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A BIM-LEAN APPROACH TO IMPLEMENT LEAN PRINCIPLES IN OFFSITE CONSTRUCTION PROJECTS: A CABLE-STAYED BRIDGE CASE STUDY

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ABSTRACT

Recently, the attention to offsite construction (OSC) has grown due to its potential for waste minimization, higher quality, and speedy construction. However, OSC projects are sometimes adopted at a slow pace due to inefficient workflow. Further, OSC adoption requires a high level of information sharing to integrate the manufacturing of components, onsite assembly, and logistics processes. Previous research on the integration of Lean principles with advanced technologies, i.e., BIM and blockchain, in OSC was limited to improving the onsite operations only. To this end, this research aims to bridge this gap by providing a BIM-blockchain system to apply lean principles in enhancing the workflow of the OSC projects considering offsite, onsite, and logistics operations. Lean principles, namely Kaizen, Heijunka, Just-in-Time, One-piece flow, and Poke a yoke, form the focus of this study. Further, the study presents a secure information-sharing system based on blockchain technology to update the status of the process, i.e., pulling material from the inventory. A case study is introduced to validate the developed system. The proposed system is expected to improve the efficiency of the OSC operations and enhance the integration of stakeholders.

KEYWORDS

Lean Construction, Offsite construction, BIM, Smart contract, Blockchain.

INTRODUCTION

Cable bridges are some of the most complex infrastructure projects that require careful planning, design, and construction (Souza et al. 2022). These bridges typically have long spans, high loads, and complex geometries, making them challenging to build. Additionally, these

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bridges are usually constructed using offsite construction techniques, as they include several prefabricated components and volumetric modules (Yu & Chen 2020). Furthermore, cable bridges often must be constructed over water bodies, deep gorges, or other challenging terrains, which adds another layer of complexity to the project. As a result, cable bridge construction projects can be expensive, time-consuming, and prone to errors (Kim et al. 2011).

To solve this problem, a plausible solution would be adopting lean construction in the cable bridge projects. Lean construction has proven to be an effective methodology for reducing waste, improving productivity, and enhancing quality in construction projects. By adopting a lean approach, project teams can streamline their processes, eliminate non-value-added activities, and focus on delivering value to the customer (Bajjou et al. 2017). Similarly, advanced technologies such as Building Information Modeling (BIM), blockchain, and extended reality technologies can also be utilized to optimize cable bridge construction. For example, Using BIM enables project teams to simulate different scenarios, collaborate efficiently, and reduce rework. Extended reality technologies provide comprehensive visualization and a better understanding of the process, leading to improved project outcomes (Goh et al. 2014). Moreover, Although several scholars have recently proposed integrating lean principles and advanced technologies to solve complex project implementations, such as offsite construction projects (Hadi et al., 2023), this approach has yet to be fully explored in the literature. To this end, this study aims to improve the implementation of cable-stayed bridges by answering the following two research questions (RQs): RQ 1: What are the current drawbacks of bridge construction supply chain, and the role of lean principles in addressing them? RQ 2: How can lean principles be implemented in bridge construction using BIM and blockchain technologies?

Hence, the study objectives can be summarized as follows: 1) Discover the difficulties in the bridge construction supply chain, the role of lean principles in addressing them, and how advanced technologies can promote the use of lean principles; 2) Analyze the current state of cable-stayed bridge construction and identify the possible drawbacks using value stream mapping method; 3) Provide improvements to the discovered drawbacks and implement these improvements with the aid of BIM and blockchain technologies.

LITERATURE REVIEW

BIM AND LEAN CONSTRUCTION

There are challenges in implementing offsite construction (OSC) due to issues with design errors and level of completeness (Hussein et al, 2021). Site restrictions must be carefully considered during the design to limit redesign and other negative outcomes, including loss of productivity and a decrease in quality and onsite safety (Jung and Yu, 2022). To address the aforementioned problem, previous researchers have adopted BIM technology in offsite construction projects. For example, Park et al (2009) concluded that the use of 3D CAD (computer-aided drafting) in cable-stayed bridge construction greatly improved the constructability of the bridge. Nevertheless, BIM research for offsite construction has mainly focused on methods and tools on the practical level but not the organizational level (Santos et al., 2017). Al Hattab and Hamzeh (2018) pointed out that even though BIM is being utilized in many companies as a tool, it is mainly used to supplement traditional management strategies and achieve short-term goals, while comprehensive and detailed implementation procedures and guidance tend to be missing.

To systematically use BIM technology and make organizational-level improvements, it is suggested that the combination of BIM and lean construction can be a plausible solution (Rafael et al., 2010). Howell (1999) describes Lean Construction as “the application of a new form of production management to construction” in reference to the Toyota Production System developed by Taiichi Ohno beginning in the 1950s (Liker, 2021). Some key lean ideas have shown their efficiency in construction include (Hei et al., 2024; Kifokeris & Tezel, n.d.; Zeng et al., 2023): Value Stream Mapping (VSM), which assists practitioners in identifying the point of deficiencies in the process; Kanban, which is a visual scheduling system used to manage and control the material and task flows in a production system; Just-in-Time, which is an inventory control strategy aimed at producing goods or delivering services only as they are needed; Heijunka, which is a method used to reduce unevenness in production and minimizing overburden for different stations; One-Piece flow, which is a production method where items are processed one at a time without batches, and Poke a yoke, which refers to techniques implemented to prevent defects from occurring during the production process.

