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Optimizing Volumetric Offsite Construction Production Line by Utilization of Value Stream Mapping – A Case Study

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The efficiency of offsite construction, particularly volumetric modular construction, can be significantly enhanced by optimizing the production process. This study uses a case-study method to explore the application of Value Stream Mapping (VSM) to identify and mitigate inefficiencies in the production line of an offsite construction factory. By analyzing the current production flow of Factory A, several inefficiencies were identified, and solutions were proposed and tested in collaboration with the factory's management team. The proposed solutions, many of which align with lean manufacturing principles, were evaluated for effectiveness. The findings provide a framework for other volumetric modular construction manufacturers to optimize their production processes, preliminary reducing schedule time and ultimately leading to reduced costs and waste.

Key Words: Offsite construction, volumetric modular construction, Value Stream Mapping (VSM), offsite factory production line.

Introduction

Offsite construction has the opportunity to enhance the efficiency of module manufacturing. In addition, offsite construction offers advantages such as cost and time reductions, decreased defects and waste, and improved environmental and safety outcomes (Karthik et al., 2020; Peng & Kim, 2022; Bhattacharjee et al., 2016). As offsite construction moves into manufacturing, perceived benefits can be increased by improving the production process. In the manufacturing industry, production processes are improved by implementing strategies such as lean manufacturing and total quality management (Goh & Goh, 2019; Zhang et al., 2016). Koskela (1992), in a seminal work, discussed applying lean philosophies to construction and, for the first time, pointed out that non-value-adding activities such as waiting, storing inventory, and moving material are generally not modeled by the critical path method for a construction project. Since then, several studies have emphasized the benefits, such as reduced production time and cost after implementing lean principles in construction (Du et al., 2023; Innella et al., 2019; Sakka et al., 2016). Since lean philosophies were initially developed for manufacturing processes, applying them to offsite production appears more feasible (Rocha & Koskela, 2020).

In contrast to traditional stick-built construction, offsite construction involves three critical steps: (1) manufacturing construction components, such as panels and modules, in a controlled setting (factory); (2) transporting components to the construction site; and (3) assembling the transported components on-site (Zhang et al., 2020). Since manufacturing the modules is one of the important steps, it is beneficial for offsite manufacturers to analyze their production process for possible waste and then develop strategies to reduce the waste.

Thus, the research applies Value Stream Mapping (VSM) to identify inefficiencies in the production line of an offsite construction factory and develop strategies to mitigate them using a case study methodology. Through VSM analysis, researchers identified several inefficiencies in the current production flow. With support from the company’s management team, various strategies were proposed and tested for effectiveness. The findings section elaborately discusses one inefficiency, proposes solutions to mitigate it, and reviews of effectiveness of proposed solutions. These findings provide a framework for analyzing production lines in volumetric modular construction factories. The strategies tested here can guide other volumetric manufacturers to develop approaches for optimizing their production processes.

Literature review

The concept of improving production by eliminating waste emerged in the 1950s in Japan and diffused to the West in the 1990s, mainly by the automobile sector (Koskela, 1992). Lean philosophy is preliminarily based on reducing waste and identifies seven common wastes namely: (1) overproduction; (2) waiting; (3) transport; (4) inappropriate processing; (5) unnecessary inventory; (6) unnecessary motion; (7) defects (Hines & Rich, 1997). On the other hand, traditionally, construction has been perceived and modeled solely as a series of value-adding activities. Activities that do not add any value to the final product are usually called waste activities. Waste activities like waiting, storing inventory, moving materials, and inspections are typically not included in Critical Path Models (CPM) or other control tools (Koskela, 1992). Historically, the focus has been on making these conversion activities more efficient to boost competitiveness. However, the lean philosophy suggests that significant improvements can be achieved by identifying and eliminating Non-Value-Adding (NVA) activities. Therefore, construction should first be viewed as a flow process that includes waste and Value-Adding (VA) activities.
Researchers such as Rother and Shook (1999) have proposed the following steps to make any production process efficient:

- Identify the routings and product families.
- Determine bottleneck machines and shared machines.
- Map the value streams of each family at an aggregated level.
- Draw the corresponding Current State Maps (CSMs), highlighting routing interrelations.
- Eliminate any form of waste using lean principles.
- Reconfigure the system using a Workload Control production management approach.
- Synthesize the improvements of the new value streams and draw the Future State Maps (FSMs).
- Define an operating work list to prioritize activities at the shop floor level.

