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THE IMPACTS OF LEAN IMPLEMENTATION REVEALED IN THE COURSE OF BUILDING A DIGITAL TWIN OF A CONSTRUCTION MANUFACTURING FACILITY

Fatima Alsakka[1], Mohammad Darwish[2], Haitao Yu[3], Farook Hamzeh[4], Mohamed Al-Hussein[5]

ABSTRACT

Successful implementation of lean philosophy in various sectors has inspired many construction manufacturing companies to foster a lean culture and embark on open-ended lean transformation initiatives. This study presents the case of a panelized construction company that has embraced the lean philosophy over the past decade. Experiments undertaken during the process of building a digital twin of the company's production facility to verify the logic underlying the developed model reveal an increase in productivity. Using the same productivity regression models to model framing operations in two different years, the simulation of combined productive and delay times results in an underestimation compared to actual production data from 2013 but an overestimation compared to actual production data from 2017. Moreover, prominent lean changes implemented over the years that are positively correlated with productivity improvement are identified. These include standardizing the design and manufacturing processes, minimizing waste (including Mura, Muda, and material waste), ensuring a continuous flow, balancing the production line, following a just-in-time approach for the delivery of materials and implementing the 5S program. The findings underscore the long-term benefits of adopting lean thinking in construction manufacturing.

KEYWORDS

Lean thinking, construction manufacturing, benefits realization, productivity improvement, continuous improvement.

INTRODUCTION

The pressing need to fulfill diverse customer needs in a timely, efficient, and cost-effective manner continues to drive the adoption of lean production principles and

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[1]PhD student, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Canada, falsakka@ualberta.ca, orcid.org/0000-0003-1777-1875

[2] MSc graduate, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Canada, mdarwish@ualberta.ca, orcid.org/0000-0002-1363-7225

[3] Research and Development, ACQBUILT, Edmonton, Canada, haitaoy@acqbuilt.com, https://orcid.org/0000-0002-7798-4867

[4] Associate Professor, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Canada, hamzeh@ualberta.ca, orcid.org/0000-0002-3986-9534

[5] Professor, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Canada, malhussein@ualberta.ca, orcid.org/0000-0002-1774-9718

methods. Although lean production is derived from the Toyota Production System, the philosophy has been translated to production models outside the automotive industry, with the construction manufacturing industry being a notable example. Despite the significant differences between the automotive industry and the homebuilding industry, there are also many similarities that have provided the rationale for the implementation of lean in construction manufacturing (Yu, 2010).

Many case studies can be found on the implementation of various lean principles in construction manufacturing and their associated benefits. For instance, a case study carried out at a modular construction facility by Moghadam & Al-Hussein (2013) found that, as a result of waste minimization—a fundamental lean principle—the duration needed to fabricate the modules for a two-storey building and the probability of a timely project completion could be improved from 36 days and 97%, respectively, under the current state, to 30 days and 98.5%, respectively, under the proposed future state. A similar study carried out at a precast factory projected that an estimated 50% reduction in production lead time could be achieved as a result of reducing batch and inventory sizes and applying the 5S program across the plant (El Sakka et al., 2016). A recent study at a modular construction manufacturer, meanwhile, estimated that lead time could be improved by 20%, along with a 15% reduction in man-hours, upon the implementation of various lean principles, including minimizing different forms of waste, balancing the workload, and balancing the workforce density on production lines (Zhang, 2017). In another case study, a cloud-based production planning and tracking system that comprised lean processes and building information modelling was applied on a construction manufacturing project (McHugh et al., 2019). Among the benefits realized by the system was reducing working at height, defects, and labor requirement by 75%, 60%, and 45%, respectively. Moreover, a comprehensive analysis of bottlenecks and the effect of incremental productivity improvement measures on the overall (i.e., global) operations (versus examining only the local effect on a particular altered process) at a modular construction facility found that a 22% increase in the weekly production rate could be achieved (Alsakka et al., 2020).