The combination of BIM and lean construction in offsite construction has also been reported in several studies. Moghadam (2014) proposed a systematic approach to offsite manufacturing management by integrating lean principles, BIM, and simulation. The proposed approach can identify the current building practice challenges and propose improvements through simulation. Gbadamosi et al. (2019) developed a design assessment and optimization system for offsite construction building assembly by combining lean construction and BIM technologies. The framework enhanced the constructability of offsite construction projects and can reduce the inefficiencies in resource use.

BLOCK CHAIN AND SMART CONTRACT

Even though the combination of BIM and lean shows a promising research trend in optimizing offsite construction processes, there are still major challenges that need to be addressed in cable-stayed bridge construction projects. Barkokebas et al. (2021) pointed out that digital strategies (like BIM) in offsite construction have not been fully implemented and have even been misused. For example, previous research was mainly focused on using lean and BIM to improve on-site operations only. To this end, a few studies tried to consider off-site operations in bridge construction projects. For example, Celik, Petri, & Rezgui, (2023) invesigated the collaboration between BIM and blockchain throughout life cycles and supply chains. They aimed to enhance the streamlined processes and improve resource traceability in projects. Elghaish et al., (2023) initiated the research effort to focus on addressing the disconnection nature of blockchain and smart contracts adoption across construction procedures. Celik et al., (2023) proposed a Blockchain-based BIM data provenance model to support information exchange in a real-world bridge construction project, where blockchain has been used to record metadata of BIM objects. These proposed approaches provide stakeholders with the availability of upstream information and enable construction practitioners to share their building components' information.

The theoretical implications of integrating lean construction and blockchain have been studied recently by scholars. For instance, Kifokeris et al., (2023) have shown the positive impact of integrating lean with blockchain and smart contracts in facilitating lean construction through building mutual trust and recording all of the data. Similar results were also discovered by Hadi et al., (2023). However, the need to implement these theoretical benefits still persists. Hence, this paper presents a BIM-Lean-supported smart contract system to comprehensively enhance the workflow of OSC projects and foster lean implementation in cable-stayed bridge construction projects by considering both offsite, onsite, and logistics operations.

RESEARCH METHOD

This section illustrates the research method that is adopted in this study. Figure 1 shows the proposed system and the overall methodological approach. Four main parts are included in this study: Literature review, process understanding and analysis, process improvement, and process implementation and validation. The literature review, as discussed in the previous section, seeks to demonstrate the association between lean construction and new technologies, i.e., building information modeling (BIM) and blockchain. In the second part, the main activities and processes in cable-stayed bridges are identified through reviewing past studies. Moreover, discovering the deficiencies and drawbacks is performed using the VSM. In order to do so, all the resources and stations (manufacturing stations) are identified. This information is used to develop the current state VSM. The current state of VSM assists practitioners in identifying the points of deficiencies in the process. These deficiencies can include the following: 1) waiting time for each process and 2) work-in-progress (WIP) items that can disrupt the workflow and create variations among stations.

To improve the process, the deficiencies identified in the previous part are studied, and ideas for improvements are proposed. To come up with improvement ideas, the authors of the current study carried out brainstorming sessions. After evaluating these improvements, they are visualized with the future state map of the VSM. A simulation model is developed to quantify the improvements achieved in the future state map. It is worth mentioning that this simulation model is detailed in another study carried out by Assaf et al., (2023). However, this study mainly focuses on the digital system that integrates lean construction with BIM and smart contracts.

In the process of implementation and validation of this study, the proposed improvements are implemented in virtual environments (BIM models). In this section, a 3D BIM model is developed to visualize the discussed improvements. This is also followed by developing a 4D BIM model to simulate the implementation of the bridge after employing the improvements. The study also goes beyond static visualization to actual digital implementation. The developed BIM models are then integrated with blockchain and smart contract technologies to serve as a digital system that keeps up-to-date tracking data and visualizes lean concepts, such as Kanban and just-in-time. The digital system will allow the user to submit a request for products (modules) when their inventory is low, without relying on fixed schedules.