The above process needs adjustments when considered in the context of a volumetric offsite construction factory. For example, instead of routing different product families, routing of different building elements is required. As there are no machines other than the master saw, instead of machine bottlenecks, task bottlenecks should be focused. In the steps mentioned above, waste identification is critical, and Value Stream Mapping (VSM) plays a crucial role in identifying waste in a process.

VSM, as a tool, helps create a process-flow diagram detailing activities and other project information to achieve the objective. This standardized method records the steps and flow of work items, followed by a systematic analysis to develop an improvement plan (Ramani & Ksd, 2021). VSM helps in visualizing not just individual workstations but the entire production process. It also serves as a common language and tool for managers and employees, integrating and displaying product and information flow on a single map (Marangoni et al., 2013). However, VSM can be applied effectively in linear production systems (Matt, 2014) as Braglia et al. (2006) showed that VSM cannot be used directly for very complex manufacturing processes that have merging flows.

Creating a VSM involves four main steps. *The first step involves* a detailed analysis of the entire production process, highlighting both VA and NVA activities. *The second step involves* examining the flow of value streams and identifying wastes in production and processing including issues such as imbalances, overloads, and inefficiencies. *The third step involves* pinpointing key improvement areas by assessing how these problems affect the product's added value, which helps in identifying optimization opportunities (Wang et al., 2020). The VSM shows all the important aspects of a production process, highlights waste, and serves as a foundation for developing a strategic plan. Once the wastes are identified, *as the fourth step*, various measures based on lean principles can be proposed. Lean manufacturing, a philosophy by Taiichi Ohno, revolves around waste reduction that shapes "lean thinking." As outlined by Womack & Jones (2003), these principles include: defining value, mapping the value stream, optimizing flow, implementing a pull production system, and striving for perfection through continuous improvement (Leite & Vieira, 2015).

Previous studies have explored VSM in the context of traditional and offsite construction. Vilventhan et al. (2019) utilized VSM to understand construction material waste production in a high-rise building in India. After understanding how and where the waste is generated, researchers proposed a framework utilizing 5S lean techniques to minimize construction waste generation. Meghwani et al. (2019) utilized VSM to identify waste in the fire sprinkler installation process. Zhang et al. (2020) have utilized VSM to identify wastes in a modular offsite construction. Major wastes identified were in the form of bottlenecks and imbalances due to variances in cycle times, the root cause being overproduction and underproduction at certain stations.

In traditional construction waste is hidden in the activities as the critical path scheduling method considers all activities as value-adding activities, therefore unable to identify hidden waste. Whereas modular construction is different. Modular construction involves creating various building modules, including panelized sections, volumetric modular units (modules) formed by connecting wall and floor panels, and complete buildings, based on the factory's production capabilities (Zhang et al., 2020). If the factory is producing modules that are 3-dimensional with all the walls, roof, and floor, then it is called Volumetric Modular Construction or Volumetric Offsite Construction.

The current literature has minimal research on analyzing and improving the volumetric modular construction production process (Esmaeili et al., 2023; McDermott et al., 2023; Zheng et al., 2024). Therefore, the research applies Value Stream Mapping (VSM) to identify inefficiencies in the production process of an offsite construction factory and develop strategies to mitigate them using a case study methodology.

