A VALUE STREAM MAPPING APPROACH TO THE IDENTIFICATION OF LEAN MANAGEMENT OPPORTUNITIES FOR OFF-SITE CONSTRUCTION PRODUCTION: A CASE OF REINFORCED CONCRETE SLABS

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ABSTRACT: *Off-site construction (OSC), including prefabrication and Modular-integrated Construction (MiC), is gaining popularity as a school of sustainable construction methods that can improve productivity, quality, and waste reduction. However, OSC projects face challenges related to technical integration, collaboration among stakeholders, and dynamic uncertainties. As a result, high-quality standards throughout the manufacturing process of OSC products are difficult to ensure, leading to costly rework, delays, and safety issues. This paper applies a value stream mapping (VSM) approach based on lean principles to OSC production for identifying lean management opportunities for off-site construction production. The case studied in this paper is reinforced concrete slabs. First, we employed a combination of field investigations and interviews to formalize the flow of materials and information for the case. Then, VSM processed the flow for the current state map, which highlights twelve opportunities to prioritize for slab production, e.g., the adoption of digital technology (VR, BIM) in information flows. The findings in value-added activities improvement of the opportunities demonstrate the potential of lean management in the slab production case. Furthermore, the VSM approach in this paper can identify the 'wastes' in lean theory, which are the control points of OSC production, for enhancing quality, efficiency, and resource utilization. The findings contribute to the existing body of knowledge by providing empirical evidence of the VSM approach to the identification of lean management opportunities for OSC production.*

KEYWORDS: *Off-site construction, Prefabricated products, Lean management, Value stream mapping, Quality assurance, Construction industrialization, Lean construction*

1. INTRODUCTION

Off-site construction (OSC) generally involves standardizing design, manufacturing components in the factories and assembling during construction (Hosseini et al., 2018). With the upgrades of industrialization (Mitolo et al., 2021), examples of OSC are Bricks, 2D slabs, 3D volumetric, and Modular-integrated Construction (MiC). OSC is recognized as a promising school of sustainable construction methods that integrates design, production, and construction to save energy, eliminate environmental wastes and maximize the value of the whole life cycle of construction products (Li et al., 2021). In the literature, OSC is confirmed capable of improving labour productivity and product quality, enhancing energy conservation and emission reduction, thus solving prominent problems such as strengthened resource constraints and labour shortages. On the other hand, OSC also faces challenges, such as complex technical integration, collaboration of multiple stakeholders, and dynamic uncertainties (Zhao et al., 2023). Thus, OSC requires the coordination and integrated application of a wide range of multidisciplinary and inter-organizational skills.

OSC production refers to manufacturing precast construction elements in the factory, which is the most important stage for the quality assurance of products, as the construction site could be responsible for limited rework and repairs (Wu et al., 2019). Unlike traditional manufacturing factories, OSC production is a complex system involving different stakeholders and various information interactions (Khalili & Chua, 2014). Therefore, the complexity also leads to quality risks frequently occurring throughout the entire OSC products production processes, including production planning, engineering design, mould production, components manufacturing, quality inspection, storage, and loading for logistics (Lee et al., 2016). Furthermore, the connections between the stages may amplify the risks from one stage to another, e.g., deformation occurs in the moulds at the beginning of

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the production will lead to defective components, but components may meet inspection requirements in the following product stage, and such mistakes can not be identified until the inspection of the finished products (Heravi & Firoozi, 2016). Therefore, systematic quality management is vital to OSC production.

Current approaches adopted in OSC production management are limited (Lu et al., 2018). For example, in the inspection process, the inspectors conducted manual spot inspection and made subjective decisions stemming from their prior knowledge in identifying products' flaws early in the production process, which inevitably suffers from labour-intensive consumption and subjectivity of opinions rather than precisely matching the substantial conditions (Xue et al., 2018). Consequently, defects are not perceived until the later stage of logistics or even the on-site installation stage (Park et al., 2013). Defects that arise during the production stage are costly for owners, contractors, and prospective clients because they are nearly impossible to chain significantly during the assembly stage.

