Process Coordination and Automation in Modular Construction Supply Chain Using Smart Contract and RPA

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Abstract –

The integration of off-site manufacturing with on-site construction in the Modular Construction Supply Chain (MCSC) presents significant challenges due to the differences in production methods and geographical distances. While various technologies have transformed construction practices, substantial improvements are still needed in on- and off-site coordination to mitigate delays, ensure quality, and lower costs. Blockchain-enabled smart contracts offer a promising workflow engine for enhancing process-oriented MCSC coordination. Additionally, Robotic Process Automation (RPA) holds the potential to further refine the modules within MCSC processes and automate tasks. This paper, therefore, aims to develop a new workflow engine that combines blockchain-enabled smart contracts, RPA, and related visualization technologies to address the coordination challenges inherent in MCSC. Demand-driven process modeling and smart contracts conversion with RPA actions are conducted with the MCSC coordination unit configuration, and the initial system is developed and validated in a real-world case study. Industrial requirements and feedback are collected and analyzed via questionnaires and interviews. Finally, practical implications are discussed, and the integration of RPA and AI is identified as a promising exploration for future work in MCSC coordination.

Keywords –

Smart Contract; RPA; Modular Construction; Supply Chain Coordination

1 Introduction

In dense urban environments such as Asian regions, the industrialization of construction has been significantly influenced by factors e.g., rapid urbanization and increasing sustainability demands. This context has spurred the fast development of modular construction (MC). The merging of off-site manufacturing with on-site construction in the modular construction supply chain (MCSC) presents challenges due to different production approaches and geographical separation [1,2]. These challenges include amplified delays, disjointed quality control systems, and discrepancies in accountability [3,4]. Numerous studies aim to enhance coordination within the construction supply chain at a macro level through strategies such as supplier alliance, organizational partnership, and value co-creation [5,6].

However, the effective implementation of these macro-level strategies requires a solid material and process foundation. Establishing a domain-spanning production flow and developing effective on-site and off-site coordination mechanisms are essential prerequisites for holistically improving the performance of the modular construction supply chain. A series of technological advancements provide a foundation for better process coordination in MCSC.

Business Process Management (BPM) and its process modeling standards, e.g., Business Process Model and Notation (BPMN) and Business Process Execution Language (BPEL), have been widely applied to construction information management with BIM (Building Information Modeling) models [7,8]. Recently, blockchain-enabled smart contracts have played a role in executing the process models in a traceable and semi-automated manner [9]. Meanwhile, the development of Robotic Process Automation (RPA) provides a possibility to further detail the modules within the MCSC processes and automate tasks. It comprises software agents that mimic the manual path taken by a human through integrated computer applications when performing certain tasks in a business process [10]. Currently, AI-enhanced RPA has been explored, and it shows the potential to elevate BPM from semi-automation to full automation [11,12].

Therefore, this paper aims to develop a new workflow engine integrating blockchain-enabled smart contracts, RPA and related visualization technologies to address the coordination issues existing in MCSC. The demand analysis is conducted at the beginning with a series of industrial engagement activities. The process models and the triggering and driving mechanisms are further developed and integrated into MCSC coordination multi-terminal devices. Finally, a real-world case study is carried out to validate the proposed methods.

2 Literature Review

2.1 BPM and BPA in Construction

Business Process Management (BPM) addresses the topic of process support from a broader perspective by integrating methods of analysis (such as simulation, verification, and process mining) and connecting processes to business and societal aspects [13]. Different process languages have been gradually developed, e.g., Petri nets, Workflow nets, YAWL, and BPMN.

In construction, the supply chain process has been early modeled and decomposed from conceptual representation to process element specification using BPMN and BPEL [14]. Recently, the integration of blockchain-enabled smart contracts and workflow engines has been newly explored and developed for Business Process Automation (BPA) [9,15]. Construction supply chain coordination and payment automation were frequently taken as use cases and application examples [16].

