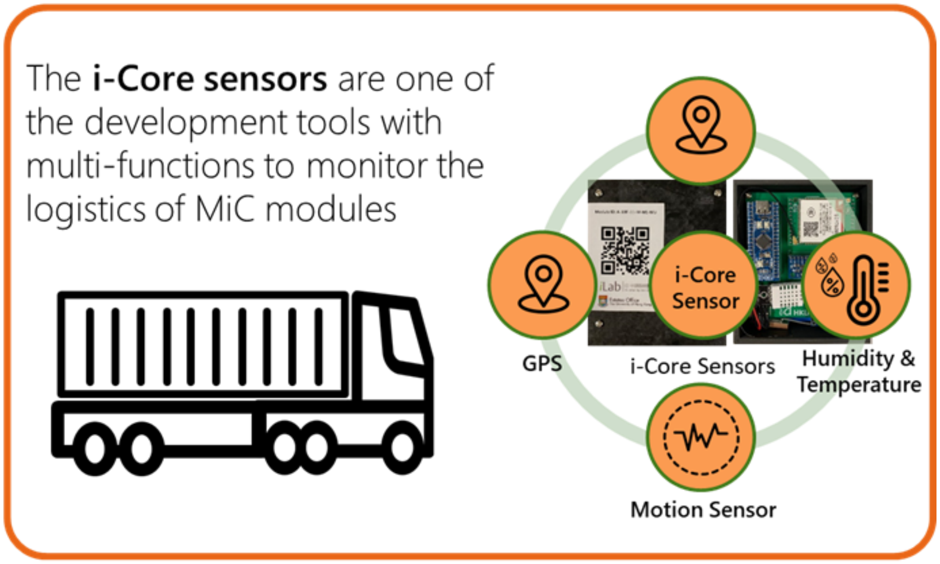

Figure 1. An example of an i-Core

Smart contracts can be considered a significant advancement in blockchain technology (Wu et al., 2022b). They consist of two primary elements: preset conditions and responsive actions that are automatically triggered when the preset conditions are met. The execution of smart contracts takes place on the blockchain using a self-executing computerized protocol, as discussed by Ahmadisheykhsarmast and Sonmez (2020). Once a smart contract is configured within a blockchain network, the execution rules cannot be changed, as highlighted by Li et al. (2021). This feature enables the digitization and automation of business processes, while also eliminating intermediaries and human interventions. For instance, when a peer initiates a transaction, the smart contract can automatically gather the transaction and send it to the network for endorsement. Once all parties endorse the transaction, the smart contract can collate it into a block and update it to the blockchain.

To summarize, despite the adoption of various digital technologies to facilitate cross-border MiC logistics, the implementation of JIT deliveries for cross-border MiC remains challenging. This research aims to address this gap by proposing an i-Core and smart contracts-enabled solution for cross-border MiC logistics.

3. Research methods

The research team first focused on collecting cross-border logistics data specifically related to a MiC project. This data included travel time and other relevant information (e.g., customs clearance time). By gathering this data, the team aimed to enable active transport planning and simulation, focusing on providing ETA for each module delivery task in the MiC project. The pilot project chosen for this research involved 400 MiC modules from two blocks of MiC buildings. These modules were manufactured by a prefabrication manufacturer located in mainland China. Subsequently, the manufactured modules were transported from the manufacturer's factory to the installation site using the Hong Kong-Zhuhai-Macau bridge. Utilizing the Hong Kong-Zhuhai-Macau bridge as the transportation route adds an additional layer of complexity to the logistics, making the research findings highly valuable for the successful implementation of cross-border MiC projects.

After collecting the data, the research team divided the delivery routes into seven segments, as shown in Figure 2. Next, by comparing the OpenAPI travel time and the actual travel time of MiC deliveries collected from i-Core sensors, a coefficient was determined for each segment to calibrate the OpenAPI model for MiC-focused ETA. By analyzing the cross-border logistics data from this MiC project, the research team aimed to optimize the transportation process and enhance efficiency in module JIT delivery.