Lean management concepts have the potential to increase quality, efficiency, and resource utilization for OSC production (Sacks et al., 2010). In lean principles, value is created by a sequence of value-adding activities. A value stream is the sequence of activities by which a company provides a product or service that delivers a specific product or service to a specific customer (Koskela, 1993). Value Stream Mapping (VSM) is an approach for illustrating the flow of materials and information in a lean manufacturing system (Ko & Kuo, 2015). It utilizes the tools and techniques of lean manufacturing to help organizations identify where waste is and, in turn, streamline the flow of production. The purpose of value stream mapping is to identify and reduce waste in the production process (Rahani & Al-Ashraf, 2012). Waste in this context is defined as any activity that does not provide added value to the end product and is often used to illustrate the total amount of waste reduced in the production process. Managers, engineers, process planners, suppliers, workers in the manufacturing industry, and customers can all benefit from value stream mapping by identifying waste and determining where to start looking for its main causes. In this way, value process mapping can also be a communication tool in linking with stakeholders of the factories (Chen et al., 2008). In general, the adoption of VSM based on lean concepts can enable the effective utilization of resources, e.g., in the automotive industry, supply chain analysis, and manufacturing industries (Rahani & Al-Ashraf, 2012).

This paper aims to apply the VSM approach based on the identification of lean management opportunities in OSC production. The objectives of the paper are: 1) To map the OSC production process; 2) To apply VSM to the map for locating the 'wastes' in the existing process; 3) To identify corresponding management opportunities for OSC production.

2. LEAN PRINCIPLES AND VALUE STREAM MAPPING

Lean manufacturing principles have been used for a long time in the manufacturing sector to boost output, productivity, remove waste, and deliver value (Sacks et al., 2020). The term "lean principle" describes the ongoing process of raising the value of a product by removing waste without sacrificing output, productivity, or quality (Koskela, 1993). Reducing non-value-added activities and achieving value-added delivery in the construction domains are the major areas of concentration for OSC. To address resource difficulties, lean principles' practices pledge to offer solutions that are lasting. Once the lean techniques were applied to the project scenarios, it became clear that significant amounts of materials were saved.

VSM is the whole of the actions—both value-added and non-value-added—currently required to move a product through the primary flows that are fundamental to every product. It is the production flow, from the raw material to the end customer, as well as the design flow, from conception to realization (Grewal, 2008). Firstly, it is a tool to identify waste and problems. It reviews operations and processes from a macro perspective, from the input-output process, and allows managers to easily identify sources of waste (excess inventory, heavy work, time wastage, handling, inspection, etc.), thus providing a scientific basis for continuous, systematic improvement. Secondly, it provides a common language. Value streams can be used as a common language for process and process improvement, making it easy to communicate between different departments. It is a method of determining and differentiating priorities for improvement, avoiding "picking the easy ones" for improvement and maximizing the return on investment. The VSM is the basis for the preparation of improvement plans and their implementation.

The integration of lean principles and OSC has been beneficial in optimizing its production processes and has recognized great potential in effectively tackling resource waste and unsatisfactory quality. As a result, numerous researchers have used VSM in conjunction with lean concepts to increase productivity and efficiency in the OSC manufacturing process as well as other areas. According to Wu and Pheng (2011), value stream mapping of precast manufacturing is essential to achieving sustainability goals. In the case of Yu et al. (2009), by applying the value streaming on a consistent work/product flow rather than on individual tasks, the delay brought on by a conflict between the predetermined schedule and the actual schedule of the complicated process of building a house can be decreased. To identify waste during the construction of concrete slabs in residential constructions, Fontanini et al. (2013) employed value spectrum mapping with lean concepts, increasing efficiency and effectiveness. However, lean principles have their roots in the manufacturing sector, where they have a mature theoretical and research base (Grewal, 2008). There is a lack of an organized framework that can be used to promote the implementation of lean manufacturing principles in the production of OSC products.

In summary, VSM indicates the key operating procedures that adds value to the targeted product. Instead of depending solely on the currently established conventional working hours, the use of VSM is combined with field study, information gathering, and interviews, capturing the flow of material and information. Cycle times, line change times, operator counts, size of batches, and quantities of semi-finished products in a process are a few of the forms of data that are capable of being exploited to analyse the lead time and added value time of the entire process. So, in addition to the VSM approach, both field research and interviews are employed in this paper.