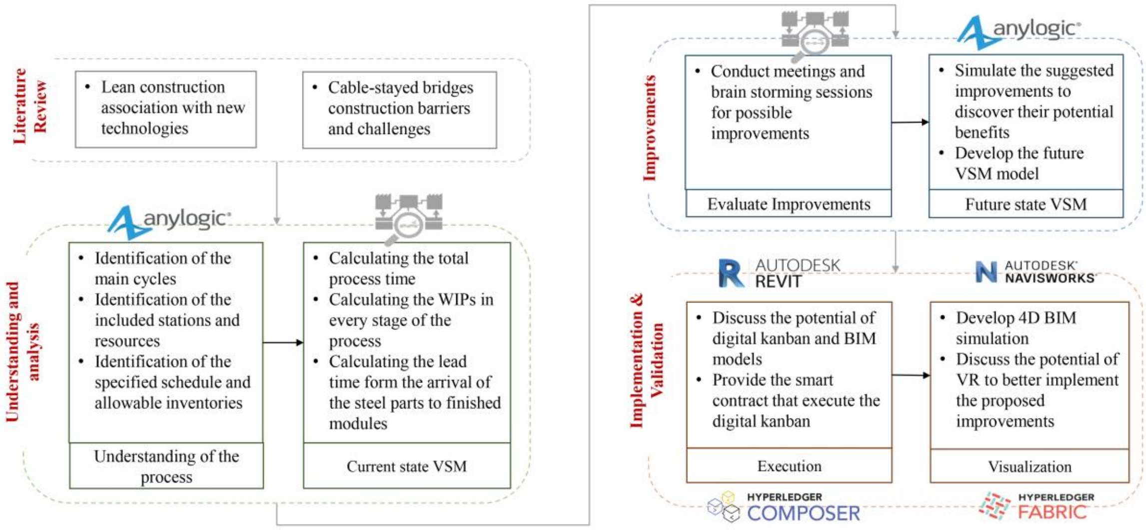

Figure 1: The proposed system in the current study

RESULTS AND IMPLEMENTATION

The proposed system is validated through a case study. The case study represents the construction of a cable-stayed bridge that was presented by Yu & Chen (2020). The bridge comprises both onsite and offsite construction techniques. The onsite technique includes the following tasks: footings construction works, columns construction works, pylons construction, tie beams construction, cables (strands) installation, and concrete works of the stitches (joints). In addition, the bridge also comprises a wide range of offsite processes, including the following:

1) the fabrication of the main and cross girders; 2) the assembly of steel modules on the yard; 3) the fabrication of precast slabs to be placed on top of the steel modules.

CURRENT STATE MAPPING

The production process of the cable-stayed bridge is hampered by several deficiencies. Hence, the lean transformation practice is discussed below. This paper uses VSM to reveal the value stream of the project and determine problem areas. The simulation results shed light on the inventory amount between each station. Based on the simulation, the current state mapping of this girder bridge project is drawn sequentially using VSM notation, as shown in Figure 2. By walking through the whole value mapping, the calculation shows that the actual value-added time for the current process is 34 days. However, the production lead time will be 110.7 working days. This indicates that the process efficiency ratio has just reached 31%, while 69% of the time will be wasted or non-value-adding.

The Takt time (5 days/module) has also been calculated by dividing the total operating time by the total daily customer demands. The analysis revealed that the cycle time of some workstations, such as cable tensioning, installing slabs, and reinforcing joints stations, is less than the takt time. However, the cycle time of the main girder station and build module station are higher than the takt time.

FUTURE STATE MAPPING

Future state mapping implements lean principles to reduce waste and improve flow. The ability to achieve a piece flow for this project is difficult due to the nature of the construction process. Each module must be fully installed, aligned, joined, and cured before the next module can be placed. This is due to the tight working space and connection requirements between modules. Each module connects to the previously installed module in the current state. As shown in Figure 3, using BIM, the construction manager can modify the installation process to install multiple modules at the same time to better achieve a one-piece flow. This is identified in the future state map as kaizen burst immediately below the construction manager to signify that the BIM Manager and construction manager work together with the information provided to and from the workstations to determine modules that can be installed independently of one another.