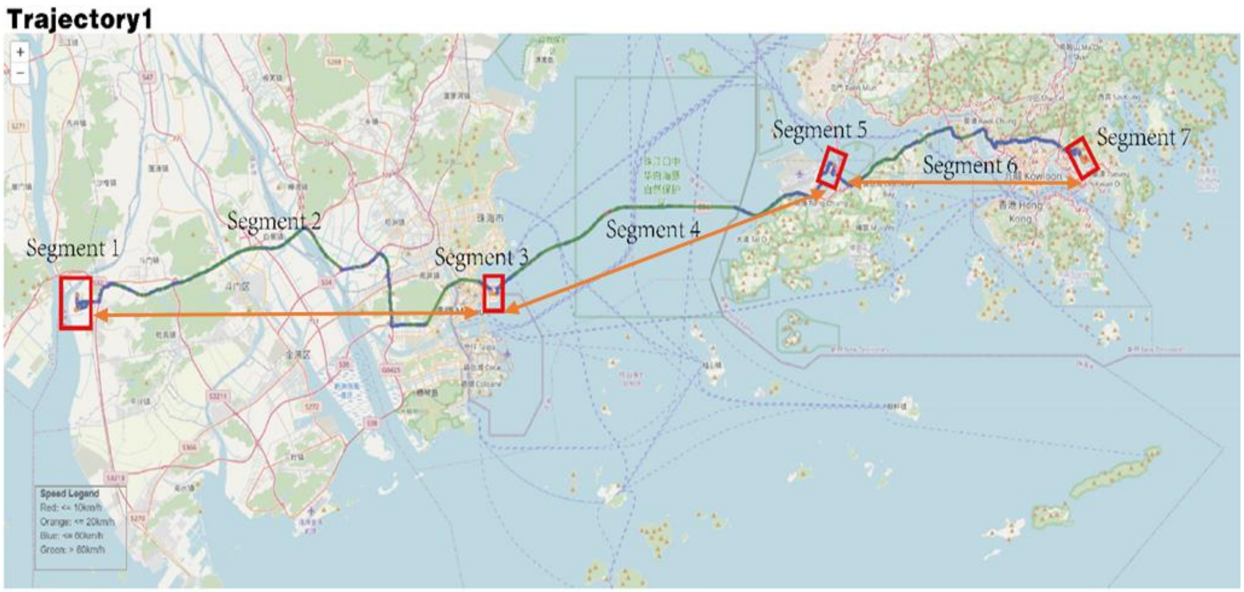

Figure 2. Divided segments of the delivery route

A JIT delivery framework for MiC deliveries was then designed based on Sections 3.1 and 3.2. The framework considered three aspects to achieve JIT. First, the framework considers the late departure scenario; that is, when the current truck departs late, the departure time of the following truck also needs to be postponed accordingly. Second, the framework considers speed and position combinational supervision between trucks during module transportation. Third, the framework considers reminding the following truck to slow down to enter the parking space when the preceding truck has yet to leave the installation site. That is because, in a high-rise and high-density city like Hong Kong, a construction site can usually accommodate only one truck at a time. Together, the above three critical hold points are taken into consideration for realizing JIT delivery for cross-border MiC.

4. Results

In the case project involving cross-border Modular construction (MiC) logistics, the research team collected travel time data for each delivery task associated with the blocks of MiC buildings. This data was collected using i-Cores, as shown in Figure 3. By utilizing this technology, the travel time for each divided segment of the transportation route was determined accordingly.

Figure 3. Data collection by using i-Core sensors

Next, the coefficient for each divided route segment was determined by comparing the travel time of the divided segment provided by OpenAPI and the actual travel time collected from i-Core sensors, as shown in Table 2. Therefore, the MiC-focused ETA is now the sum of the OpenAPI travel time of each segment multiplied by the coefficient.

Table 2. Coefficients table of estimated time of arrival

Segment ID	Segment description	Coefficient
1	The trajectory between the starting point and the Zhuhai port	1.28
2	Trajectory at the Zhuhai port	1.71
3	The trajectory between the Zhuhai port and the Hong Kong port	1.24
4	Trajectory at the Hong Kong port	1.21
5	The trajectory between the Hong Kong port of entry and the destination area	1.11
6	The trajectory between the Hong Kong port of entry and the depot area	1.03

7	The trajectory between the depot area and the destination area	1.17

Finally, the framework that considers the scenarios of late departure from factory, en-route slow or fast moving, and late departure from installation site was then proposed. As shown in Figure 4, when the leading MiC truck is delayed in departure, the following truck driver will receive a warning via the mobile phone application sent by smart contracts automatically. Likewise, if the distance between the rear truck and the front truck approaches the preset 20-minute interval, the rear truck driver will also receive a message through the same mobile app sent by smart contracts automatically, reminding him or her to slow down. Also, when the previous truck arrives at the installation site and has not yet left the site, and the next truck is only 20 minutes away from the previous truck, the driver of the next truck will receive a slow-down reminder message sent by smart contracts through the same mobile application. As a result, drivers will drive slower.