Methodology

Since the primary goal of the research is to evaluate and improve the performance of a selected production line in an offsite construction facility using the Value Stream Mapping (VSM) tool (i.e. production process of a single company), it aligns with a case study approach (Yin, 2003). The case study approach develops an in-depth understanding of a single real-life case or explores an issue using a case (or several cases over time) as a specific sample (Yin, 2009). Generally, multiple sources such as observations, interviews, audiovisual material, documents, and reports are utilized to understand the case. A case study method is effective when the researcher(s) have well-defined cases with clear boundaries and aims to gain a deep understanding of these cases or to compare multiple cases (Creswell, 2013). Challenges include selecting and delimiting a case and decision about selecting a single or multiple cases. At the same time, the research method suffers disadvantages such as the limited ability to generalize the findings since each case can be unique.

There is no recorded exact number of modular companies, but as per the MBI (2024), approximately 100 modular construction companies are currently active in the USA, out of which 60 focus on the residential sector (Fleisher, 2024). As it was possible to gather data for a longer duration (a month), the modular home builder's (company A) production plant was selected for study as a convenient sample. Company A's factory is 140,000 sf and employs 70 shop floor workers and 11 office employees. Yin (2003) mentions threats while selecting a case based on convenience, however, also emphasized the importance of spending more time on the site. It is suggested to justify the case selection to address potential concerns about bias or limitations in scope. In the case of this research, along with the convenience of gathering data for a longer period (a month), the selected factory has a linear production line which is a requirement for applying VSM effectively. These factors align with the goal of this study and are important for collecting meaningful data. The produced modules in this company are shipped and set up on-site to create multifamily permanent houses (not HUD / not manufactured homes). The study was conducted on an ongoing multifamily project with two typical modules.

After selecting the case (Factory) based on the abovementioned parameters, several steps were followed to conduct this research. First, the study was discussed with higher management for better planning and synchronization with the ongoing production schedule. Then a combined meeting with the president, production manager, design manager, and head- supervisor was conducted to update about the planning and steps of the study. Then, during data collection, all shop floor activities were observed, noted, and timed over fifteen days (45-60 hrs). This included observing the execution of activities in real-time on the production floor, recording the duration for each task, steps involved in the process, and construction methods. As a next step, a visual representation of existing activities, including flow and time durations, was created to be used as the Current State Map (CSM). CSM is an important step in the process of VSM, as it helps to visualize the gathered data and makes further analysis easy. The developed CSM was analyzed to pinpoint areas where productivity issues and delays occurred. The CSM was compared with the production managers' station time records. These records outlined estimated times for each station on the production line, identifying bottleneck stations. However, these records did not detail VA and NVA activities at each station. After confirming the problem areas and waste or NVA activities, several brainstorming sessions were conducted with production managers and factory supervisors.

Initially, during this brainstorming session, the basic principles of lean philosophy were explained. One production manager had knowledge of lean philosophy from an online course on the subject. The creation of several strategies and implementation-planning was done during these brainstorming sessions. The final step involved assessing the effectiveness of the changes made by recording the CT after strategy implementation. These after-improvement recordings and revisions in the strategies with re-recordings were done over 20 days. The productivity of activities is measured and compared to previous records, tracking improvements in terms of time. The findings are discussed in the next section and summarized in the conclusion and limitations section. The following diagram elaborates on the research process (refer to Figure 1)