Robotic Process Automation (RPA) is an emerging automation technology in BPA that uses robots to partially or fully automate simple or complex repetitive tasks [17]. These robots, for example, process transactions, manipulate data, and communicate with other digital systems or agents [11]. Therefore, RPA and smart contract-enabled workflow engines can work together in a complementary way when deploying and monitoring automated processes. RPA automates a specific set of tasks, while smart contract-based workflow engines automate the flow among tasks and rule-based decision-making in each logical branch [9].

2.2 MCSC Coordination

The development of information technologies to improve visibility, enable coordination, and promote performance through information sharing in the construction supply chain is a continuously explored topic. The applications of blockchain-enabled smart contracts in conventional construction supply chain management mainly concern aspects including procurement, inventory management, traceability, sustainability, cross-border logistics, etc. [18].

In the general construction supply chain research field, regarding boundary-spanning interdependence, the off-site and on-site domains and domain-spanning processes and activities underneath have been analyzed [3]. In MCSC, the domain-spanning effect shows great importance. The typical MCSC process-oriented scenarios, including production, logistics, and business processes, have been identified as critical application areas [19]. The use of blockchain-enabled smart contracts and automation technologies as an MCSC coordination enabler is still in the early phase. According to a systematic review, currently, only about 18% of studies in modular construction practically implemented digital tools and applications [20]. It also indicated that the on-site and off-site fragmentation is a critical issue for MCSC and requires more digital solutions [20].

3 Methodology

3.1 Top-level Design for MCSC Process Collaboration and Automation

Smart contract generation necessitates accurate process models (e.g., in the BPMN format). Establishing such process models requires clear specifications of each participant's responsibilities and requirements, combined with BIM models, plans, and real-time site information. In different scenarios, the process participants and task complexity may vary. The MCSC process encompasses complex tasks and many participants, including the contractor, client, designer, and suppliers. Process splitting and subprocess modeling can be performed to simplify highly complex processes.

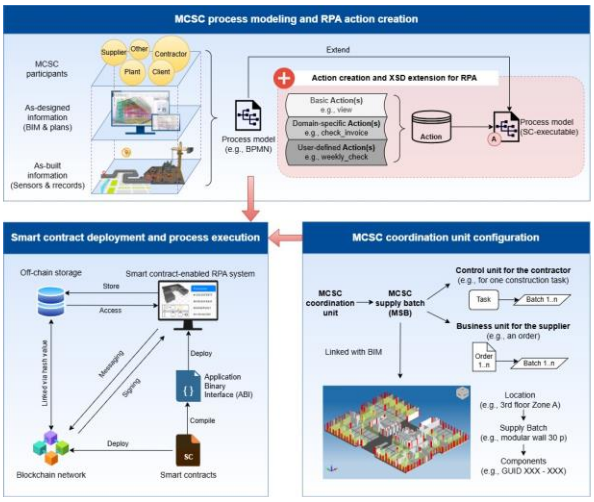

Figure 1. The framework of MCSC process coordination and automation

Because the initiation of tasks in the MCSC process is affected not only by the participants but also by asdesigned and as-built information, process modeling and automation can be conducted by combining BIM and IoT applications. Figure 1 shows the details of the top-level design of the MCSC coordination framework.

There are three key aspects that form the foundation of MCSC coordination: 1) demand-driven process modeling and smart contracts conversion with RPA actions; 2) MCSC coordination unit configuration from a managerial perspective; and 3) blockchain-enabled smart contracts deployment and MCSC process automation.

3.2 MCSC Process Modeling and Conversion

The industrial opinions were collected from a survey with 146 questionnaires and a series of interviews with practitioners involved in MCSC. Regarding the functionality of smart contract and RPA-enabled coordination systems or tools, the majority of respondents recognize that these tools ensure the authenticity of construction supply chain data (with 94% of respondents assigning high scores), traceability (with 81% of respondents assigning high scores), and automation capability (with 96% of respondents assigning high scores).