While the added value of implementing lean principles is evident in these case studies and similar ones that can be found in the literature, most of these studies evaluate the effect of lean based on abstract representations of the actual operations (i.e., virtual models of reality) at the time of the study and do not evaluate the long-term effects of implementation. When we build virtual models of reality, we filter out details that we deem unnecessary in order to reduce the complexity of the model. Nevertheless, the real world constantly changes, and this makes it challenging to anticipate the long-term effect of changes made in the present based on static virtual models. Hence, it is of value to observe the long-term effect of implementing lean practices. In this context, this study examines the productivity improvements achieved by a case company that has been actively implementing lean principles for more than a decade. These productivity improvements having been identified in the process of building a digital twin for the case company, as detailed in the methodology section. The case company specializes in panelized construction manufacturing and operates production lines in which walls, floors, and roofs are manufactured (to be shipped to construction sites for installation). The company's current operations are semi-automated and comprise a combination of manual, semi-automated, and fully automated activities. The company’s management team participated in lean training more than a decade ago and then sought support from researchers at the University of Alberta to devise and implement a lean transformation plan. Since then, many lean practices have been implemented and sustained throughout its supply chain. The company has been fostering a lean culture as these lean practices have become habitual and an inherent part of the company's operations. The study focuses particularly on the wall production line in showcasing the benefits obtained over time as a result of lean implementation.

METHODOLOGY

MODEL DEVELOPMENT

The work presented in this paper is a by-product of an ongoing research project in which a digital twin of the case company's manufacturing plant is being built using Simio software. (The architecture of the digital twin under development is outside the scope of this paper.) The digital twin mirrors the manufacturing operations as they proceed at the plant. After modeling the actual workflow at the plant as shown in Figure 1, experiments were needed in order to verify the logic underlying the model prior to further development.

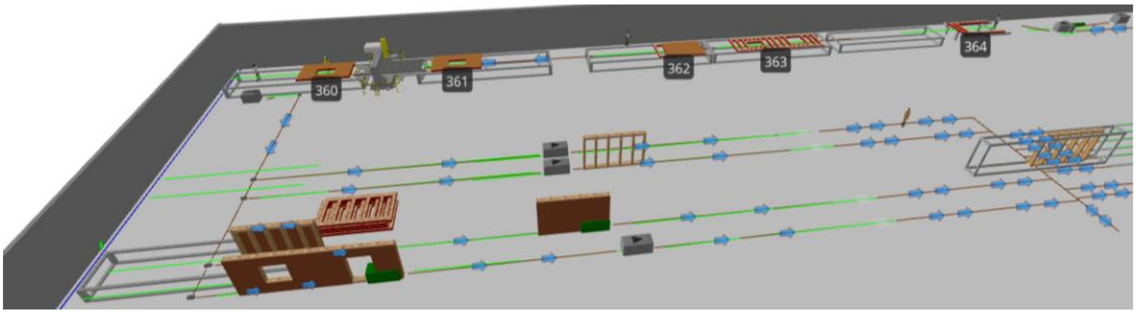

Figure 1: Digital Twin Under Development

To conduct these experiments, task time regression models, trained in a prior study by Shafai (2012) for the same wall production line, were deployed to model the durations of tasks performed at different workstations. The regression models were used to estimate the time required to complete a task (e.g., framing, installing sheathing, nailing sheathing) as a function of the design attributes of each panel (i.e., the number of studs, windows, doors, nails etc.). As such, the wall panel data fed into the model included both the design attributes and the manufacturing sequence, as shown in Figure 2. It should be noted that, although these regression models were trained based on time studies conducted in 2012 and were only used on a provisional basis to verify the logic of the model, using these regression models was key to discovering the benefits of the lean changes made by the company, as described in the "Value Gained from Having a Lean Culture" section of this paper.

Panels List | Single Panels List | Mag_Node | Jobs List | Manufacturing Stats | Framing Stats | Sheathing1 Stats | Sheathing2 Stats | Bridge Stats | Door Ir

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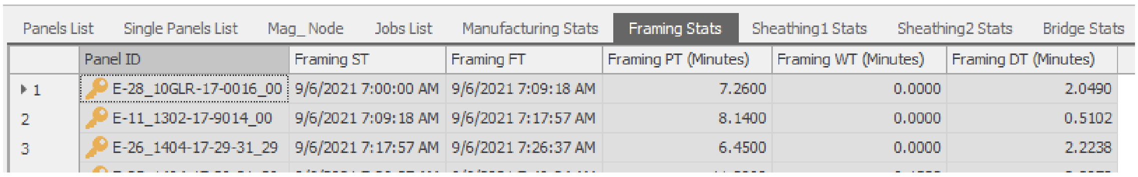
	Panel ID	Sequence (Seconds)	Job Nb	Wall Type	Floor	Nb Walls	Length	width	height	Window	Large Window
1	E-10_1302-17-9014...	3	1302-17-9014	EXT	2nd	6	11968	2467	140	2	1
2	E-11_1302-17-9014...	1	1302-17-9014	EXT	2nd	1	11474	2467	140	0	1
3	E-12_1302-17-9014...	8	1302-17-9014	EXT	2nd	4	12107	2467	140	1	1

