Proceedings of the 2020 Winter Simulation Conference
K.-H. Bae, B. Feng, S. Kim, S. Lazarova-Molnar, Z. Zheng, T. Roeder, and R. Thiesing, eds.

DEPLOYING DISCRETE-EVENT SIMULATION AND CONTINUOUS IMPROVEMENT TO INCREASE PRODUCTION RATE IN A MODULAR CONSTRUCTION FACILITY

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ABSTRACT

Aiming at continuous improvement, a modular construction company attained favorable results by implementing recommendations that were based on value stream mapping analysis. Yet, there is still a need to assess the production lines in a unified and integrated manner. As such, this study employed simulation to model five major production lines in the factory to evaluate their performance concurrently and suggest improvements. Bottlenecks were identified by tracking the waiting times at different stations, and an iterative and sequential approach was adopted. After eight suggested improvements and tested scenarios, results showed a 17.8% reduction in the unit cycle time and 22% increase in the weekly production rate. The study's major takeaway is the importance of studying improvements in an integrated manner to avoid shifting bottlenecks, achieving local improvements that do not guarantee global improvements, and underestimating the effect of minor changes on the overall process. Simulation modelling helped target these issues.

1 INTRODUCTION

The construction industry's productivity is perceived to have fallen behind that of other sectors for decades and action is needed in different areas to improve this productivity (McKinsey&Company 2017). A tenfold productivity increase could be achieved if the industry moves to a more standardized manufacturing-like production system through the use of modules built in offsite factories (McKinsey&Company 2017). This approach is called modular construction manufacturing, where the units or modules are manufactured in a facility and, then, on-site assembly and installation are performed. This is considered a more efficient and time-cost effective strategy in construction projects, even in the context of high-rise buildings (Lawson et al. 2012). Accordingly, more attention is given to improving modular construction processes at the factories to harness the benefits of modular construction.

Numerous studies have employed a variety of well-established tools, such as simulation and value stream mapping, and established philosophies, such as the lean philosophy to analyze and optimize construction manufacturing processes. Although successful implementations of value stream mapping have been recorded in this context (ex: Moghadam and Al-Hussein 2013; El Sakka et al. 2016; Zhang 2017), it is usually avoided in situations where dynamic behavior and production complexities are encountered (Lian and Van Landeghem 2007). Alternatively, simulation is mostly effective when (1) problems are characterized by uncertainty and are technically complex, (2) repetition is evident, (3) an integrated solution is required, and (4) details and accuracy matter (AbouRizk 2010). Hence, simulation is deemed valuable for improving production processes. Yet it has been frequently used for modelling small portions of the factory independently of other parts (Afifi et al. 2016; Altaf et al. 2015; Ritter et al. 2017; Shafai 2012). This could create the risk of making changes of no added value as a result of shifting bottlenecks. A bottleneck is defined as the stage or element in the production system that has a dominant effect on slowing down the entire system (Roser et al. 2002). The problem of shifting bottlenecks has been recognized in practice, and researchers have invested in finding a means to mitigate this problem (e.g., Subramaniyan et al. 2016). When modelling portions of factory operations, a modification to any part of the production lines could potentially shift the bottleneck to a part that is excluded from the model. This implies that subsequent modifications will not have an effect on the overall factory operations in practice. Following the same reasoning, it is also integral to improve and analyze a process in a gradual manner. In this context, the concept of continuous improvement borrowed from the lean philosophy plays a vital role in avoiding unnecessary changes. Continuous improvement is defined as the small and gradual improvements that maintain and improve working conditions by targeting inherent wastes (Koskela 1992).

In light of this, this study aims at increasing the production rate at a modular construction factory through gradual and iterative improvements tested by simulating production on the floor, roof, and wall production lines as well as wall and roof erection stations as an integrated process. Specifically, the study covers the process from the start until the different elements are combined to form a box, excluding some minor activities that follow this stage, such as internal finishing processes. Factory production is improved by performing several iterations to identify and eliminate bottlenecks using the developed model. The case study presented herein is a continuation of the study performed by Zhang (2017) and is aimed at optimizing the manufacturing process at the factory using value stream mapping. Following the recommendations made by Zhang (2017), the factory currently has a more efficient process and a production capacity of about 12 boxes per week. However, the factory's ultimate goal is to reach a production capacity of 15 boxes per week.

2 METHODOLOGY

A well-defined methodology was followed in this study. The first step consisted of defining the experimental framework under which the process was to be modelled. This is an essential step as it results in specifying what factors should be modelled and what factors are not relevant to the purpose of the study. For this purpose, a factory visit was conducted, and work by Zhang (2017) on the facility's production lines was analyzed and built upon, with efforts to overcome its limitations. The scope of the study was defined such that five production lines were modelled and tested for improvements: floor, external walls, internal walls, roof, and roof/walls erection. Consequently, a convenient level of detail was selected as described in Section 4.1.