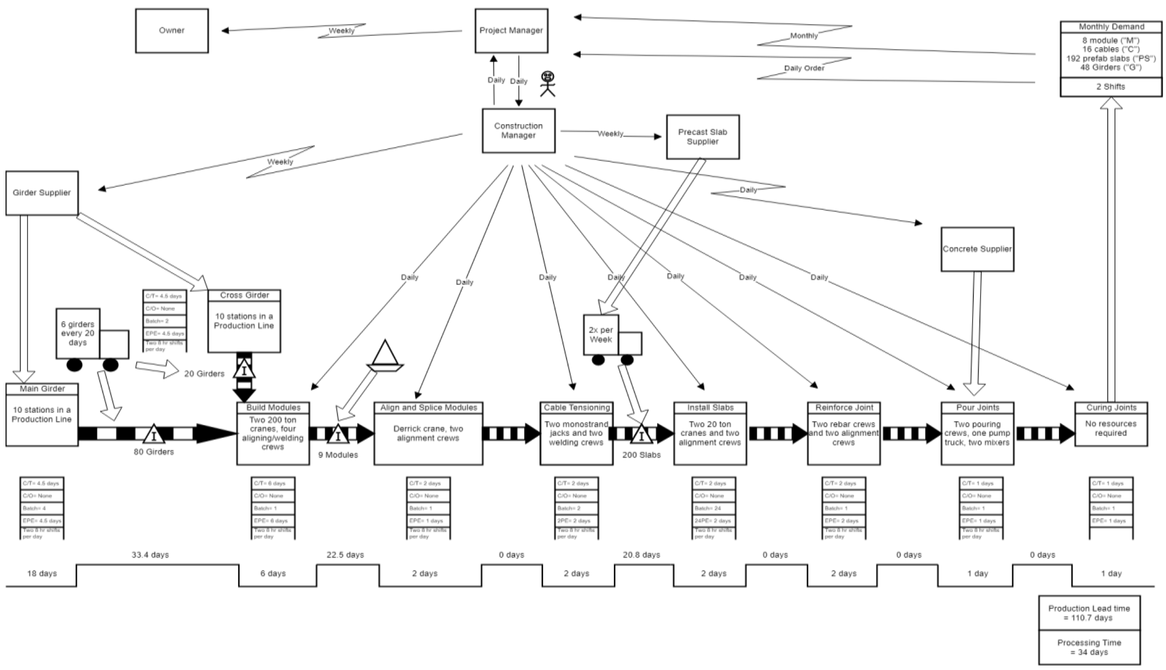

Figure 2: Current State Mapping

The inventory associated with the precast slabs can be eliminated by delivering slabs “just in time”. A safety stock of 24 slabs is provided, which is enough to complete one module, and is available in the event there are supply issues with the slab provider.

The girder supplier can build a girder every 4.5 days. Their process allows them to create a cross girder and main girder at the same time, without changeover. Since we require four main girders and two cross girders per module, the total time for girders per module is 18 days. Due to the duration of the girder construction compared to the downstream module construction (6 days), the girders were pre-ordered and are required to be stored on-site, creating waste. The future state map indicates the need to go and see the girder production to better understand and reduce the timing of the girder supply. Options include introducing a changeover for the cross-girder assembly line to also create main girders or finding an additional girder supplier.

The girder inventory is waste in that it must be managed, moved, and takes up valuable working space on site, and in the event that there is an issue with the girders, the amount of inventory accumulated will exacerbate the level of waste. The upstream girder supplier requires significant lead time, so there is a need to create a supermarket, sized appropriately, with attention given to the kanban so that the girder supplier has ample time to create the necessary girders while limiting the amount of storage required. This is identified on the future state map with the supermarket pull system. Moreover, kanban helps ensure that inventory levels are optimized and that materials are available when needed. A kanban system is developed through BIM to signal when more materials are needed for the construction process. By doing so, it is expected to minimize waste by reducing excess inventory and preventing stockouts.

The align and splice module activities and the cable tensioning must be completed at a minimum before starting a new alignment and splicing of a module. This means that the duration of the activities, starting from aligning and splicing modules to the curing, could vary between 6 and 10 days. As such, a pull process between the Align and Splice Modules activity and the Build Modules Activity was appropriate, as the beginning of the construction of a new module was dependent on the availability of the downstream processes to accept it. This is identified on the future state map as a pull process.

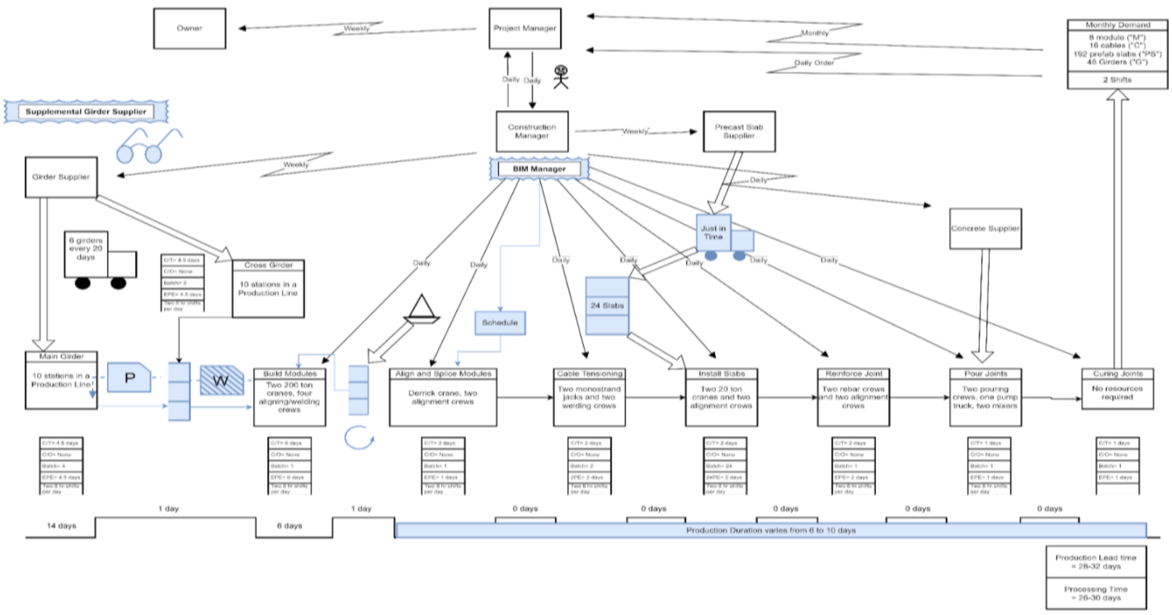

Figure 3: Future State Mapping

IMPROVEMENT IMPLEMENTATION

Knowing we can improve the process, we still lack a system that can implement these improvements. To address this, we applied a BIM-based smart contract approach to implement these improvements on a digital system that allows the user to perform the following tasks: 1) submit a request for specific elements when needed; 2) submit any document any defects at any point of the project; 3) inquiry of any past resolved issues.