3. RESEARCH METHODS

3.1 Case selection

The case selected in this paper is the reinforced concrete (RC) slab in the prefabricated construction. The selection was based on the product family matrix defined in the VSM approach (Fontanini et al., 2013). Usually, RC slab production accounts for >80% in both prefabricated construction and RC MiC (Loss et al., 2016), which fulfil the requirements of the product family matrix. The case factory is in Shenzhen, which has major products including various types of precast elements such as facades, partition walls, floor slabs, staircases, columns, integrated kitchens and washrooms. The involved projects include residential, commercial buildings, roads, and tunnels.

3.2 Production process mapping

The scope of activities includes added-value activities at each level, from the raw materials to the finished products, which includes conceptual design, product design, and process designs (Sacks et al., 2020). In OSC production, it is the in-factory value stream, i.e., the manufacturing stream from design to ready-to-transport stage.

In the site investigation, observations were made regarding the plant layout, the machinery used, the sequence of activities and the time taken for each activity by visiting the site and also interacting with the staff working there. The typical activities are (A) mould assembly and preparation, (B) fixing of rebars, (C) concreting and curing, (D) de-moulding and (E) transferring for storage.

Mould assembly and preparation. Casting begins with the assembling of the mould. The front-work used to pour and cast concrete is called a mould. Using overhead cranes, the mould plates are removed from the inventory area and set down on the fixed table. Using bolt and weld connections, mould assembly and preparation entails assembling the mould plates. Based on the shop drawings that the design team produced, the assembly is carried out. The timeline of the activities taking place at the mould assembly is shown in Fig.1.

Fixing of rebars. The rebars are then fixed into the mould as the following step. Cutting, bending, and forming the reinforced cage in accordance with shop drawings are all steps in the fabrication of the rebar cage. A separate reinforcing cage is created, and then it is added to the mould. The Fig. 2 is the order of activities that take place as the rebar cage is transferred to the mould.

Concreting and curing. Concreting is the following step. Before the concreting process begins, the raw materials are fed into the mixer. Both the mixing and transporting of concrete are automated and simple to use. The system of the flying bucket is employed. The Fig. 3 is a listing of activities that take place during concreting and curing.

Demoulding and transferring to storage yard. Demoulding is followed by moving the precast concrete component with a crane to the storage location. At the storage location, curing is carried out using a sprinkler system that operates for three days. The storage location keeps the finished components for further transportation. Before delivering the components to the construction site for assembly, it is important to (i) inspect the physical state of the final product, (ii) verify the important parameters, (iii)apply the proper identification markings to the elements that indicate position, individual category, weight, size, and placement in accordance with the shop drawing, and (iv) check whether the components have reached 75% of their design strength in concrete.

