Abdel-Jaber, O., Itani, A., & Al-Hussein, M. (2022). Discrete Event Lean Value Stream Mapping Simulation. *Proceedings of the 30th Annual Conference of the International Group for Lean Construction (IGLC30)*, 153–163. doi.org/10.24928/2022/0118

HYBRID LEAN DECISION-MAKING FRAMEWORK INTEGRATING VALUE STREAM MAPPING AND SIMULATION: A MANUFACTURING CASE STUDY

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ABSTRACT

Lean value stream mapping has been applied extensively in manufacturing settings to benefit the industrial sector by boosting productivity, improving product quality, and decreasing capital costs, in turn leading to customer satisfaction and manufacturer profitability. Notwithstanding the benefits, lean value stream mapping can be enhanced to dynamically reflect the statistical productivity and economic improvements to enhance the process efficiency of production lines. Findings reported in the literature points to the benefits of integrating simulation-based tools with traditional lean value stream mapping in a hybrid framework to validate the feasibility of a given improvement. The main criteria are to reduce lean waste, increase productivity, and dynamically optimize manufacturing trade-offs for push–pull and just-in-time production systems by enhancing the efficacy of lean value stream mapping using a simulation-based approach. In this context, the proposed framework leverages value stream mapping to visualize the production system's current state. It then integrates the discrete-event simulation model in order to assess the various lean improvement scenarios proposed that to transform the system to its future state. The framework is implemented in a window manufacturing production stream to test and validate its feasibility in a mass customization environment. The case study results demonstrate the value of the framework in assisting decisions-makers to evaluate different scenarios and visualize their impact for better transformation.

KEYWORDS

Lean value stream mapping, simulation-based, push–pull, just-in-time, mass customization

INTRODUCTION

Lean management was introduced to the manufacturing industry by Toyota Production System, TPS at the beginning of 1930s as an innovative approach to competing with other world-leading car manufacturers. Lean management concepts focus primarily on achieving a continuous flow of value within the production system and on reducing waste

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by analyzing the activities in a production system to distinguish between value-added activities and non-value-added activities (Sundar et al., 2014). Value stream mapping (VSM) is a lean tool that helps to define, measure, and analyze the flow of the operation or process being transformed. VSM can be used to identify problems and propose countermeasures in plain, descriptive, and enthralling ways that often cause previously dubious team members to become supportive of the proposed changes. Moreover, it engenders a holistic, interconnected, “bird’s-eye” perspective within a collaborative team environment to direct the team to the "True North". However, as Abdulmalek and Rajgopal (2007) have argued, VSM alone may be insufficient to convince decision-makers to adopt lean management. They go on to suggest that while VSM can predict the future state of production with modest success, it falls short of accurately predicting some aspects of production, such as dynamic productivity.

This paper aims to develop a hybrid framework to aid management teams in identifying deficiencies in complex production systems and facilitate creating solutions by overcoming the limitations of LVSM. This tool would help decision makers to evaluate different scenarios and visualize their impact accurately by adopting trade-off analysis. Thus, helping management to implement lean concepts with a high degree of confidence of their impact on the production line. In this context. Discrete-event lean simulation (DELS) is a promising tool to complement VSM in assessing the future state of production. Moreover, economic feasibility studies must be conducted to evaluate the feasibility of implementing the proposed improvement measures identified using lean tools., and a trade-off analysis must be performed.

LITERATURE REVIEW

Lean principles were first developed by a Japanese car manufacturer, Toyota. When Toyota developed lean principles, they were striving to achieve a flow of activities with no waste in between (Sami Abdelhamid et al., 2008). Lean as a concept was first introduced to the west by “The Machine that Changed the World” book (Womacket al., 1990). The book successfully illustrated the differences between lean thinking and mass production (Melton, 2005). After the successful implementation of Lean principles, it grew in popularity and was adopted by many companies across various industries (Sami Abdelhamid et al., 2008). Lean success was mainly dependent on its focus on creating an uninterrupted flow of value-added activities and reducing waste. Producing high-quality products at the pace of customers’ demands with little to no waste (Larteb et al., 2015). Lean tools are tools that were developed to achieve this endeavor; however, the literature shows no consensus on what is considered a lean tool or not (Larteb et al., 2015). Nonetheless, some of the most known techniques and tools in lean management are just-in-time, continuous improvement, pull-flow, 5S, 5 why’s, last planner system, and lean value stream mapping.