BIM-Based Smart Contracts

This subsection discusses the development of the BIM-based smart contract model that helps implement lean improvements (González et al. 2022). Figure 4 shows the developed BIM model and details the included prefabricated components. The model comprises three main prefabricated components: precast slabs, manufactured steel modules, and steel girders. Every component in the model is marked with an ID that will be used in the smart contract system. The component ID specifies the component type and installation location. The processes of installing the prefabricated components, along with the onsite works, form the primary operations of this case study. The following section shows the development of a smart contract that facilitates the implementation of the discussed lean principles.

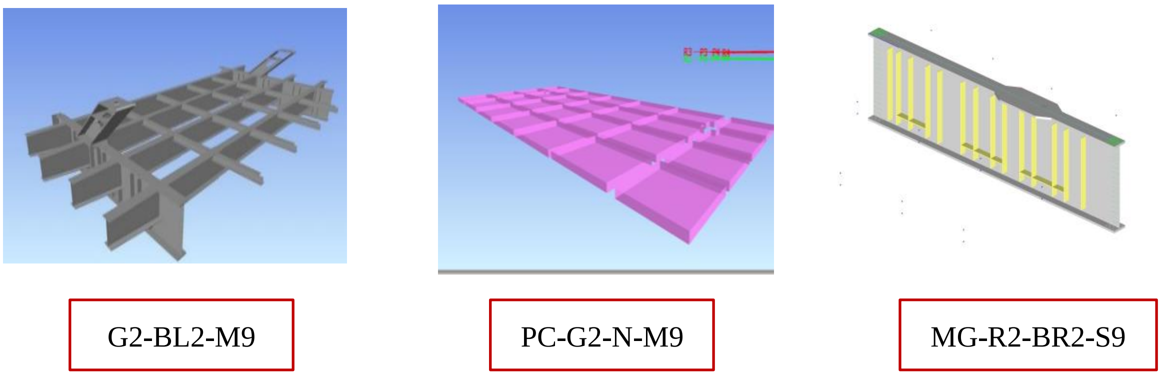

Figure 4: the developed BIM model showing the prefabricated components

Developed Smart Contract

This section shows the development of the smart contract that is associated with the BIM model. The system functions according to lean principles. These included lean principles can be summarized as follows: 1) *One-piece flow*, the developed system facilitates the operator of each station to request products when needed, without relying on a fixed schedule; 2) *Heijunka*, the system levels out the process by mitigating the inventory between stations by implementing the Just-in-time approach; 3) *Quality at bay*, the system allows the participant to submit a notification when a defect is discovered to the other operators. This notification is attached with the element ID, location, description, and deficiency degree. 4) *Poke a yoke*, any submitted quality issue and how it was solved is stored in the system transaction part.

The developed smart contract comprises many operators. Figure 5 illustrates the operators included in the network. Operator one is responsible for the fabrication of the steel girders, and Operator two is responsible for assembling these steel girders into modules. Operator three is responsible for the onsite works, and Operator four is in charge of the fabrication of precast slabs. Three main transportation routings are included in the system: transporting the steel girders from the factory to the yard by truck, shipping modules from the yard to the bridge by ships, and trucking the precast slab to the bridge deck from the offsite slab construction facility.