In the demand analysis of MCSC coordination, the majority of respondents identified the following key needs: preventing supply delays, interacting with suppliers to control progress and costs, obtaining quick responses from suppliers, planning and controlling inventory based on production activities, implementing more automated supply management systems, and ensuring traceability.

Based on industrial requirements, this study modeled the MCSC process using precast components as an example, as shown in Figure 2.

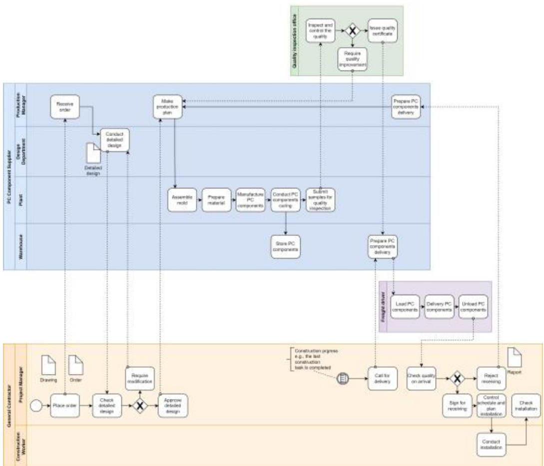

Figure 2. MCSC process model example

In this process model, all essential schedules and quality control gateways are set, and the information flow among the contractor, precast component supplier, logistics service provider, and quality inspection unit are modeled.

Based on the process model, blockchain-enabled smart contracts can be generated using our previously developed generation method [9], as shown in Figure 3. Smart contracts work as the global workflow engine for process execution and flow automation, which can provide traceable reports of the execution records.

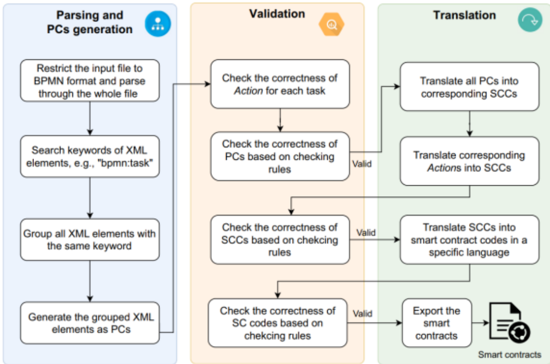

Figure 3. Smart contract generation method (permission obtained)

Meanwhile, a series of RPA actions were defined for internal task automation. To conform to the context of MCSC, RPA actions are defined in three levels: general (basic level for general purpose), domain-specific (e.g., logistics, payment, warehouse and construction), and user-defined (customized level under the requirements of a specific user).

Some manual actions can be replaced with fully or semi-automated RPA actions using smart contracts and blockchain (e.g., a "pay" RPA action), where the smart contracts are used as robots to realize RPA. Other manual actions, which cannot be simply executed via smart contracts (e.g., "check progress" action or "tracking" action), can be transformed into RPA actions by further integrating other devices or agents (e.g., sensors).

3.3 MCSC Coordination Configuration

MCSC Supply Batch (MSB) is defined as the smallest element within the coordination framework, which helps facilitate interactions and processes across different stages and parties in the supply chain, as shown in Figure 4. The attributes of MSB can be generated from predefined templates and integrated IFC properties from the BIM model.

The configuration of MCSC coordination with the basic unit, i.e., MSB, is shown in Figure 4. The defining and planning of MSB are based on project decomposition and a location-based perspective. A construction project can be decomposed from division work, sub-division work, and sub-item work, into construction tasks, and the MSB is linked to a construction zone, which contains a series of construction tasks following the sequence. The location-based perspective [21] is for better collaboration to provide the MCSC participants with a BIM model view. This project decomposition and a location-based perspective is mainly for the construction and project management side, e.g., the contractor, client, and consultant.