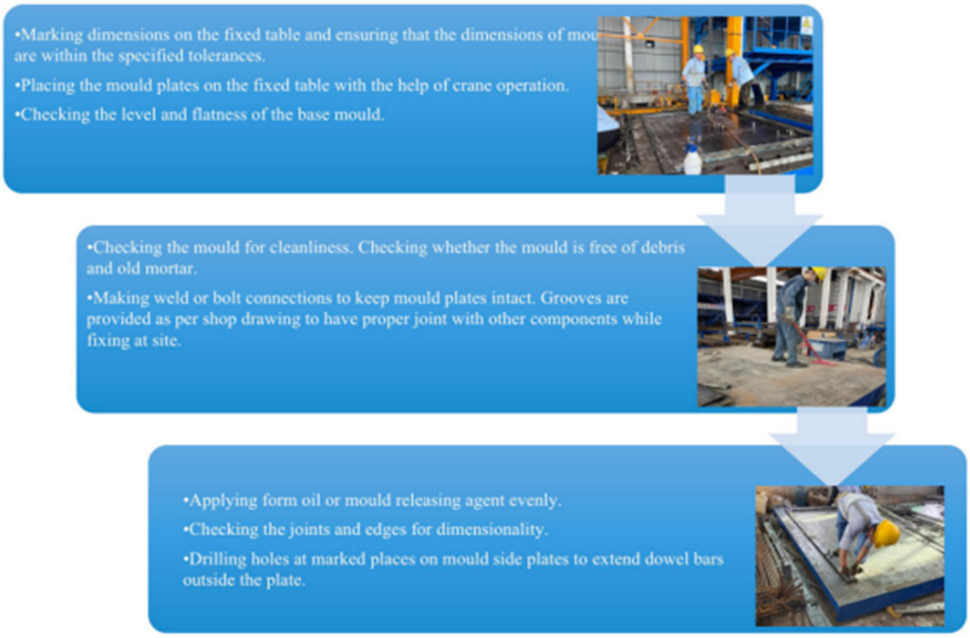

Fig. 1: Mould assembly and preparation of a prefabricated RC slab.

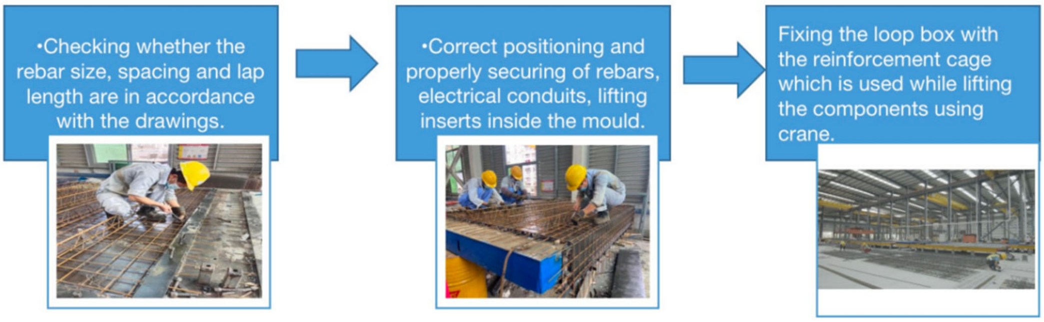

Fig. 2: Fixing of rebars of a prefabricated RC slab.

Fig. 3: Concreting and curing of a prefabricated RC slab.

3.3 Non-value-added activities located using VSM

This step aims to apply VSM to locate the non-value-added activities. Non-value-added activities, referred to as waste, are activities that do not directly contribute to the product's value or the customer's perception of value. These activities consume resources (time, materials, labour) but do not enhance the product or service in any meaningful way. As a result, by identifying the non-value-added activities and location of waste, the potential improvement could be a promising action. The categories and identification of non-value-added activities are listed below (table 1).

Table 1: Categories and identification of non-value-added activities.

Categories of non-value-added activities	Identification
Transportation	Unnecessary movement or transportation of materials or products between different process steps, leading to delays, damage, and increased lead times.
Inventory	Excess inventory or work in progress that is waiting to be processed, increasing capital and space without providing immediate value.
Waiting	Idle time for products, materials, or employees waiting for the next step in the process, reducing efficiency
Over-production	Producing more than what is currently needed, which leads to excess inventory and waste.
Over-processing	Performing more work than necessary, such as using high-precision processes for tasks that don't require it.
Defects	Activities required to fix mistakes, rework, or correct defects, increasing costs and schedule delays.

3.4 Identification of corresponding management opportunities

The goal of this step is to adopt VSM analysis to identify opportunities for improvement. The identifying process is based on two basic processes: the information flow and the material flow. The information flow is the process that starts when the marketing department receives an order or has already forecasted the customer's needs and makes it into a purchasing plan and a production plan. The material flow refers to the physical process, i.e., the process that starts with the supply of raw materials into the warehouse from the supplier, followed by the outbound manufacturing, the finished products into the warehouse, until the product reaches the customer. In addition, the material flow includes the inspection and storage of products. Furthermore, there are eight waste principles on which judgement is based, including waste of repair, waste of over-processing, waste of movement, waste of handling, waste of inventory, waste of making too many/too early actions, waste of waiting and waste of management. Therefore, in the analysis of this paper, any part of a product that exceeds the minimum amount of resources necessary to add value to the product is considered waste – a waste is not only an activity by definition that does not add value but also a process that overuses resources.