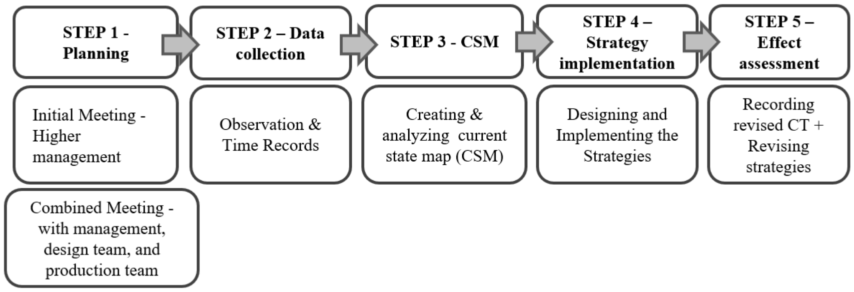

Figure 1. Research Steps

Findings

Overview of the production line flow

The selected case (factory) has a linear production flow, with a few short sub-assembly production lines feeding sub-assemblies to the main line (Figure 2). All the stations were arranged linearly, with the main production flow directed from station 1 to station 13, with station 6 and station 12 being kept for surge or delay. The volumetric module or part of the volumetric module moved from one station to another with the help of casters. Five sub-flows fed five building elements (floor frame, interior walls, exterior long walls, roof/ceiling, cabinets) into the main production line. There is no cross-flow between these sub-lines. The performance of these sub-lines impacts the main line's performance as sub-lines act as inventory for the main line.

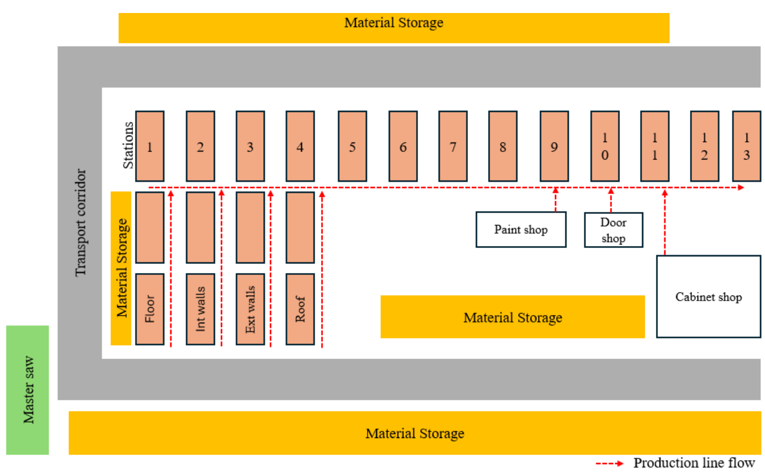

Figure 2. Factory layout and production flow

A total of 32 major construction activities were identified in the whole process. Two timings, Cycle time (CT) and value-added activity time (VA) were recorded for each activity. Cycle Time is the time to complete the activity and VA is the time to complete just value-adding tasks. The process is initiated at the start of the sub-assembly line for station one, where the floor frame is assembled. The floor frame is transferred to the next sub-station to be covered using Oriented Strand Board (OSB) and vinyl floor coverings. The floor travels in the main production flow and takes shape as a volumetric module at the end of the production line. With all underfloor MEP installations completed, the floor is moved to station 2, where internal walls and bathtubs/showers are placed. In addition, internal walls are installed on this station with one side kept open without drywall to pull the electrical/plumbing risers to the desired height. Then external long walls and roof are installed on the module at stations 3 and 4. From station 5, the three-dimensional volumetric box moves onto the production line, where the rest of the interior and exterior work is completed. At station 10, doors and windows are installed. A separate cabinet shop feeds ready-to-install cabinets and countertops to the main production line at station 11. VSM of cabinet shop is not included in this study. The production line finishes at station 13, where the final inspection is conducted, and modules are packaged for shipping. The production goal for the factory was to produce one module each day. The production flow during the study was close to 0.75 modules/day with minimal overtime.