Figure 2: Sample Model Input

The model simulates the manufacturing operations of the panels and calculates (1) the processing time of each panel at each workstation, (2) the time the panel waits to be transferred from one station to another (i.e., from when the manufacturing tasks are completed at a given station to when the downstream station becomes available), and (3) the delay time at each workstation, attributable to different sources of delay such as machine breakdown, material shortage, and rework, to name a few examples. It should be stressed that these delays are based on time studies conducted in 2012, and they have been reduced through various process improvement interventions over the years. A sample output of the model is presented in Figure 3.


Panels List | Single Panels List | Mag_Node | Jobs List | Manufacturing Stats | Framing Stats | Sheathing1 Stats | Sheathing2 Stats | Bridge Stats

	Panel ID	Framing ST	Framing FT	Framing PT (Minutes)	Framing WT (Minutes)	Framing DT (Minutes)
1	E-28_10GLR-17-0016_00	9/6/2021 7:00:00 AM	9/6/2021 7:09:18 AM	7.2600	0.0000	2.0490
2	E-11_1302-17-9014_00	9/6/2021 7:09:18 AM	9/6/2021 7:17:57 AM	8.1400	0.0000	0.5102
3	E-26_1404-17-29-31_29	9/6/2021 7:17:57 AM	9/6/2021 7:26:37 AM	6.4500	0.0000	2.2238

Figure 3: Sample Model Output

MODEL DEPLOYMENT

Productive, waiting, and delay times were computed and analyzed for the framing workstation using actual production data, and the model was deployed to simulate one day of operations (39 wall panels) in 2017. The model was fed data encompassing both the design attributes and the manufacturing sequence for the wall panels manufactured on that day. The results were compared to actual data on the time and location of each panel as it flowed throughout the wall production line (tracked using a radio-frequency identification system). At the case company, the timestamps when a panel enters a workstation on the wall production line as well as when it leaves the workstation are recorded. Based on these timestamps, the time elapsing while a panel is at a given workstation can be calculated. These time values include the processing time at each workstation, any delay time, as well as the time the panel waits before being transferred to the downstream station. It should be noted that the simulated day (in 2017) was a normal working day for which the radio frequency identification data did not include any outlier values unrepresentative of reality.

In previous R&D carried out by the case company, a simulation model was built based on the same task time regression models used in this study to simulate days of operation dating back to 2013. Similar patterns were observed for all these days, although, in the interest of brevity, only the results corresponding to a single day in 2013 (35 wall panels) are presented in this paper.

LEAN EVALUATION

An increase in productivity having been observed in comparing the 2017 data to the 2013 data, Q&A sessions were held with the case company's R&D department in order to gather more information about the lean practices adopted by the company. Moreover, lean-related research studies undertaken at the plant were reviewed. The most prominent lean practices adopted by the company were identified accordingly and are described in the "Lean Changes Implemented by the Case Company" section of this paper. Although the direct impact of the lean changes identified is difficult to evaluate, clear correlations between lean implementation and actual productivity improvement were identified, as discussed below.

VALUE GAINED FROM HAVING A LEAN CULTURE

The cumulative "*simulated productive + delay times*" and cumulative "*simulated productive + delay + waiting times*" at the framing station were computed for every iteration of a panel being framed. The purpose of these calculations was to determine the difference between simulated and actual values as the day progressed. The results for the 2013 and 2017 data are plotted in Figure 4 and Figure 5, respectively.