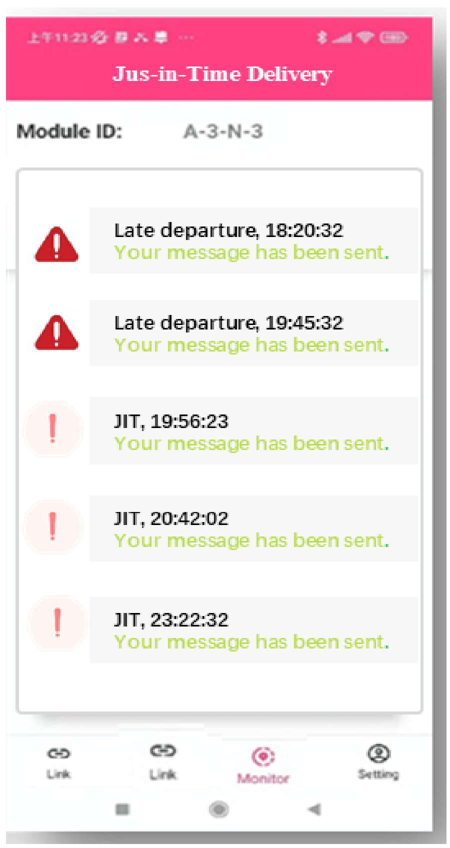

Figure 4. A mobile application for MiC just-in-time delivery

5. Discussion

The use of MiC has gained widespread popularity in recent years due to its potential to increase construction efficiency and reduce costs. However, MiC projects require a high degree of logistics planning to ensure JIT delivery of modules to the construction site. The traditional approach to logistics planning in construction projects is often manual, time-consuming, and error-prone, resulting in potential delays and cost overruns. The generalizability of the proposed model for JITe delivery of modules lies in its capacity to be implemented across diverse contexts and disciplines. By assessing the model's adaptability to various subject areas, researchers can ascertain its effectiveness in facilitating timely and relevant delivery of various products.

The JIT delivery of MiC modules is of utmost importance in high-rise and high-density cities with limited parking zones. In these urban areas, where space is at a premium, parking and storing construction materials are significant challenges. By adopting a JIT delivery approach, MiC modules can be transported directly to the construction site when they are needed, eliminating the need for onsite storage and minimizing the disruption caused by material handling and storage. This optimizes the utilization of limited parking zones and reduces congestion and inconvenience to the public. Additionally, the timely delivery of MiC modules ensures that construction projects progress smoothly and efficiently, minimizing construction timelines and reducing the overall impact on the surrounding urban environment.

Compared with previous studies, this paper is novel in three ways:

1. I-Cores are used to collect and analyze actual logistics data of cross-border MiC module delivery, while previous studies lack travel time data specifically for MiC cross-border logistics.
2. It proposes a MiC-focused ETA module for MiC logistics providers instead of using OpenAPI travel time for logistics planning.
3. This study proposes a resilient and interactive framework that enables MiC truckers to implement JIT in high-rise and high-density cities dynamically.

6. Conclusions

The construction industry increasingly recognizes the need for sustainability, considering its significant energy and material consumption. Modular Integrated Construction (MiC) has emerged as a more sustainable approach, offering numerous benefits such as enhanced safety, productivity, and reduced waste. However, efficient cross-border logistics, particularly Just-in-Time (JIT) deliveries, are crucial for the success of MiC projects. Despite the adoption of advanced project management software and technologies, persistent challenges in JIT implementation remain. In order to address these challenges, this paper proposes an i-Core and smart contracts-enabled framework for JIT deliveries of MiC modules. By overcoming these persistent problems, the framework is expected to enhance the overall efficiency and sustainability of MiC, contributing to the construction industry's sustainability goals.

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