Current state value stream map

The CSM is created by recording each task's CT and VA activity time. A key principle in VSM is to carry a stopwatch while tracing the actual routes of material and information flow and to depend solely on firsthand information (Rother and Shook, 2003), which was followed for data collection. However, offsite construction's complexity and variation made it difficult to record each task involved. Therefore, task completion durations were recorded for (CT) and unit time taken for value-added activities was recorded separately to calculate (VA). PP shows the number of people working on tasks. Surge stations were omitted from the VSM. As shown in the CSM, 32 activities were recorded (Figure 3). All the readings were taken during July - August 2024 by the author and assistant production manager. CSM was utilized for the most inefficient activities using the following equation.
Potential for improvement (%) = {1- [(VA)/ CT]}*100

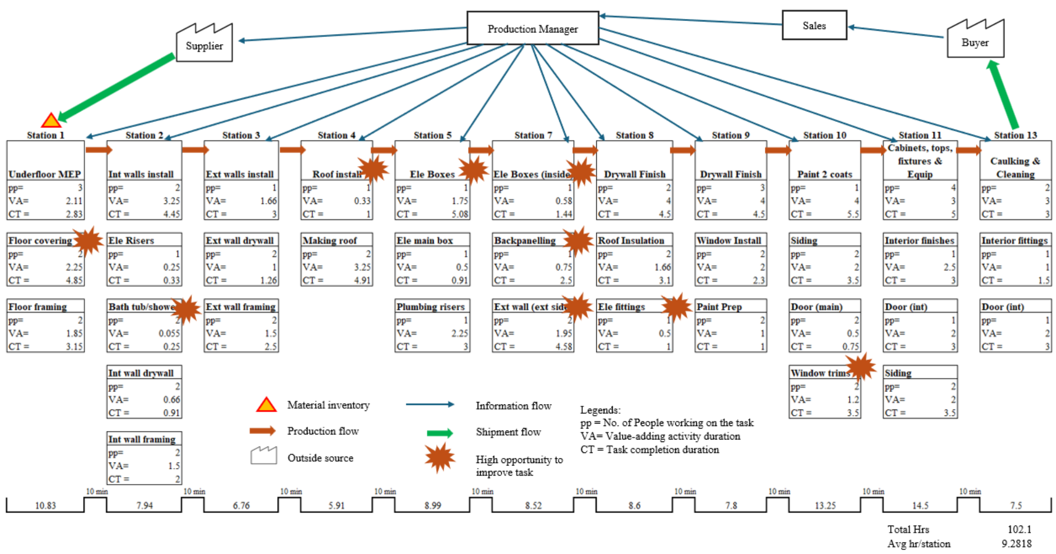

Figure 3. Current state value stream map

CSM observations

The CSM identified eight activities with an opportunity for more than 50% improvement. The highest scope for improvement was installing a bathtub or shower in the module (Figure 4).

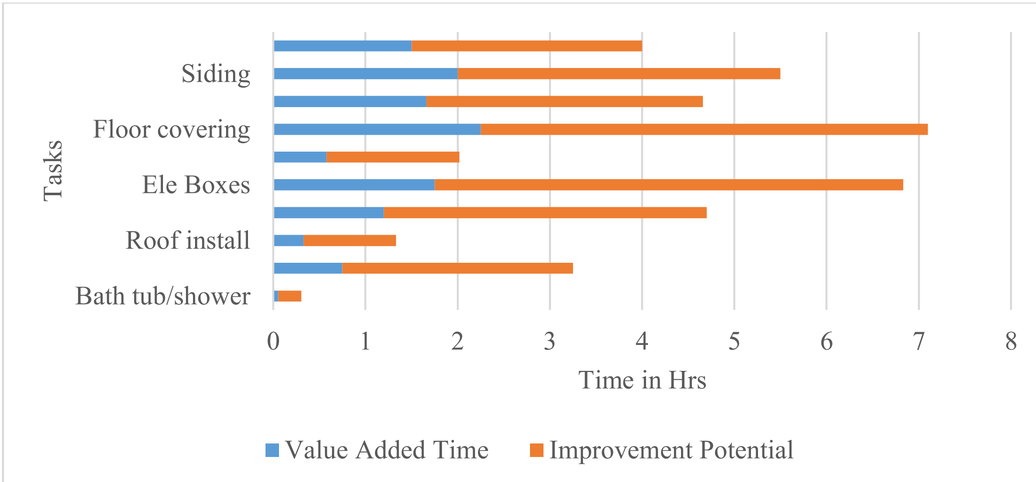

Figure 4. Value Added Activity Time, Cycle Time, & Improvement Potential (in Hrs)