Then, data was collected, and a time study was conducted on the specified production lines to build the model in later stages. Based on the experimental framework, the conceptual model was developed, representing the links among the different production lines and stations. Assumptions adopted in the conceptual model are explained in the following section. Afterwards, the current state of the system with all the necessary details was modelled. A computer model using Simphony.NET (AbouRizk et al. 2016) was built to represent the current state.

The next step consisted of validating and verifying the developed model to ensure its soundness before experimenting with it. For this step, the authors selected two tests for model validation, *Event Validity* and *Face Validity,* and two others for verification, *Extreme Condition* test and *Parameter Variability- Sensitivity Analysis,* suggested by Sargent (2013). The *Event Validity* test consists of comparing the events in the model to the real system (Sargent 2013). The *Face Validity* test is associated with knowledgeable personnel who are familiar with the system and are able to assess whether its behavior is reasonable. As for the verification tests, the *Extreme Condition* test suggests testing the model for an extreme selection of factors or values and analyzing the output (Sargent 2013). The *Parameter Variability- Sensitivity Analysis* evaluates the variation in the output of the model based on changes in the input; those input-output relationships shall match the real system. It should be finally noted that the computerized model is automatically tested for an error-free simulation language when run. This feature is offered in Simphony as the coding language is simplified, and logical errors are reported in pop-ups to warn the user of such errors (AbouRizk et al. 2016).

After ensuring a valid and verified computer model, the results obtained from running the model were analyzed. Both cycle times and waiting times, explained under Section 4.2, were recorded at different stations, and bottlenecks were identified following each change in the model. When the main bottleneck was revealed in a system, it was approached by reducing the cycle time at the station. Accordingly, based on those two statistics, suggestions and tested implementations were performed. Then again, the results of the improved model were analyzed. This is a cyclic or iterative process that needs to be continuously performed to reach the intended results. Further details on these steps will be provided.

3 DATA AND ASSUMPTIONS

The data used for building the model corresponds to the stations, the activities performed on each station and their sequence, the duration of activities, and the type and number of resources allocated to different activities. The data were mainly obtained from two streams. First, a time study was conducted where different activities' durations were observed and recorded at different stations of the production lines. The time study was conducted after the implementation of several suggested improvements by the previous study. As such, data was recorded, and different probability distributions were fitted to the activities' duration data and fed into the model elements. Note that the data collection process was performed when the factory was operating at full capacity. Second, activities' durations data available for some of the production lines were not sufficient to obtain a good fit. Hence, triangular distributions were used in these cases, and the optimistic, most likely, and pessimistic durations for each activity were solicited from an expert who is familiar with the processes at the factory.

Two main simplifications were made for model development. First, the remaining stations that were not modelled were assumed to have a faster production rate with respect to the modelled stations. In other words, when a box is completed at the last station of the modelled portion, it directly leaves the station. Therefore, the suggested improvements would be fully effective for the overall factory's production process only if the assumption holds true. Otherwise, further improvements would be needed downstream of the modelled portion to realize the benefit. Second, scheduled breaks, process interruptions, and wasted time were not separately modelled, but rather embedded in the fitted distributions. In what follows, a thorough explanation of the process is provided and demonstrated in the current state model.

4 CURRENT STATE

4.1 Process Description

The current state model is based on the current practices at the facility. The floor, wall, and roof production lines are parallel to each other and flow to meet at the downstream wall and roof erection line. In the following sections, the tasks performed at the stations on each production line are presented along with their sequence.

4.1.1 Floor Production Line

There are eight workstations on the floor production line. In the first station (F-S1), the work begins with the framing of the wood-framed floor panel using rim boards and dimensional lumber joists. Then, floor sheathing is installed in the form of sheathing panels. The floor is then moved using a crane to the next station (F-S2) for plywood installation. After a specific portion of the floor is installed, the locations of the walls need to be marked on the floor. This is manually done through nailing small pieces of sheathing to the plywood where the walls are located. The floor is moved again using the crane to the third station (F-S3) for plumbing and electrical rough-in. Also, cross bridging between adjacent floor joists is performed at this station if required. Next, floor lamination (sanding then lamination) and floor cushion are performed as needed. These two tasks are lengthy and, hence, are completed in parallel, and each task is divided into two separate parts performed at the fourth and fifth stations (F-S4 and F-S5). The finishing of plumbing and electrical works is performed at the sixth station, F-S6. Afterwards, the floor needs to be insulated at the seventh station, F-S7. Finally, some final preparations are performed at the eighth station, F-S8, where a protective layer is placed on top of the floor before moving the floor to the wall erection station. It needs to be noted that no inventory is allocated between the floor workstations.