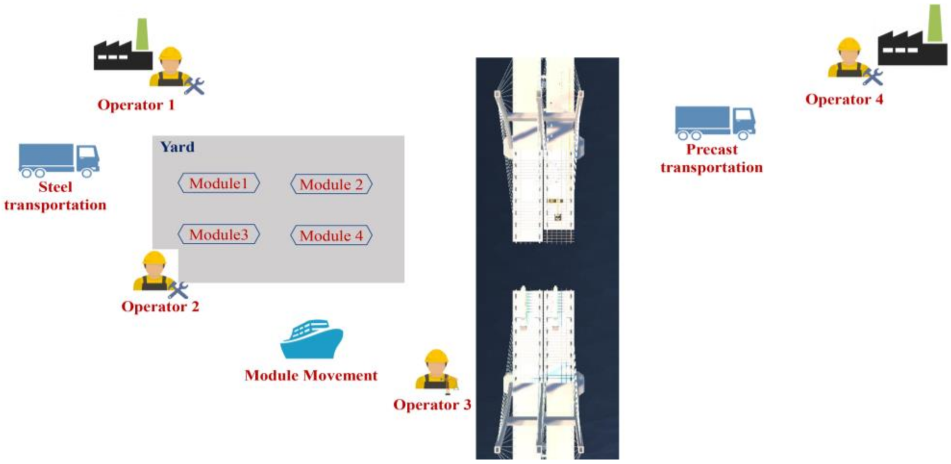

Figure 5: The included operators in the systems

The structure of the developed system uses two main systems: Hyperledger Fabric and Hyperledger Composer. The Hyperledger Fabric is an open permissioned blockchain framework that was developed by the Linux Foundation (Eltoukhy et al., 2022). The system comprised four main elements: participants, assets, transactions, and access control. Figure 6 shows these components in accordance with the proposed system. The participants in the network are all the operators identified above. The assets include the data of the inventory in each inventory. For example, in the operator1-operator2 inventory, the information of the two operators, the current available inventory, and the maximum allowable inventory are defined.

The transactions part includes the following elements: 1) submission of a request for more elements, specifying the quantity and elements IDs; 2) submission of the needed elements by the corresponding operator and update of the ledgers on the system; 3) notify any quality issue (Andon) by an operator; and 4) query of any submitted defect resolution (mistake proofing).

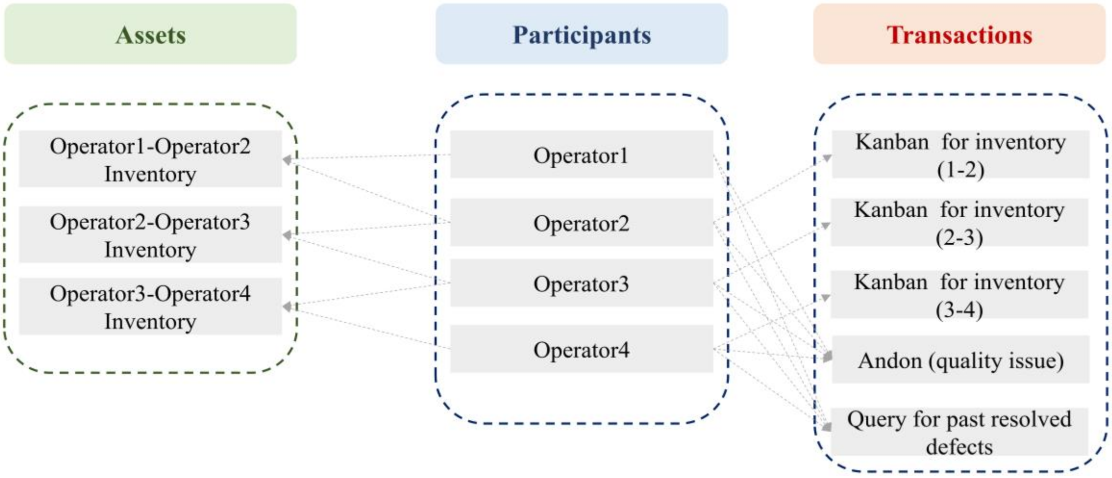

Figure 6: the components of the blockchain system

To implement the above transaction components, a smart contract was developed and deployed in the model script of the Hyperledger Composer tool. JavaScript is the language supported by the tool and was used to write the smart contract. All of the functions of the smart contract, as discussed above, are related to element ID. When participants submit a request to supply or inspect a particular element, they must specify the element ID. Figure 7 shows an ID of a steel module and what it represents.

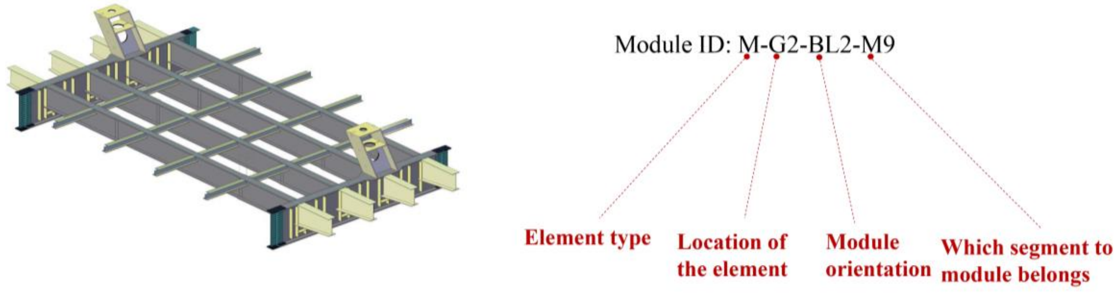

Figure 7: the representation of an element ID

Any transaction made by any participant is timestamped and saved in the transaction with a hash value that is immutable through time. This ensures the security of the network and promotes trustworthiness between participants (Assaf et al., 2022). The transactions available in the system focus on the digital kanbans to request more materials, notification of a quality issue at any time, and a request for a historical record of any issue and its solution method. Figure 8 visualizes how the transactions work in the system.