LVSM was developed by the lean production movement as a tool to analyze the production system as a means to reorganize it with a lean vision (Lasa et al., 2008). First, LVSM is used to inspect the current state of the production system to develop a visual representation of the current plan. This visual representation mimics the current flow of materials and information to produce the product from its conception till its delivery to the customer (Belokar et., 2012). Showing cycle times, uptimes, etc as well. By then, analyzing the current state map, proposed solutions are developed to enhance the production system. Then, takt time is calculated and an LVSM of the future state is drawn. Subsequently, value is identified and lean techniques such as Kanban are applied to remove non-value-adding activities and bottlenecks to transfer the production system from the current state to the future state. Ensuring a seamless flow for the product through value-creating steps (Lummus et al., 2006).

However, despite the various advantages of LVSM, the literature showed multiple drawbacks. Schmidtke et al. (2014) stated in their paper that the most frequent drawbacks mentioned in the literature are mainly due to the static and low-detailed nature of the tool. For example, LVSM cannot handle describing multiple lines converging together (Braglia et al., 2009). Another prominent drawback is the difficulty of collecting relevant data in a complex production system (Forno et al., 2014). This is apparent when the data to be collected are not deterministic values (Braglia et al., 2009). The latter illustrated that this resulted in making LVSM an incompetent tool to analyze what-if scenarios. Last known problem is that LVSM does not give a clear indication about the feasibility of the proposed solutions. Hence, complementary tools shall be used to fill in the gaps where LVSM is not competent enough.

After a thorough investigation and examination of the literature, there was a clear trend encouraging the use of discrete event simulation (DES) in support of the LSVM. For instance, Grimard et al. (2005) stated that DES is essential for validating the output of multiple cells of manufacturing. According to the latter, this helps reduce the required time for such cells to reach their desired productivity. Also, illustrated in their work the promising capabilities of simulation in capturing complex production systems with variable data (Schmidtke et al., 2014). Lastly, for the cost-effectiveness of the proposed solutions, a feasibility study must be conducted to ensure the proposed solutions satisfy the customers' demands (Schmidtke et al., 2014). They also explained that the solutions sometimes require changes that might affect the quality and time of the production system, hence, a time-cost tradeoff analysis must be performed. Applying lean techniques such as push-to-pull, and just-in-time requires substantial changes to the production system. These changes seldom require continuous improvement and investment. Moreover, these changes might affect the quality of the products and the benefits are reaped later in time. Hence, trade-off analysis is essential for management teams to decide if the proposed changes justify the time, cost, and quality changes.

In researching the difference between LVSM and DELS, it can be concluded that LVSM can be utilized to assist the decision-maker in implementing the desired and feasible improvements by visualizing the production flow, identifying the bottlenecks and potential waste sources, creating the communication link that supports the information and material flow, and assessing multiple improvements scenarios. However, LVSM also has its shortcomings and limitations since it provides a stagnant representation of the process with limited view on the shop floor at a specific timeframe. Also, it becomes a time-consuming activity when dealing with complex manufacturing processes and different product families. In addition, LVSM main focus is on internal process analysis for a company, including scheduling, re-work, in-service quality, and material flow. Finally, the future state extracted from an LVSM exercise can be based on many inclusive and exclusive assumptions that can solve a secondary problem in isolation of the primary concern.

To overcome the limitations of the LVSM, DELS is utilized as an extension and alternative by providing the decision-maker with a dynamic representation and a digitized simulated process of the manufacturing process combing different product families. Also, it focuses on the external analysis merged with the internal one to include supply chain and logistics, market conditions and competitors, and customer demands.

METHODOLOGY

The methodology described in Figure 1 was developed to fulfill the research objectives and then implemented in a dedicated window production line. A high-demand product category within this plant was investigated and analyzed to improve overall throughput productivity without affecting the economic trade-off of the product and the overall business. First, the inputs to the framework were collected using a conventional time study in which the value-added and non-value-added activities were recorded. In addition, the resource allocation, sequence of operations, and production line settings were monitored, and data collected in a systematic manner. Next, information on daily orders, including product specifications and planned working schedule, was extracted from the company's Enterprise Resource Planning (ERP) database.