4.1.2 External & Internal Wall Production Lines

This production line is used for the production of external walls, including long walls and short walls. The stations and the corresponding tasks are defined in Table 1. Again, no inventory is allocated between stations. However, a limited storage area is assigned to store finished walls that are ready for erection.

Table 1: Stations and tasks for the external wall production line

Ex. Wall Station	Tasks	Sequence of Tasks
EXT-S1	Loading plates; Loading components; Loading studs	Sequential
	Nailing studs; Loading sheathing	Parallel
	Nailing sheathing for short and long walls	Parallel
EXT-S2	Installing boxes; Roughing in cables; Installing insulation	Parallel
EXT-S3	Gluing; Installing wrapping; Nailing wrapping; Cutting wrapping; Loading drywall; Fastening screws; Cutting drywall around the openings	Sequential

For internal wall production, there are only two stations, and it is noted that this fabrication process is relatively fast. Once the floor and the external walls are ready for erection, the next set of internal walls is initiated for production. At the first station (INT-S1), at which framing is performed, the following sequential tasks are undertaken: loading studs, nailing studs, and moving to storage. At the second station (INT-S2), the following sequential tasks are undertaken: installing electrical boxes, loading drywall, fastening screws, and cutting openings for electrical boxes. After the walls are completed, a crane is used to move them to storage. Here, the set of all the walls included in a unit shall be fabricated before they are moved for erection.

4.1.3 Roof Production Line & Walls/Roof Erection Line

There are two separate production lines for roofs, as their fabrication process is lengthy. However, the first activity of framing is undertaken at only one station, R-S1, on one of the two lines and is common for both lines. There is a parallel table on the second line, but it is currently used for the fabrication of trusses. At the second station (R-S2) on each line, the following tasks are performed: drywall installation, roof crack filling, electrical work, stack plumbing, air exchanger installation. At the third station (R-S3), the performed tasks include roof sanding, gyptex installation, wall painting, and in parallel to these activities, roof sheathing installation. The next stage consists of moving the roof to the erection phase using the roof crane. Also, no inventory exists between stations.

When the floor and walls are ready for erection, work commences at the Walls Erection station (WE). After finishing the wall erection stage, the unit is moved to the Roof Erection station (RE), where the roof is added.

4.2 Simulation Model

A simulation model was developed for the current state of the five production lines described above. The main purpose of the model is to identify bottlenecks throughout the system in order to experiment with different scenarios to improve weekly throughput. Accordingly, the model was designed to reflect the actual process and serve this purpose. Each production line was modelled separately and then merged with other lines at specific points in the process. A portion of the model is illustrated in Figure 1 below.

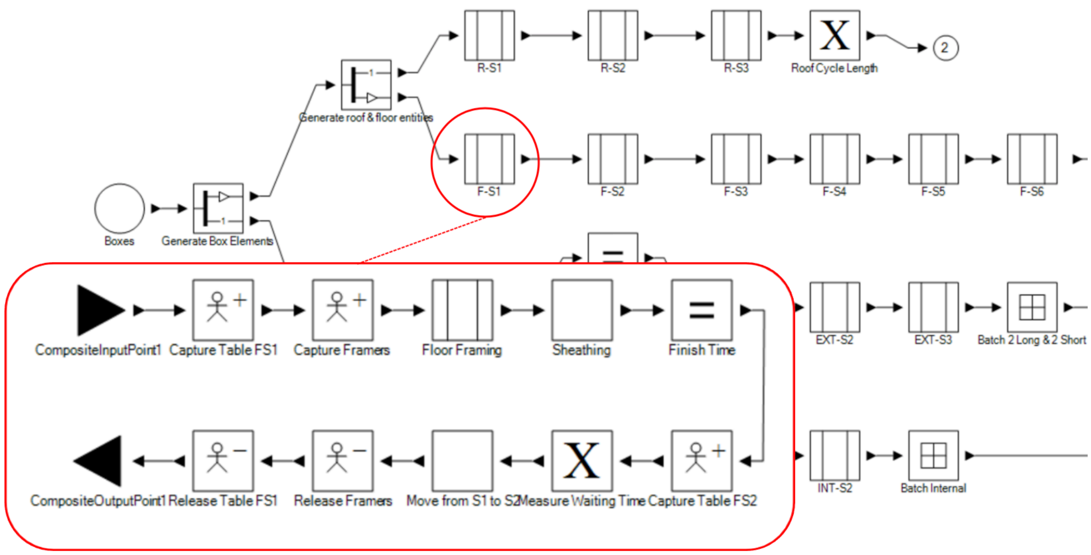

Figure 1: Portion of the simulation model.