4. RESULTS

Fig. 4 shows the results of process mapping, the adoption of the VSM analysis for locating wastes in the current process map, and the current state map with information flow, material flow and lead time ladder. The information flow depicts the communication between the management team, the production team, the supplier, and the client. The material flow displays the movement of materials through different steps from supplier to finished product. Cycle time denotes the duration of each step, whereas lead time indicates the length of time it takes to produce precast components from an order to their completion. While cycle time solely includes time for value-added activities, lead time contains time for both value-added and non-value-added activities. The sequence of activities is named from A to E. Evidences of the current waste locating. 1) Waiting. A curing period of 12 hours is required when employing the water pond method, thereby extending the waiting duration for subsequent procedures. 2) Defects. Damage to mold plates occurred when the welded connection was disrupted during the demolding process. 3) Overprocessing. Remediation of damaged finished components was carried out through epoxy injection, thereby elongating the lead time. 4) Motion. The Reinforcement cage production area is situated 200 meters away from the molding table, resulting in an increased travel time for the crane during the transfer to the table platform. 5) Transport. The storage area for mold assembly parts is situated at a distance of 400 meters, leading to an extended travel time for the EOT crane during the transfer to the table platform.

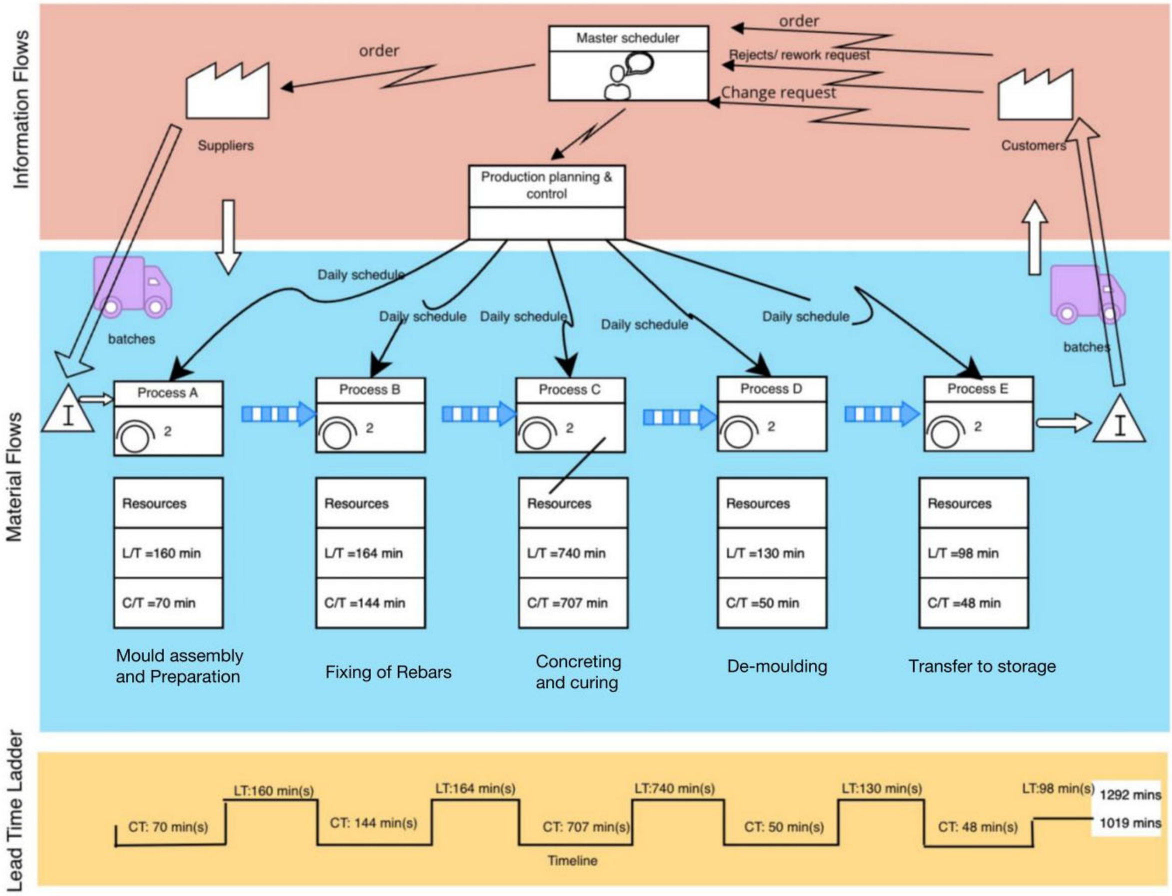

Fig. 4: VSM of the RC slab production. (Note: Process A- Mould assembly and Preparation, Process B- Fixing of Rebars, Process C- Concreting and curing, Process D- De-moulding and Process E- Transfer to storage)