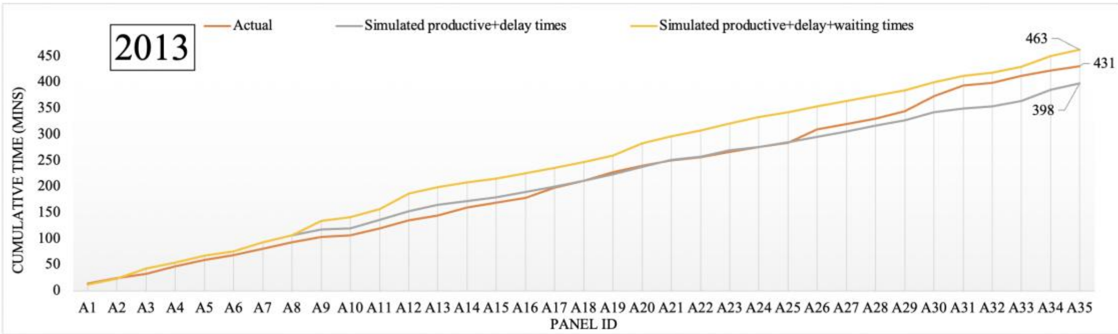


Figure 4: Actual Versus Simulation (2013 Data)

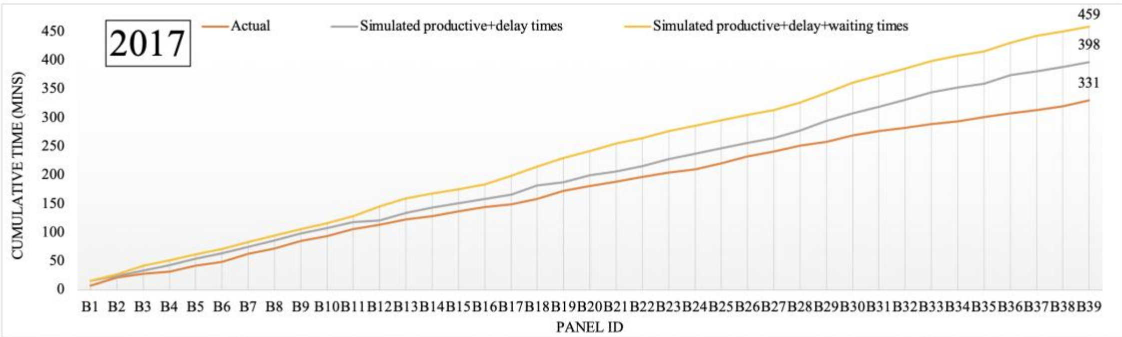


Figure 5: Actual Versus Simulation (2017 Data)

The simulation models generally overestimated the durations of tasks, with the simulated "*productive + delay + waiting times*" being higher than the actual times. However, it should be emphasized that the purpose of presenting these results is not to assess the accuracy of the task time models (which are outdated), but rather to determine whether any discernible improvements have been realized as a result of the lean transformation implemented at the case company in recent years. Among the most noticeable differences between the two charts is the position of the actual time curve (refer to the orange line) relative to the simulated time curve "*productive + delay times*" (refer to the gray line). The total actual time needed to frame all the panels on a specific day was found to be higher than the total simulated "*productive + delay times*" in 2013, but lower than the total simulated "*productive + delay times*" in 2017. Moreover, the difference between the actual time and total simulated "*productive + delay + waiting times*" increased from about 7% for the day in 2013 to about 38% for the day in 2017. Since the same task time regression models were used for both years, the resulting differences indicate that the actual framing times decreased. Based on the limitations of the available data, it is not possible to determine whether this decrease was the result of a reduction only in delay times and waiting times or also in productive times. Either way, the results show productivity improvements accompanying the lean transformation implemented at the case company over the past decade.

LEAN CHANGES IMPLEMENTED BY THE CASE COMPANY

While the case company seeks to continuously improve its overall operations, the main wall production line has been the focal point of its lean-related R&D over the years. As such, it is currently deemed the "most lean" production line at the factory. This section describes some of the most prominent lean applications implemented on the wall production line (i.e., the lean applications most clearly correlated with productivity improvements).

STANDARDIZATION

In the context of lean manufacturing, it is not possible to improve a process that is not standardized (Liker, 2004). Indeed, the effect of an improvement made to a variable process will vary depending on the state of the process, and may become counterproductive. Let us consider the example in which an extra worker is permanently assigned to reduce workload at a workstation where the cycle time highly fluctuates. When cycle time drops at this workstation, the extra resource becomes waste.

One prominent example of the case company's efforts to standardize its operations has been the establishment of standard operating procedures (SOPs) for each workstation. A well-defined set of activities and fixed resources (workers, tools, and machinery) is assigned to each workstation. The workers assist in the formulation of these SOPs, and as such they have a thorough understanding of all the information they contain. Each worker also carries a copy of the SOP for the workstation to which they are assigned so they can retrieve information about the tasks they are responsible for in a timely manner as needed.