4.2.1 Modelling Flow of Entities

The entity that flows between the modelling elements represents a box. When a box is created, it gets cloned into multiple entities to simulate the production of its components (i.e. floor, roof, short external walls, long external walls, and internal walls). Entities flowing through different lines represent the components that are processed on each line. Then, on each production line, each entity becomes ready to flow from one station to the next after all the activities are completed at the former. Since no inventory is allowed between stations on the roof, floor, and external wall production lines, entities flowing through these lines cannot leave one station until the following station becomes available. This was modelled by defining each station as a resource with one server and forcing the entity to capture the resource corresponding to the next station before it can start the following activities. If the server is not available (i.e., there is work in progress at the next station), the entity starts waiting, and all the resources assigned to the station it is occupying become idle. Once the server becomes available, if the crane is needed for movement and is also available, the entity captures both resources and initiates the task of moving the entity to the next station. When the entity moves to the next station, the first station gets released for another entity to capture it and so on. The internal wall production line, however, has inventory between the two stations, and no similar conditions are imposed.

4.2.2 Modelling End-of-Line Conditions

When modelling an integrated process that involves multiple streams that merge with each other at specific locations, it is integral to meticulously represent the actual behavior at these points. At the end of the floor, external walls, internal walls, and roof production lines, the entities wait until they can capture the wall erection station and the crane, storage which is modelled as a resource with servers that designate space, an internal-wall storage server, and the roof erection station and the crane, respectively. If any of these resources are busy (e.g., a station is occupied, the storage is full, or the crane is busy), the flow on the corresponding line ceases. Once a floor is moved to the wall erection station, a batch of two long and two short external walls are taken from the storage, and the corresponding space servers get released. Similarly, the internal walls get pulled from the storage, releasing its servers, and a new entity flows into this production line to initiate the fabrication of a new batch of internal walls. Internal walls production is fast enough not to delay the whole manufacturing process despite the current state setup. Finally, the entity that completes the tasks at the wall erection station requires to capture the RE station to start moving to the latter. Since the roof entity needs to capture this station simultaneously, two distinct resources are defined to represent the roof erection station, one for the roof entity and one for the consolidated floor and wall entities (i.e., a box without a roof).

4.2.3 Statistics Collection

Two main performance measures are collected from this model: 1) The cycle time of each element (floor, external wall, internal wall, roof, and box), which is defined as the time between two consecutive pieces of this element coming off the production line's end. In other words, it is the difference between the time at which the fabrication of one element (e.g., first floor) is completed and the time at which the subsequent element (e.g., second floor) is finished. 2) The waiting time at each station that measures the duration starting from when entities complete the tasks at one station and when they become capable of moving to the following station. These two variables, cycle time and waiting time, are used to identify where improvements are needed in the process as well as the impact of any implemented changes on the whole production process. In particular, if this measured waiting time at a certain station is long, it indicates there is a bottleneck downstream from the station (i.e., the upstream process is faster). Alternatively, if this waiting time at a station is very short, it means the bottleneck is at or upstream from this station (i.e., the downstream process is faster). Hence, if a station has a waiting time shorter than that of all the stations upstream and shorter than that of the stations that are downstream (i.e., the minimal value), then this station constitutes a bottleneck in the process. Then, changes in the cycle time of boxes are traced to evaluate the effect of any modifications made in an attempt to remove the bottleneck from that station.

Cycle times are collected by defining a global attribute at the end of each production line. This attribute takes the value of the current simulation time whenever an entity flows through it. Before the attribute takes the updated time value, the difference between the current simulation time (i.e., the time at which the current element left the last station on the production line) and the current value of the attribute (i.e., the time at which the previous element left this station) is collected. As for the defined waiting time at each station, it is computed by defining two local attributes. The first attribute takes the value of the simulation time at which an entity completes all the tasks at one station; meanwhile, the second attribute records the time at which the entity starts moving to the next station. When an entity starts moving again, the difference between the values of these attributes is recorded. This difference is a measure of the waiting time at that particular station.

4.3 Verification & Validation Results

First, the *Event Validity* method was performed by comparing the cycle time of one complete unit to be fabricated to the actual factory production rate. The current state model revealed a production capacity of 11.8 boxes per week, which matches, approximately, the full-capacity production rate of 12 boxes per week at the factory. Additionally, the current state model has cycle times that are close to the real system, indicating the validity of the model by reflecting the real system. Second, for the *Face Validity* test, the model was evaluated by an expert who is knowledgeable with the production at the factory; assistance for checking the logic of the conceptual model and examining the reasonableness of the model inputs and outputs was offered. Third, the *Extreme Condition* test was implemented by eliminating the table resource in R-S1 (i.e., setting the number of servers to zero). This resulted in having zero cycle time for the roof and, accordingly, zero cycle time for the box, which couldn't be completed without the roof element. Other production lines still completed their processes until no flow was further possible since roof erection cannot start. This is in line with the real system since the production of the roof would stop if the station is not available for processing. Finally, the *Parameter Variability* test was done by only changing the duration of the bottleneck floor laminating activity on the floor production line. The duration was increased by 40% to check the effect on the floor cycle time and overall production. The results showed an increase in the cycle time of all production lines of around 16% (from 228 min to 266 min). The production decreased from 12 units to 10 units per week, which is logical given the fact that the task was already slowing down production, and the station was a bottleneck. This again verifies that the model is working accurately.