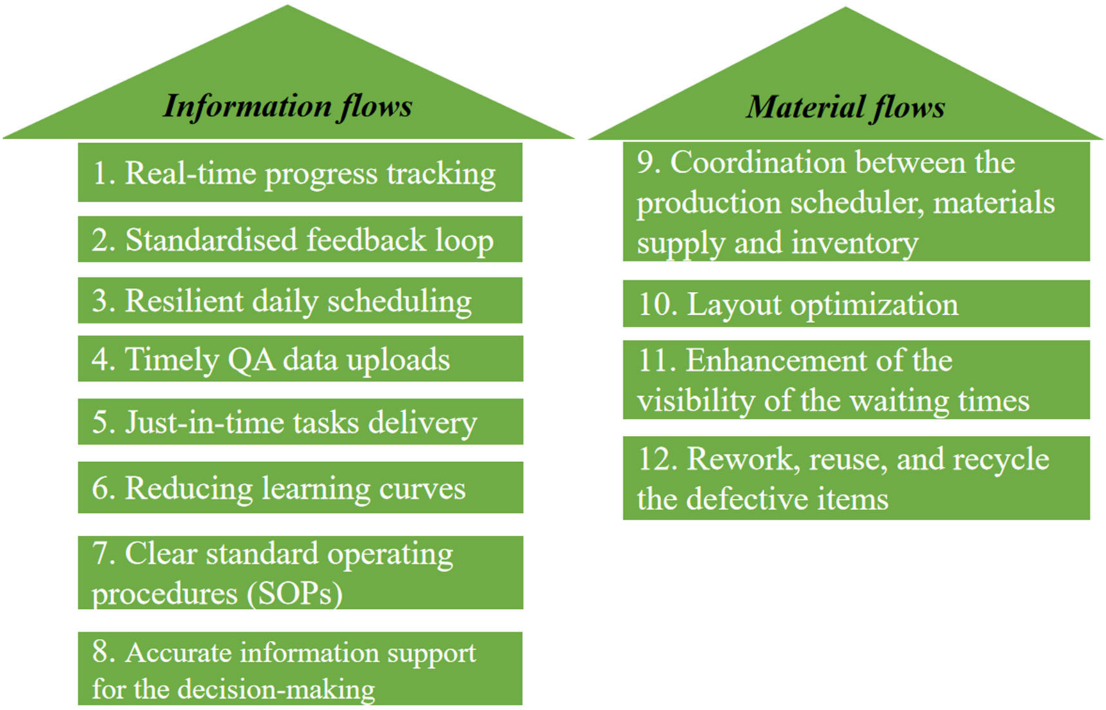

Fig. 5: 12 opportunities for potential improvement

Twelve opportunities are highlighted, as shown in Fig. 5, in information flows and material flows based on the VSM of the RC slab production. In the information flows, eight opportunities are concluded. **Opportunity 1**: real-time progress tracking, such as the adoption of Virtual Reality (VR) (Rahimian & Ibrahim, 2011) and Building Information Modeling (BIM) (Xue et al., 2021), enables the off-site production team to monitor every step of the production process as it happens. This visibility facilitates quick identification of bottlenecks, inefficiencies, or delays. With the assistance of a real-time view of progress, the stakeholders can take proactive measures to optimize workflow, allocate resources more effectively, and prevent unnecessary downtime. **Opportunity 2**: implementing a standardized feedback loop creates a systematic process for collecting insights and suggestions from various stakeholders involved in the factory. The information loop contributes to continuous improvement, as the feedback is used to identify areas for refinement and innovation. By incorporating valuable input from workers, the production process becomes more streamlined, and waste is reduced through collaborative problem-solving and optimized processes. **Opportunity 3**: a resilient daily scheduling approach acknowledges the dynamic nature of off-site construction and prepares for potential disruptions. By building flexibility into the schedule, the stakeholders can better adapt to unexpected changes without causing significant interruptions. **Opportunity 4**: timely quality assurance data uploads play a crucial role in maintaining high-quality production standards. By promptly uploading quality assurance data, any deviations or defects are identified early in the process, allowing for timely corrective actions. This reduces rework, minimizes waste associated with defects, and ensures that the final product meets or exceeds quality expectations. **Opportunity 5**: adopting a just-in-time task delivery approach optimizes the timing of task completion to match actual production needs, preventing the accumulation of excess inventory or work in progress. **Opportunity 6**: emphasizing the reduction of learning curves through proper training and skill development enhances the expertise and efficiency of the production workforce. Skilled workers are less likely to make errors or require additional time to complete tasks. **Opportunity 7**: establishing clear and well-documented standard operating procedures (SOPs) provides a structured framework for the entire off-site production team to follow. These SOPs guide consistent and standardized practices, reducing variations that can lead to errors or inefficiencies. Clarity in procedures minimizes waste associated with defects, misunderstandings, and unnecessary deviations from the optimal workflow. **Opportunity 8**: access to accurate and timely information forms the foundation of effective decision-making in off-site production execution. The reliable data leads to quicker and more confident decisions, aligning with lean principles by reducing delays and uncertainties that can lead to waste.