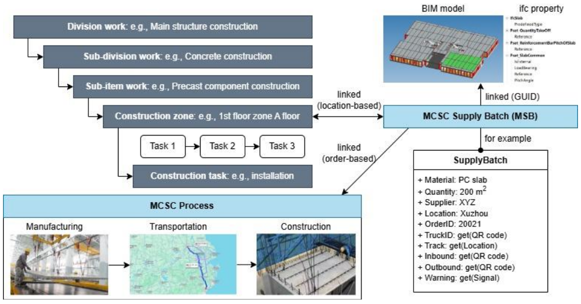

Figure 4. The basic unit of MCSC coordination

Another essential perspective is the order-based perspective, which is mainly for the supply side, e.g., the suppliers and logistics service providers. The order can be generated automatically after the contractor sets up the MSB in the system. The supplier can prepare the delivery and related documents according to an MSB order or link the MSB order to an existing purchase contract. All automatically collected data (e.g., sensors), semi-automatically collected data (e.g., QR code), and manually input data (e.g., mobile device or computer) can be linked to the MSB unit. Therefore, the life-cycle process of an MSB from off-site to on-site can be easily tracked and monitored. With inbound and outbound functions, the as-built information of MSB can also be tracked and shown in the BIM model view.

3.4 MCSC Process Automation

The MCSC process can be executed through semi-automatic operations by authorized personnel and predefined automatic triggers. Figure 5 shows the MCSC coordination process execution with RPA actions.

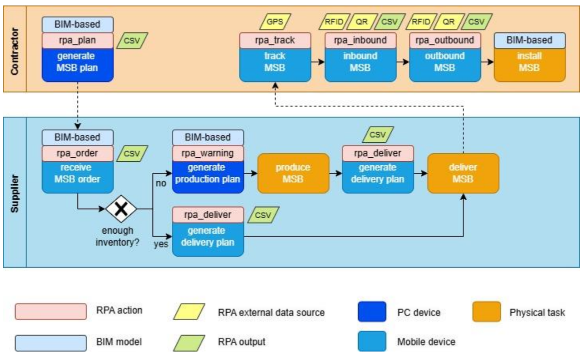

Figure 5. MCSC coordination process execution with RPA actions

In the initiation stage, an MSB plan can be generated with BIM models (components selection) and schedules, including the MSB name, construction zone, and required date. The quantity and associated components can be extracted from the IFC properties. The generation process can be semi-automatically executed using the rpa_plan action. For example, a CSV document of the MSB plan can be automatically created with manual adjustments on quantity unit and required date.

When the supplier receives the MSB plan, the rpa_order action will automatically convert it into an order so that it can be better understood from a business perspective, which also can be a part of a purchase contract.

When there is enough inventory, the supplier can confirm the MSB order and provide a delivery plan with a planned arrival date and other essential information including related staff account information. The rpa_deliver can automatically create a CSV document and send it back to the contractor. This situation is common in practice when a series of MSBs belong to one purchase contract. However, when the MSB is an ETO or MTO-type material or equipment, the production process is required, and the rpa_warning action will calculate if there will be any potential production delay according to real-time data.

After the supplier delivers the MSB, the rpa_track action can update the transportation location automatically, integrating GPS data, while the rpa_warning action will also calculate if there will be any potential transportation delay.

When the MSB arrives, the rpa_inbound action will automatically generate an inbound receipt according to previous WSB data and related staff account information to better assign responsibility. When the MSB is taken for use, the rpa_outbound action will automatically generate an outbound record and assign as-built information, such as construction zone, material requisitioner and outbound clerk.

All manual operations can be performed using mobile devices, except MSB planning and production planning, which are usually integrated into existing PC systems.

The overall workflow is deployed on the blockchain network, and all tasks and gateway decisions will be recorded into transactions to ensure traceability. The automation mechanism of blockchain-enabled smart contracts has been introduced in our previous study [9]. Meanwhile, the status of internal task RPA actions can also be recorded and ensured via the blockchain network.

4 Implementation

This study applied the initially developed system to a project in Nanjing South New Town in China, one of the smart construction pilot projects in Nanjing city, covering commercial, office and residential areas, to test the proposed blockchain-enabled smart contracts and RPA integrated method.