4.4 Model Results & Discussion

The model was run 100 times to obtain representative statistical figures pertaining to the actual manufacturing process. The average cycle time of boxes under the current conditions is 228.6 min with a standard deviation of 1.5 min. This translates into 11.8 boxes produced per week, on average, at the end of the portion of the process modelled in this study. A histogram summarizing the average cycle time results of the 100 runs is shown in Figure2.

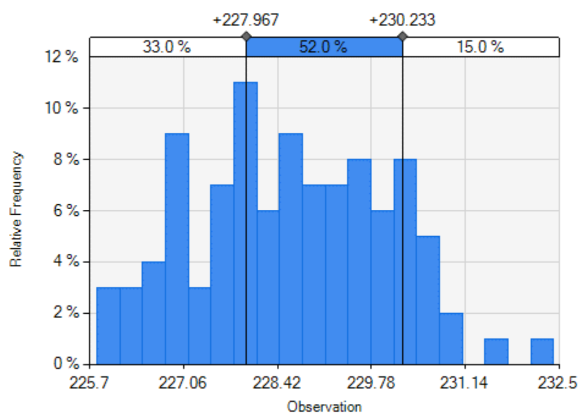

Figure 2: Current state model results.

The waiting times at different stations on the floor, external wall, and roof production lines, as well as the wall erection station, are summarized in Table . Note that the waiting times on the internal wall production line are not listed as the cycle times at both stations are very short relative to all the other stations in the process. This implies that the bottleneck will not transfer to this line unless major improvements are implemented on all the other lines. On another note, since the model represents a portion of the real process, the waiting time at the last station (i.e., roof erection) will always be zero since there is no restriction on the flow of entities out of that station. In reality, the waiting time at this station is dictated by the whole process. Thus, changes are first made in the upstream stations, and once realizing further improvements becomes challenging, modifications at the roof erection station are investigated.

Table 2: Waiting time results under current state.

Floor				External Wall		Roof		Wall Erection
Station	Avg Wait (min)	Station	Avg Wait (min)	Station	Avg Wait (min)	Station	Avg Wait (min)	Avg Wait (min)
F-S1	90.4	F-S5	0.9	EXT-S1	43.8	R-S1	13.1	5.7
F-S2	1.1	F-S6	18.1	EXT-S2	39.4	R-S2	129.7	-
F-S3	1.6	F-S7	1	EXT-S3	23	R-S3	200.3	-
F-S4	1.3	F-S8	3	-	-	-	-	-

From this table, it can be seen that the shortest waiting times are found on the floor production line. This means that the floor production line is currently dictating the speed of the whole process. As a first note, multiple stations with the shortest average waiting times have close values which imposes the risk of not realizing significant improvements in the overall process if changes are made at only one station. This is because the bottleneck would shift to another station, which has a similar limiting performance. However, it is essential to experiment with the model to evaluate the effect of each change at a time as the results cannot be accurately anticipated given the stochastic nature of the process. Hence, it could be said that the F-S5 is the bottleneck under the current state of the process, with an average waiting time of 0.895 min. It should be noted that the noticeably long waiting times at R-S2 and R-S3 are due to the fact that there are two lines for these stations while only one roof goes to the roof erection station at a time. Thus, the second line will not move until the roof erection process is over. The roof erection process's most likely duration is about 3 hours, which explains an average waiting time of 200 min at the third roof station. Based on these results, modifications are implemented in a sequential manner in the model, as explained in Section 5.