The company seeks not only standardized processes but also standardized products. For instance, they adopted the concept of the "multi-wall panel" as proposed by Liu et al. (2017). In this system, a set of wall panels of the same height and dimensional lumber type are grouped and produced together as a single multi-wall panel. The multi-wall panel is then cut into single panels towards the end of the production process. The multi-wall panel system helps to reduce variability in production by reducing design variability in this manner. The adoption of this system has helped to mitigate variations in cycle times, thereby reducing idle and waiting times and supporting a more balanced production line.

CONTINUOUS FLOW

In a process that is founded on continuous flow, work in progress flows between workstations as they get pulled from downstream workstations when they are needed instead of getting pushed by the upstream stations once they are processed (Liker, 2004). Continuous flow has the benefit of eliminating multiple forms of waste when implemented on a production line, as the work in progress flows with minimal stoppages (i.e., waste in the form of waiting time in queue) between stations (Bulhões et al., 2006). This approach also exposes inefficiencies, which can then be minimized, thereby reducing cost and saving time (Liker, 2004). One-piece flow is the ideal version of continuous flow. In this approach, components and materials are processed one piece at a time and proceed directly from one workstation to the next (Liker, 2004). Nevertheless, it is not efficient to establish one-piece flow on production lines where variability cannot be controlled, since doing so will result in frequent disruptions to the flow (i.e., stopping the production line). As such, for settings in which cycle times tend to fluctuate (as is the case in construction manufacturing), the concept of FIFO (first-in, first-out) lanes has been introduced to control inventory between workstations. A FIFO lane is a production lane that has a limited capacity for work in progress (Rother & Shook, 2009). The first unit that enters the lane is the first one to get out, and, when the lane reaches full capacity, the upstream process must be stopped (Rother & Shook, 2009).

At the company under study, there is continuous flow between the first four workstations on the production line where most of the work is completed (as shown in Figure 6). The maximum panel length that can be accommodated on these workstations is 40 ft, so multi-wall panels can be up to 40 ft in length. This means that there is a one-piece flow when 40 ft long multi-wall panels are manufactured. On the other hand, when panels are shorter than 40 ft, a conveyor that is part of the framing station serves as a FIFO lane, as it can accommodate multiple panels waiting to be pulled to the sheathing workstation. The use of this conveyor as a FIFO lane is justified by the fluctuations in cycle times at the sheathing workstation. In particular, the cycle times at the sheathing workstation vary significantly depending on whether the wall is an exterior or an interior panel. An interior panel does not require sheathing and therefore can be passed directly through the sheathing workstation, whereas an exterior panel may spend even more time at the sheathing station than at the framing workstation. Hence, depending on the panel type, the sheathing workstation may be faster or slower than the framing workstation, and the use of a FIFO lane helps to reduce idle time at the framing workstation or starvation time at the sheathing workstation.

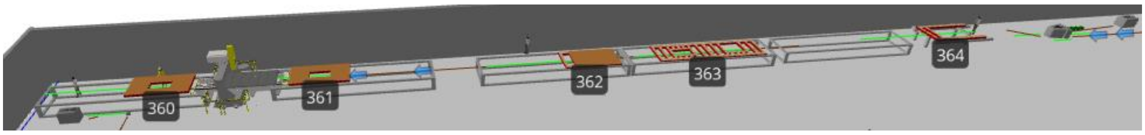


Figure 6: Continuous Flow

MINIMIZATION OF DIFFERENT TYPES OF WASTE

The key objective of any lean system is to eliminate waste in all its forms. Any inefficiencies that lead to use of equipment, materials, labor, or capital beyond what is deemed necessary for production are characterized as waste (Anearo & Deshmukh, 2016). The following subsections describe the case company's efforts to reduce waste in various forms.

Balancing the Workload: Minimization of Shop Floor-Mura

"Mura" is a type of waste in which imbalance in production results in overloading of human resources and machines at times but underutilization at other times (Liker, 2004). This can result from fluctuations in demand and/or inefficiencies in the design of operations. Leveling out production allows for the efficient use of available resources by evenly distributing the workload across all workstations and ensuring that no workstations are idle while other stations are overloaded (Binninger et al., 2016).