Though bathtub and shower installation have the highest improvement potential, the total CT was 0.25 hr. This indicates that, even after the improvement, the overall effect on the production line will remain minimal. Therefore, tasks with bigger CT were selected for implementing improvement strategies. An imbalance in the CT at each station is also observed. This imbalance caused bottlenecks both downstream and upstream of the production line, making workers adopt inefficient improvisations. This often means crew members move from their allocated workstations to other stations, resulting in higher time wastage and movement of tools, materials, and inventory that can further enhance inefficiencies. CT on CSM also pointed out that the production line is busier downstream at stations 10 and 11, with CT of 13.25 hrs and 14.5 hrs. On these stations, more trades worked at single stations parallelly causing congestion and adding to the delays. In terms of CT, more scope for improvement is seen in the midline area from stations 4 to 8. Improving midline efficiencies can also help shift some of the tasks from end-of-the-line stations to midline, which would help achieve a balanced production line. A total of 102.1 hours were required to complete one volumetric module ready for inspection. Considering 11 active stations, the time weightage per station is 9.28 hours. As the working shift is 8 hours, the extra 1.28 hours at each station result in surge stations being always occupied. The surge stations needed to be converted to regular stations if improvements worth 9.28 hr were not made. However, the production line after strategy implementation showed a reduction of more than 13 hours in the overall production schedule.

Strategies for optimizing production

After discussing the inefficiencies with production managers, it was decided to first target inefficiencies in the back paneling process. This task has a 70% opportunity for improvement and 2.5 hours of CT. In the current back paneling process, the steps involved were to measure the drywall required for two wall surfaces, go out of the module, measure-cut and bring the drywall in, and install it using screws. There was waste observed in unnecessary motion, transport, and waiting. In a brainstorming session with production managers and supervisors, it is decided that the worker shall pre-cut all the drywalls required at once and bring them to the module. This strategy shall reduce the time required to walk in and out. As visual management is vital in lean principles (Du et al., 2023b), the design team issues a drywall drawing with all the required measurements to save time on measuring the wall surfaces. A trolley was used to carry and keep all the drywall cut pieces in the correct sequence near the module door. The recorded back paneling time for the first module with pre-cut panels was 2.75 hrs, an 11% increase in CT. The following day, the worker followed the old way of back paneling and was reluctant to pre-cut because referring to drawing and loading panels in the sequence was extra effort compared to the old way. Also, on one occasion, confusion about panels led to a couple of mistakes and rework. In the next brainstorming meeting, the issue of the sustainability of this strategy was raised as the drywall installer's reluctance for pre-cutting. The resistance to the change was an isolated incidence and not common across different strategies.

On the other hand, a few other tasks, such as siding, and window trims, also required pre-cutting. The mass saw operator was asked to cut drywall sheets for back paneling, siding, and window trims. It is requested that the panels for each room should be kept separate to reduce confusion during installation. The recorded time for installation was just below one hour. However, the pre-cutting time for the first module was fifty-five minutes. Overall, 35 minutes were reduced, i.e. 23% of improvement. This was much less than the possible 70% improvement. However, the pre-cutting can be done without syncing with the production line schedule, which means the time reduction in the production line will be approximately 1.5 hrs. Other identified inefficiencies were also discussed, and strategies were suggested. Strategies such as moving inventory locations closer to the work area, dedicated places for tools, adding a visual schedule for each station with each worker's responsibility noted, drawings with better visual representation (especially for MEP), and using stencils for marking and cutting, were implemented and tested for its effectiveness. Varied effectiveness was observed during the implementation of different strategies. The table below gives an overview of implemented strategies and their effect.