5 PROPOSED IMPROVEMENTS

The modifications that were applied to the model and their corresponding impact on the model are described in this section. For each iteration, the station with the shortest waiting time was identified, and improvements were proposed and tested. Although previously mentioned, it should be emphasized that sometimes targeting a bottleneck at a specific station will not reduce the box cycle time as the improvements would be absorbed by other bottlenecks that exist in the process. Hence, improving the model is an iterative process, and each applied modification must be revisited to maximize the positive impact of the change on the process relative to the invested cost. For example, if adding one extra laborer at a specific station is enough to move the bottleneck to another station, adding another laborer in that particular iteration is considered waste, i.e., it would result in an additional cost without any cycle time reduction in the overall process. The changes were made in the same order as listed below:

- 1st & 2nd improvements: The task of laminating the floor is the limiting activity at F-S5. This task is improved (i.e., accelerated) by adding a fourth laborer to the station. In reality, the effect on task duration of adding an extra laborer cannot be confirmed until tested. This is due to the fact that the productivity of a crew is subject to multiple influencing factors. Doubling the number of laborers does not imply a 50% reduction in the activity's duration. One example of similar factors is congestion; As more laborers are added, the space that could be freely accessed by a certain laborer decreases, which, in turn, could negatively impact the worker's productivity. To account for such factors, a 10% productivity reduction factor is applied when computing the new activity duration. Following this change, the station with the shortest waiting time became F-S4, the station at which the first part of the laminate and cushion flooring activities are undertaken. The same strategy of adding a fourth laborer is followed. Upon applying this change to the model, the shortest waiting time was found at the second station, F-S2, on the floor production line.
- 3rd improvement: The current practice of marking the wall layout on the floor at F-S2 is deemed ineffective. There are many automated means that could be employed to accomplish this in a much shorter duration. One commonly encountered method to mark floors consists of using a multifunction bridge. A multifunction bridge is a bridge that moves on side rails above the element and that, depending on the extensions it is equipped with, can be used for cutting, nailing, and marking precisely and quickly. Typically, the multifunction bridge can finish the nailing task in approximately 15 to 20 min. However, this duration depends on many factors including the size of the floor, the speed versus the accuracy of the machine, and others. To maximize the benefit of investing in this machine, it is proposed to combine F-S1 and F-S2 into one station. First, framing would be performed manually. Once it is done, the multifunction bridge would be used for sheathing, subfloor installation, and marking. Thus, two workers would be removed as the process

becomes automated, and workers who perform framing can operate the bridge. Implementing this change in the model moved the bottleneck to F-S7.

- 4th improvement: The insulation activity is currently a long process that could be shortened by adding a third worker. The same reasoning explained above was employed to decrease the task duration. By applying this change, the station with the shortest waiting time became R-S1.
- 5th improvement: The most suitable change to make at R-S1 is to relocate the truss fabrication process and use the corresponding table as a second table for roof framing. The space freed up from the floor production process could be used for this purpose. Adding another table for roof framing moved the bottleneck to F-S8.
- 6th improvement: A third worker is added to the preparation process at F-S8. The station with the shortest waiting time becomes EXT-S3. Given the nature of the activities performed at this station, which are relatively short, it is considered more practical to investigate the impact of incorporating changes at RE at this stage.
- 7th improvement: By adding one extra worker at the roof erection (RE) station, the station with the shortest waiting time becomes WE.
- 8th improvement: The cycle time at WE can be shortened by assigning an additional worker. After this improvement, the bottleneck moves back to F-S, and the pattern of waiting times tend to match, approximately, those of the current state model. Hence, additional reductions in the box cycle time mean going through the same iterations again. Thus, the improvement process is stopped at this stage.

The detailed results obtained upon incorporating each one of these proposed improvements, as well as the results of the future state model, are presented in the following section.

6 FUTURE STATE RESULTS, COMPARISON & DISCUSSION

Upon implementing the proposed improvements, the average cycle time of boxes became 187.8 min with a standard deviation of 1.3 min, which means that, on average, 14.4 boxes could be produced at the end of the process portion modelled in this study. A 17.8% reduction in the box cycle time was achieved. In other words, by implementing the proposed improvements, it is expected to produce, on average, 2.6 additional boxes per week. This is equivalent to a 22% increase in the number of boxes produced over a period of one week. The various improvements that contribute to this time reduction are summarized in Table 3. A histogram summarizing the average cycle time results of the 100 runs is shown in Figure.

Table 3: Time reductions following each improvement.

Ord -er	Proposed Improvement	Avg cycle time (min)	Time reduc- tion (min)	Ord -er	Proposed Improvement	Avg cycle time (min)	Time reduc -tion (min)
1	Add a worker to F-S5	228.6	0	5	Add another table for roof framing	209.2	8
2	Add a worker to F-S5	228.5	0.1	6	Add a worker to F-S8	205.2	4
3	Multifunction bridge instead of F-S1 & F-S2	219.6	10	7	Add a worker to RE	192.7	13
4	Add a worker to F-S7	217.8	2	8	Add a worker to WE	187.8	5