The case company has devoted a significant effort to balancing its wall production line. Major improvements have been realized by implementing strategies to alleviate bottlenecks and even the workload. This has resulted in reducing the waiting times at workstations that were originally faster than the other workstations on the same line. Examples of these strategies included the following:

- Some tasks that were performed at slower workstations on the production line (e.g., backing and blocking installation for interior walls) were not predecessors for the tasks assigned to the immediate subsequent stations and could be completed at later stages in the manufacturing process. Such tasks were accordingly moved to workstations later in the production line.

- Production scheduling was altered so that material preparation activities (e.g., cutting sheathing, cutting studs) are completed one shift or half a shift before the material is needed at workstations. This limits the waiting times resulting from delayed internal material supplies to workstations.
- The company regularly conducts analyses to determine whether, based on the current state of operations, various activities should be carried out at the plant or subcontracted. As part of this analysis, they actually perform the activities under investigation to evaluate whether completing them in-house is having an adverse effect on overall efficiency. For instance, they have performed this analysis for insulation, drywall, and siding installation activities, and in the latter case they in fact opted to discontinue their practice of installing siding as a result of this analysis, which had revealed that demand had declined to the point that they were not able to maintain a continuous workflow for this activity.
- The team lead responsible for the wall production line has the authority to allocate additional workers to a specific workstation based on demand in order to expedite production. For example, when there is a large number of exterior wall panels scheduled for a given day, the team lead may add an extra worker to the sheathing workstation in order to prevent a bottleneck.

Material Waste Reduction

Material waste (in which additional costs are incurred without adding any value to the final product) is among the most frequently targeted forms of waste in construction (Viana et al., 2012a; Anearo & Deshmukh, 2016). In this regard, automated approaches have been devised and applied at the case company for material waste reduction. Manrique et al. (2011) developed a combinatorial analysis algorithm to optimize the process of cutting lumber and sheathing materials for walls in order to reduce material waste. In addition to this optimization method, the company's implementation of the multi-wall panel system, previously explained, contributes to waste reduction, as a group of wall panels are framed together, which reduces the need for material cutting (and resulting material waste).

Additional Muda Minimization

The practices of leveling out the production line and reducing material waste have been adopted by the case company, as explained in the previous sections, to reduce waiting times and overprocessing of materials. Waiting and overprocessing of materials are categorized as Muda, which refers to any activity that does not add value to the final product (Liker, 2004). The company also takes measures to reduce other types of Muda, such as unnecessary transport of materials or movement of workers. Excessive transportation waste in particular, it should be noted, can lead to other adverse outcomes, including material damage, ergonomic problems, and unsafe working conditions (Pérez & Costa, 2018).

The case company has redesigned its factory layout to minimize unnecessary transport of material and excessive movement of workers. Material preparation mills as well as material inventories have been relocated to within close proximity to the workstations at which they are needed (refer to Figure 6 and Figure 7). One example was moving the mill for cutting sheathing to a location closer to the sheathing station. This has significantly reduced the time wasted on delivering pre-cut sheathing from the mill to the workstation.

Another example is the setup of the framing workstation. An automated feeding machine transfers pre-cut studs to a location from which the worker can directly pull them without needing to move from one location to another. Moreover, a workstation at which subassemblies for window and door openings are separately framed (before being directly nailed to the wall panel frame at the framing station) is located directly next to the framing workstation. Once the subassemblies for openings have been framed, they are placed on a table located between the two workstations in the same order in which they will be required by the framer. Such practices have contributed significantly to minimizing Muda.