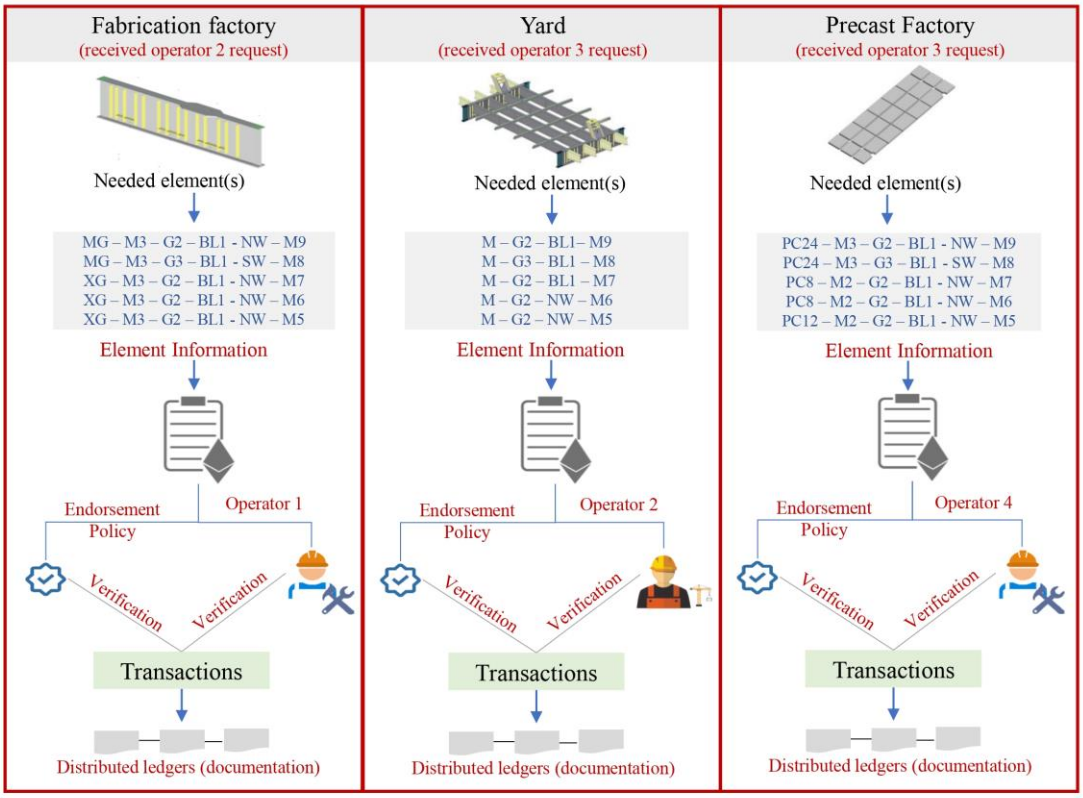

Figure 8: visualization of the functions of the smart contracts

Functionality of the Smart Contract

In this subsection, several scenarios were identified to prove the functionality of the model. First, the model is tested when a material (steel girders) is needed by Operator 2 (the yard) from Operator 1 (the steel factory). Firstly, Operator 1 logs into the system by their digital identity. This operator would have certain access to the system defined by the access control feature (ACL) of the system. Figure 9 shows the network cards that are issued to the participants and allow them to access the system. Operator 2 then selects the transactions section and submits to Operator 1 a digital kanban specifying the following: elements' IDs, quantities, and location. Operator one then receives a notification on the system of the needed items. The smart contract verifies the request first based on an endorsement policy, and then Operator 1 verifies this transaction based on the available data.

Table 1 shows the inventory assets after accepting the submitted request by operator 2 along with the submitted request. The available inventory for Operator 1 will go down by the submitted needed items, and the available inventory for the supermarket between the two stations (factory and yard) will increase by the same amount. In a scenario where the steel factory does not have enough steel girders to cover the operator 2 request, the system itself will notify the operator about the unavailability of the materials. The eligible participant can then view any of the submitted requests at any moment to keep track of the available inventory, as will be shown in the second section.