Four opportunities are summarized in the material flows. **Opportunity 9**: effective coordination between the production scheduler, materials supply, and inventory management is vital for lean management in off-site construction. By synchronizing production schedules with the availability of materials and maintaining an optimized inventory level, the production process could embrace increased efficiency. **Opportunity 10**: optimizing the layout of the factory is a strategic improvement opportunity that can significantly enhance lean management. By arranging workstations, storage areas, and production lines logically and efficiently, material flow is streamlined. This optimization reduces unnecessary movement, transportation, and waiting times, leading to improved overall efficiency and resource utilization. A well-organized layout also supports just-in-time delivery and minimizes the chances of defects or errors. **Opportunity 11**: increasing the visibility of waiting times is crucial for waste reduction and process improvement. By close monitoring and making waiting times transparent to all stakeholders, bottlenecks and delays are quickly identified. This visibility prompts immediate action to address issues, prevent idle time, and maintain a consistent production flow. **Opportunity 12**: the practice of reworking, reusing, and recycling defective items is a sustainable and lean-approach. Efforts are made to salvage and repurpose them where possible, leading production management to the more resource-efficient and environmentally responsible.

5. DISCUSSION AND CONCLUSION

The OSC production is that the dynamic nature of the production requires a rapid response. However, OSC production, unlike a generic manufacturing facility, has long order lead times, relies on several tiers of subcontractors and casual labours, and requires close coordination. This paper maps OSC production processes in the factory and applies the VSM approach from lean manufacturing to lean OSC management opportunities. The findings from the RC slab case demonstrate the identification of the existing wastes, non-value-adding activities, and potential lean management opportunities. Examples of the opportunities include eight opportunities in information flows and 4 opportunities in material flows.

The contribution of this paper mainly lies in advancing lean management practices in the field of off-site construction. By offering practical, and customized solutions, it is promising to drive positive changes, optimize production processes, and foster continuous improvement within the OSC production.

There are several limitations in this paper as well. First, this paper involves one typical case of RC slab without detailed analysis on the generalizability to other products. Further, VSM is a dynamic tool, and the process should be revisited periodically to ensure ongoing improvements. Future research could focus on how to apply a more scientific and rational approach to further improve the quality and management efficiency of OSC products in the identified management phases.

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