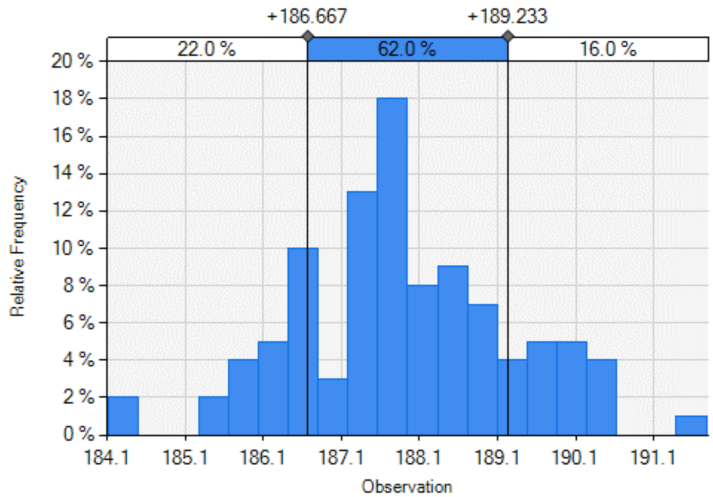

Figure 3: Future state model results.

The results support the theory that local improvements do not guarantee global improvements. In other words, accelerating activities at one station does not necessarily improve the overall production rate. Reducing cycle time at a bottleneck station in the first iteration and doing the same in the second station did not have any impact on the box cycle time. This is because multiple stations were simultaneously slow relative to the other stations in the process. If one station is targeted independently of the others, the overall cycle time would still be dictated by the others. It could be argued that adding one worker at RE was more effective than replacing the first two stations on the floor production line with a multifunction bridge. However, two important considerations must be highlighted in relation to this behavior. The first one is that the significant reduction of 13 min realized by enlarging the crew at RE would not have been possible if the previous improvements were not implemented. In fact, if this change is made before all the other changes, the process does not experience any improvement. The second consideration is that although the direct contribution of adding the bridge is not significant in this cycle relative to the size of the required investment, the accompanied benefits include and are not limited to 1) an increased production accuracy and, hence, less potential rework, 2) cost savings resulting from replacing the current workers, 3) freeing a significant area of the factory floor space (around 2,250 square feet), and 4) a step forward towards process automation and, thus, a higher level of standardization. Buying a multifunction bridge might be the only investment in the proposed scenario. In fact, with a proper analysis of resource allocation and utilization of individual resources, all the additional workers needed can be allocated from within the factory.

Although the purpose of the study is to improve the production rate at the factory, assessing the impact on the waiting times is of interest because waiting times represent pure waste and should not be compromised. The waiting times under the proposed future state are summarized in Table.

Table 4: Waiting time results under future state.

Floor				External Wall		Roof		Wall Erection
Station	Avg Wait (min)	Station	Avg Wait (min)	Station	Avg Wait (min)	Station	Avg Wait (min)	Avg Wait (min)
F-S1-S2	39.7	F-S6	18.1	EXT-S1	29.4	R-S1	159.1	6.5
F-S3	25.4	F-S7	0.9	EXT-S2	25	R-S2	82.3	-
F-S4	11.3	F-S8	4.6	EXT-S3	8.4	R-S3	116.1	-
F-S5	4.8	-	-	-	-	-	-	-

The waiting time at the roof framing station increased significantly, implying that this process became much faster than the downstream stations. This means that the resources allocated to this station will become idle for longer durations. Hence, it is not recommended to fully dedicate resources to the second table assigned for framing. Alternatively, the resources could be shared with other processes to maximize their utilization. Generally, the fluctuations among waiting times at the various stations are reduced. The standard deviation of the average waiting times at the stations decreased from 56.5 to 46 min. More similar waiting times indicate a more balanced process and facilitate reducing overall waiting in the whole process.

7 CONCLUSIONS

The following conclusions were reached based on this study:

- Local improvements in an integrated process do not guarantee global improvements in the overall process. The process might require multiple simultaneous modifications to realize the benefits.
- The bottleneck could easily jump from one production line to another. The stochastic nature of production processes aggravates this behavior. Hence, it is fundamental to consider the whole process if the purpose is to realize overall improvements. This would reduce the risk of making investments that have no significant returns.
- Sometimes making a minor change, such as allocating an additional worker to a station that does not have an economic burden, could have a significant direct impact on the process. Meanwhile, a major change might not be as effective if only the direct impact is evaluated. A closer analysis must be undertaken to assess the indirect impact a change has on multiple factors, including the utilization of allocated resources, unnecessary waiting, work quality, the total cost versus returns, etc.
- When no inventory is allocated between stations, the process becomes integrated. This means that a small change in a single activity can possibly impact the whole production. Hence, careful evaluations must be performed following any proposed change.

The study has shown the importance of deploying simulation to experiment with different scenarios. The uncertainty and variability in similar manufacturing processes make it almost impossible to locate which part of a process is slowing down the overall production. Moreover, it makes it difficult to predict what could happen in the process following some changes. Physical experimentations with similar processes are impractical and costly. Thus, simulation is a useful tool for evaluating the effectiveness and soundness of decisions aimed at improving a manufacturing process. It should be finally noted that a comprehensive cost analysis of the suggested improvements is important to ensure a proper return on investment. This will be addressed in detail in a future study in continuation of this research.