Table 1. *Overview of implemented strategies and their effects*

Task	Value added activities hr (VA)	Cycle Time in hrs (CT)	Improvement potential	Strategies implemented	Reduct-ion in CT in hrs	Reduction in Production schedule (%)	Revis-ed CT hr
Bathtub/shower	0.055	0.25	78%	NA	0	0	
Back-paneling	0.75	2.5	70%	Pre-cutting, visual management, stencil	1.55	1.52%	1.0
Roof install	0.33	1	67%	right sequence	0.58	0.57%	0.4
Window trims	1.2	3.5	66%	Pre-cutting, visual management	3	2.94%	0.5
Ele Boxes	1.75	5.08	66%	Visual	2.83	2.77%	2.3
Ele Boxes (inside)	0.58	1.44	60%	management, stencil	0.14	0.14%	1.3
Ext wall (ext side)	1.95	4.58	57%	NA	0	0	0.0
Floor covering	2.25	4.85	54%	QC of material, stencil	0.35	0.34%	4.5
Ele fittings	0.5	1	50%	NA	0	0	0.0
Roof Insulation	1.66	3.1	46%	NA	0	0	0.0
Ele main box	0.5	0.91	45%	NA	0	0	0.0
Ext walls install	1.66	3	45%	right sequence	1.8	1.76%	1.2
Siding	2	3.5	43%	Pre-cutting, visual management	1.5	1.47%	2.0
Siding	2	3.5	43%	Pre-cutting, visual management	1.5	1.47%	2.0
Floor framing	1.85	3.15	41%	NA	0	0	
Ext wall framing	1.5	2.5	40%	Inventory closer to the station	0	0.00%	2.5

Conclusion

Ample research is available about utilizing VSM for OSC; however, available literature has minimal studies focusing on improving the volumetric offsite construction production process by utilizing VSM. This study aimed to identify and reduce inefficiencies in the production process of company A’s volumetric offsite construction factory. VSM is utilized to identify waste in the production process in the units of production time represented in CSM. The CSM showed issues in the current state of the production line. These issues were mainly related to unnecessary movement, such as walking to material storage, and non-value-adding tasks, such as measuring and cutting. VSM analysis showed the potential for improvement ranging from 11% to 78% in CT in individual tasks. In collaboration with the production team, strategies for waste reduction were developed. These strategies eliminated activities such as measuring and cutting from the main production line. Assigning a dedicated person to pre-cutting various materials proved useful. Also, changing the installation sequence proved to be a useful strategy while installing long walls, ceilings, and roofs.

Looking ahead, other volumetric OSC factories can utilize the methodology of this paper to assess their production line performance. Especially OSC factories that have a similar production flow. The strategies mentioned here can guide other OSC factories to develop personalized strategies to reduce waste. Researchers can utilize this method to assess the volumetric offsite construction of modules with metal as a structural material. The CSM indicated that drywall finishing is an area requiring attention. Drywall finishing is a non-standard process that consumes considerable time. As this process depends on a worker’s skill, the performance varies depending on the person responsible and even during different times of the day. Overall, the VSM proved to be a very effective tool for visualizing the production line process and helped to identify inefficiencies in the volumetric offsite construction production line. Simple strategies were found helpful in minimizing the waste and progressing towards the production goals of Company A.

Limitations

Among the suggested strategies, many align with lean philosophies; however, strategies were not particularly crafted by following a particular lean philosophy. During the CSM and improved state mapping, overall workers' attendance varied. However, the number of workers working on tasks under observation remained the same in CSM and improved state mapping. As workers knew they were being observed, there might have been a possibility of a Hawthorne effect (Sedgwick & Greenwood, 2015) that might have impacted the worker's performance. However, the span of the recording was long, which can mitigate the effect to a certain extent. Due to time constraints for most tasks, only two cycle-time recordings were taken. Multiple recordings of the same task would give more accurate CT. As a single case study, the findings of this research can be applied to similar cases only, however, the methodology can guide the strategy development for other volumetric offsite manufacturers.

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