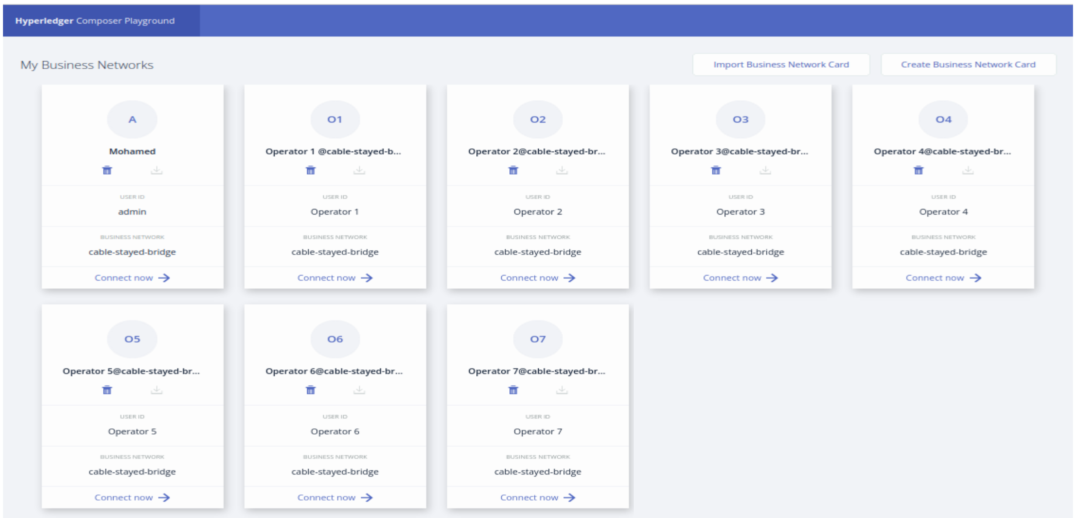

Figure 9: Network cards given to each operator

Table 1: Details of the test scenario

Step	Details
The submitted request by operator one	
The supermarket update after accepting the request	

Besides digital kanbans, the system provides operators with a *Pulling Andon* feature. In a scenario where an operator discovers a quality issue in one or more of the elements, he/she can submit an Andon on the system. The Andon specifies the following data: the element ID, the name of the station, a description of the issue, the Andon pulling time, and the degree of the quality issue (red or yellow). The transaction is visible to all operators in the system. If the issue is not resolved, the operator then submits another Andon with a red deficiency degree, and all operators in the system will stop the work. Further, all of these submitted Andon are documented in the system with its resolving strategies (Poke a yoke). Figure 10 shows a historical submission of an Andon, showing every detail of the quality issue.

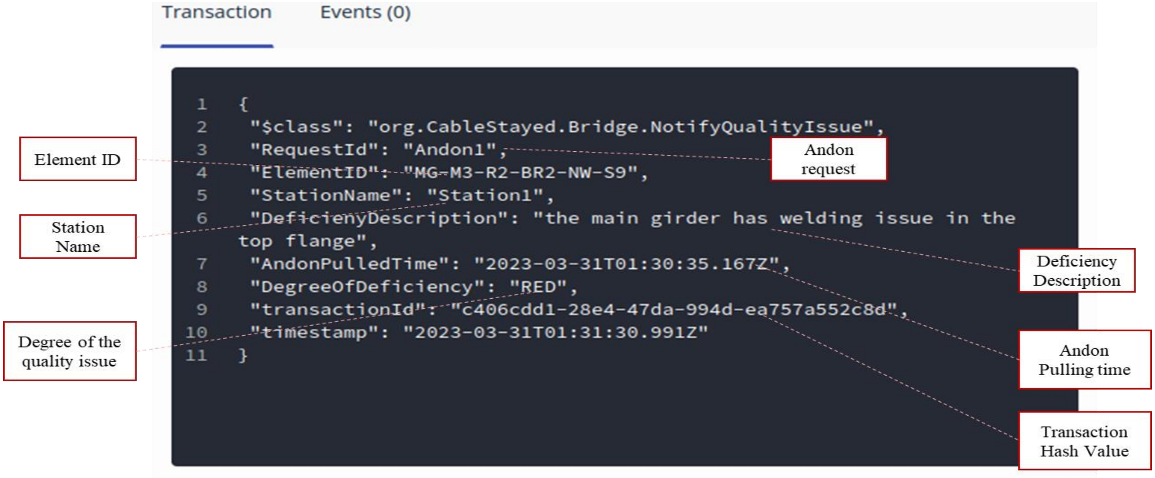

Figure 10: A historical record of a submitted Andon on the system

CONCLUSIONS

This study tackles the challenges in implementing OSC projects through the combination of advanced technologies, such as BIM, blockchain, and smart contracts, with lean principles. The study was motivated by the need to have a holistic framework that addresses the OSC challenges in onsite, offsite, and logistics operations. *Kaizen*, *Heijunka*, *Just-in-Time*, *One-piece flow*, and *Poke a yoke* are the main lean principles that were considered in this study and implemented through the mentioned technologies. Four main areas were addressed in this study. These include an extensive literature review, understanding of cable-stayed processes, providing of improvements, and implementation of the proposed improvements. The application of Value Stream Mapping (VSM) through the current state and future state mapping outlined areas of improvement that the application of BIM was able to exploit. Discrete event simulation was used to observe the impacts of providing these improvements. Further, the study provides a secure information-sharing system based on blockchain technology to fully exploit the benefits of the BIM-Lean approach. The potential incorporation of virtual reality (VR) into this process also is expected to provide an efficient training ability for the operator to be familiar with and train on lean principles.Besides the contribution provided by the current study, it also includes a number of limitations. The developed model future and current VSM do not consider the processes included in the manufacturing factories. Future research may explore the possibility of extending the scope of the presented study. Also, the smart contract system needs the participant to manually specify the element tag number. Future research may explore the full automation of the system.

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