The demo system of the blockchain-enabled smart contracts for precast components supply coordination is shown in Figure 6.

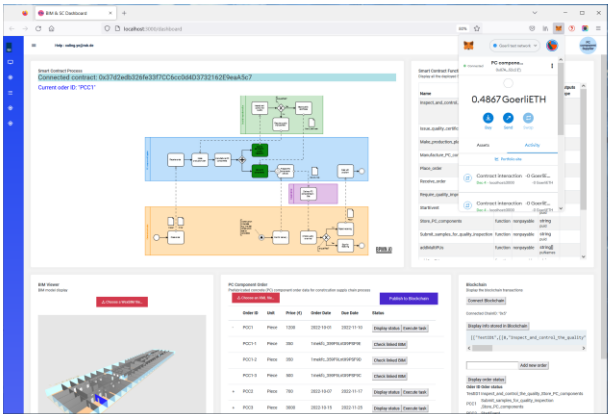

Figure 6. The demo system of the precast components supply coordination

Based on the further requirements from the project managers and communication with suppliers, the first version of the MCSC system has integrated the MSB concept and RPA actions. In this project, the MCSC coordination is not only about the precast components but also includes the prefabricated decoration components, for example, wood flooring materials and decorative wall aluminum plates. An example of the user interface of this system translated into English is shown in Figure 7.

Figure 7. Example interface of MCSC coordination system in case project

In this case, an example of MSB is "Building B Zone A 3rd floor slab", of which quantity amount is 200 m^2, and the required arrival date is 2024-09-01. This MSB was assigned to the process model and triggered by predefined conditions and manual decision input in the process model, which was displayed using the BPMN standard in the interface, while on the backend, it was deployed on the blockchain in the form of smart contracts.

In this project, the B/S system was mainly applied for the main contractor to plan, generate, and track the MSBs. The planning of MSBs is the most difficult step since it guides all the following data collection, tracking and warning. Therefore, in this project, the MSBs were defined and planned by a small group of one project manager, one construction manager, and one researcher. The supplier only used mobile devices to receive MSB orders and deliver MSB products. All the logistics processes utilized GPS devices for tracking, and the inbound and outbound processes used QR codes, which are attached to each MSB and scanned by the on-site staff and construction workers' phones.

The tools and system provided solutions to issues such as on- and off-site process fragmentation, information silos, data redundancy, untimely logistics tracking and untraceable.

During this project execution, several issues arise, such as a lack of understanding of new technologies, especially among material suppliers with low levels of information technology adoption. Distinguished by the abstract, on-chain coding mechanisms, smart contracts differ fundamentally from more visually intuitive technologies like BIM or Virtual Reality (VR). This often requires significant effort and time for communication and system adjustments. This is one of the key reasons for choosing mobile devices on the supplier side. Most experienced project managers have no problems with the B/S system and can easily deal with BIM elements. Meanwhile, most MCSC participants are not familiar with BPMN tools, and sometimes, additional UI design is required to simplify the process models for better coordination.

5 Conclusion

Given the practical issues of the modular construction supply chain and industrial requirements, this study proposed a blockchain-enabled smart contract and RPA-integrated method to improve process coordination. Three key steps are elaborated: 1) modeling processes driven by demand and converting them into smart contracts with RPA actions; 2) configuring the MCSC coordination unit from a managerial viewpoint; and 3) deploying blockchain-enabled smart contracts and automating MCSC processes. A real-world project validation provided positive results from both technical and managerial perspectives.

Further work can be improved in several aspects. First, the process models and RPA actions can be decomposed into process pattern base and RPA action base for more flexible assembly for various scenarios. Second, the deployment and execution of the smart contract can be optimized by adopting advanced blockchain or other encrypted database technology. Third, practical training and tool usability are essential for better MCSC coordination practices, and the design of systems based on unrealistic assumptions should be avoided. Additionally, the integration of RPA and AI will be a promising research topic in future MCSC coordination.

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