ACKNOWLEDGMENTS

This research is supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) under the Industrial Research Chair program (grant file no. IRCPJ 419145-15) and by Kent Homes in New Brunswick, Canada.

REFERENCES

AbouRizk, S. 2010. "Role of Simulation in Construction Engineering and Management". *Journal of Construction Engineering and Management* 136(10):1140–1153.

AbouRizk, S., S. Hague, and R. Ekyalimpa. 2016. *Construction Simulation: An Introduction Using Simphony*. 1st ed. Edmonton, Canada: University of Alberta.

Afifi, M., M. Al-Hussein, S. Abourizk., A. Fotouh, and A. Bouferguene. 2016. "Discrete and Continuous Simulation Approach to Optimize the Productivity of Modular Construction Element". In *Proceedings of the 33rd International Symposium on Automation and Robotics in Construction*, July 18th-21st, Auburn, Alabama, USA, 309-314.

Altaf, M. S., H. Liu, M. Al-Hussein., and H. Yu. 2015. "Online Simulation Modeling Of Prefabricated Wall Panel Production Using RFID System". In *Proceedings of the 2015 Winter Simulation Conference*, edited by L. Yilmaz, I. Moon, W. K. V. Chan, T. M. K. Roeder, 3379-3390. Huntington Beach, CA, USA: Institute of Electrical and Electronics Engineers, Inc.

El Sakka, F., K. Eid, T. Narciss, and F. Hamzeh. 2016. "Integrating Lean Into Modular Construction: A Detailed Case Study of Company X". In *Proceedings of the 24th Annual Conference of the International Group for Lean Construction*, July 18th-24th, Boston, USA, 23-33.

Koskela, L. 1992. "Application of the New Production Philosophy to Construction". CIFE Technical Report #72, CIFE Center for Integrated Facility Engineering Stanford University, Stanford, California.

Lawson, R. M., R. G. Ogden, and R. Bergin. 2012. "Application of Modular Construction in High-Rise Buildings". *Journal of Architectural Engineering* 18(2):148–154.

Lian, Y. H. and H. Van Landeghem. 2007. "Analysing the Effects of Lean Manufacturing Using a Value Stream Mapping-based Simulation Generator". *International Journal of Production Research* 45(13):3037–3058.

McKinsey&Company. 2017. Reinventing Construction: A Route to Higher Productivity. https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights, accessed 27th March.

Moghadam, M. and M. Al-Hussein. 2013. "Resource Optimization for Modular Construction Through Value Stream Map Improvement". In *Proceedings of the 21th Annual Conference of the International Group for Lean Construction,* July 31st-August 2nd, Fortaleza, Brazil, 503-512.

Ritter, C., Y. Zhang, R. Dupuis, and M. Al-Hussein. 2017. "Simulation of Production Line Improvement in Modular Home Manufacturing". In *Proceedings of the 25th Annual Conference of the International Group for Lean Construction,* July 9th-12th, Heraklion, Greece, 737–744.

Roser, C., M. Nakano, and M. Tanaka. 2002. "Shifting Bottleneck Detection". In *Proceedings of the 2002 Winter Simulation Conference*, edited by E. Yücesan, C. H. Chen, 1079–1086. San Diego, CA, USA: Institute of Electrical and Electronics Engineers, Inc.

Sargent, R. G. 2013. "Verification and Validation of Simulation Models". *Journal of Simulation* 7(1):12–24.

Shafai, L. 2012. *Simulation based process flow improvement for wood framing home building production lines*. M.Sc. thesis, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta. https://era.library.ualberta.ca/items/ca8c0775-1d20-4d8d-93a6-6566751d2e68/view/7cf4d2df-7cbe-4172-be37-4d48dc51524b/Shafai_Leila_Fall-202012.pdf, accessed 27th March 2020.

Subramaniyan, M., A. Skoogh, M. Gopalakrishnan, H. Salomonsson, A. Hanna, and D. Lämkull. 2016. "An Algorithm for Data-driven Shifting Bottleneck Detection". *Cogent Engineering* 3(1):1239516.

Zhang, Y. 2017. *A Framework to Improve Modular Construction Manufacturing Production Line Performance*. M.Sc. thesis, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta. https://era.library.ualberta.ca/items/69379a40-bd76-4155-8eb8-6c14e97b6ca3/view/d7aa37c3-005d-437c-be5c-a593dc77f6ff/Zhang_Youyi_201702_MSc.pdf, accessed 27th March 2020.

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