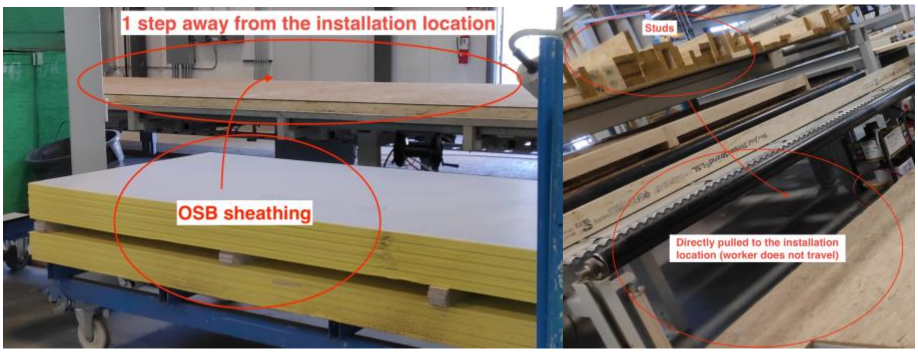


Figure 7: Material Inventories and Installation Locations

JUST-IN-TIME DELIVERY

The just-in-time (JIT) philosophy aims to deliver exactly what is needed when it is needed (Liker, 2004). The importance of such a philosophy is manifest in terms of reducing inventory and its corresponding drawbacks (e.g., storage requirement, material damage, material waste, double-handling, overproduction). The most notable example of JIT at the case company is its practice of procuring material and parts from the suppliers who pose the least risk in terms of delayed deliveries. For example, the company procures doors and windows from a local supplier who regularly delivers the ordered parts one day before installation. Moreover, the workers do not transport the delivered parts to the door and window installation workstation until the morning of the scheduled day of installation.

5S PROGRAM

The "5S" (*sort, straiten, shine, standardize, and sustain*) program is an important lean concept that helps to mitigate the risk factors that can result in errors, defects, and injuries in the workplace (Liker, 2004). A dirty and disorderly work environment is associated with inefficiencies, defective production, and safety hazards (Patra et al., 2005). As such, the implementation of the 5S program to address these issues has been proven to improve the performance of manufacturing systems (Omogbai & Salonitis, 2017).

The 5 Ss are clearly manifest in the case company's daily operations. For instance, only the tools and materials that are needed for a given activity are on hand (Sort). Moreover, every tool or material has a place, tagged with its corresponding label, and can be found in its place when not in use (Straighten). These practices are easily observable at the plant, as is the commitment to keeping the workplace clean (Shine). Although working with wood generates a considerable amount of sawdust and wood scrap, the floor is kept clean at all times. In addition to this, the mills are equipped with sawdust collection systems that workers must check and empty as needed on a daily basis. All cleaning instructions are clearly outlined in the company's SOPs and are part of the workers' daily routine (Standardize) as shown in Figure 8. Maintaining the S standards is critical to ensuring their ongoing beneficial effect (Sustain). As such, the practices of “Sort”, “Straighten”, and “Shine” are continually reinforced at the case company. For instance, it is well-established at the company that an employee should be confident at any given time to eat a slice of pizza that has been dropped. The president actually did this, reinforcing in a memorable and tangible way the importance of maintaining a clean and orderly workplace.

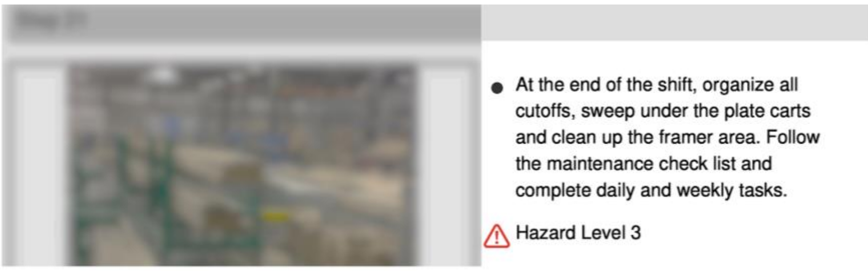


Figure 8: Snapshot from a Standard Operating Procedure

CONCLUSIONS

This paper highlighted the value gained from adopting lean practices at a construction manufacturing company. An analysis of actual and estimated productive, waiting, and delay times recorded and simulated, respectively, for the framing operations undertaken in two different years revealed significant changes in productivity corresponding to increasing implementation of lean principles. In particular, the same productivity models were used to estimate productivity-related measures for production days in two different years.

The results show that the simulated combined productive and delay times at the framing workstation represented an underestimate of actual times with respect to the 2013 data but an overestimate of actual times with respect to the 2017 data. In other words, the case company’s actual productivity performance has generally improved over the years corresponding to its adoption of lean thinking and a culture of continuous improvement. Accordingly, some of the most prominent lean changes made to the case company’s wall production line over the years, which contributed to the overall productivity improvements that the company has realized, were identified and described. These include standardizing the design and manufacturing processes, minimizing different types of waste, including Mura, Muda, and material waste, ensuring a continuous flow, balancing the production line, following a JIT approach for the delivery of parts, and implementing the 5S program.

It should be noted that the direct effect of implementing lean principles is difficult to measure, as numerous factors could alter the results. Specifically, if a very well-defined change is made to operations, corresponding variations are not necessarily solely attributable to this particular change, given the various sources of variability encountered in such working environments. Nevertheless, we observed general trends of productivity improvement accompanying the implementation of the operational changes.

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