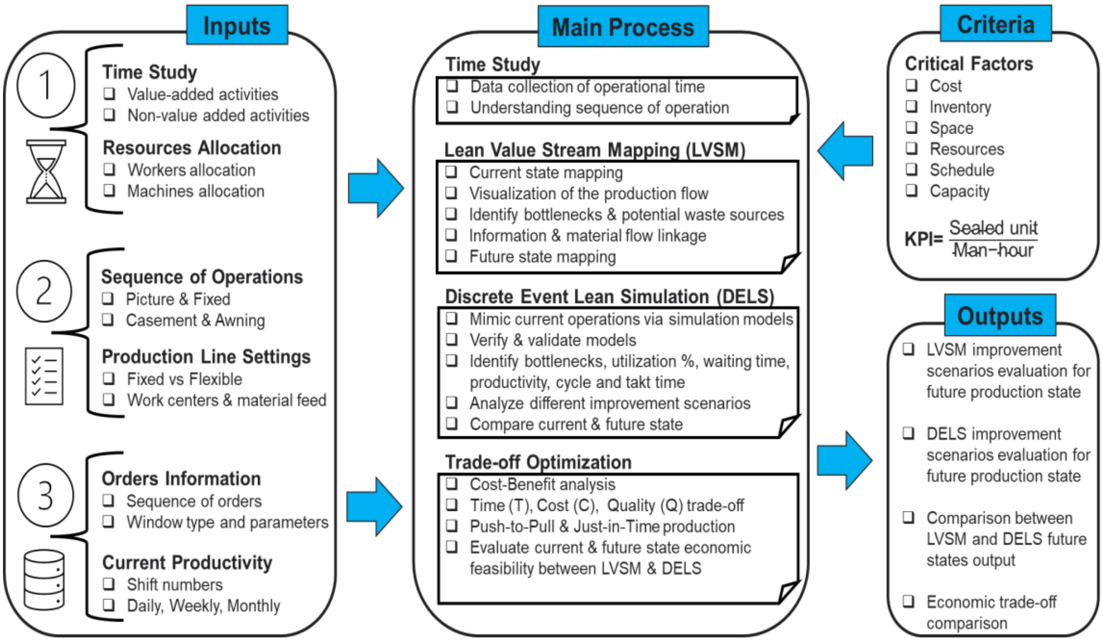

Figure 1: Overview of Methodology

Using LVSM, the current state of the production line was simulated in order to identify and visualize the eight forms of process waste identified in lean theory within the window production line. By deploying lean manufacturing methods to transform the production process from the current state to the future state, low-risk and high-risk process bottlenecks were identified, cycle and takt times were recorded, inventory and capacity limitations were flagged, and customer demand was linked with system information and material flow. It is worth noting in this regard that, in many value stream mapping cases, the desired future state can be reached by using the manual method explained in Rother & Shook (1999). This method helps the decision-maker to achieve a feasible future state that can be quickly integrated with the current production line.

However, using LVSM to define the future state can be overwhelming, time-consuming, and complicated in some instances. For example, predicting resource utilization and current and future stock demand during the production process is not achievable with such static models. To overcome these obstacles, a DELS model was built to mimic the current state of the windows production line. The simulation model was developed using Simphony, a simulation software developed at the University of Alberta as a dynamic modeling tool to emulate the manufacturing process (AbouRizk et al., 2016). The simulation model helped to visualize the desired dynamic features of the future state prior to implementation, thereby assisting decision-makers in accurately estimating the impact of the proposed changes on the production line. Before the implementation phase, the simulation model was verified and validated using statistical methods, current ERP data, and productivity analysis. The current and future process states were then compared based on six different scenarios.

It should be noted that simulation models are not used for economic optimization purposes. Thus, trade-off economic optimization was added to the framework to validate the scenarios from a cost-benefit perspective and using the time(T), quality(Q), and cost(C) trade-off technique for push-pull systems in addition to JIT production. Trade-off optimization, it should be noted, is a powerful tool for assessing proposed improvements before transformation takes place. Although this research focused on one particular window production line in a manufacturing setting, the proposed methodology can be modified and applied to other manufacturing cases as a generic hybrid framework, as illustrated in Figure 2.

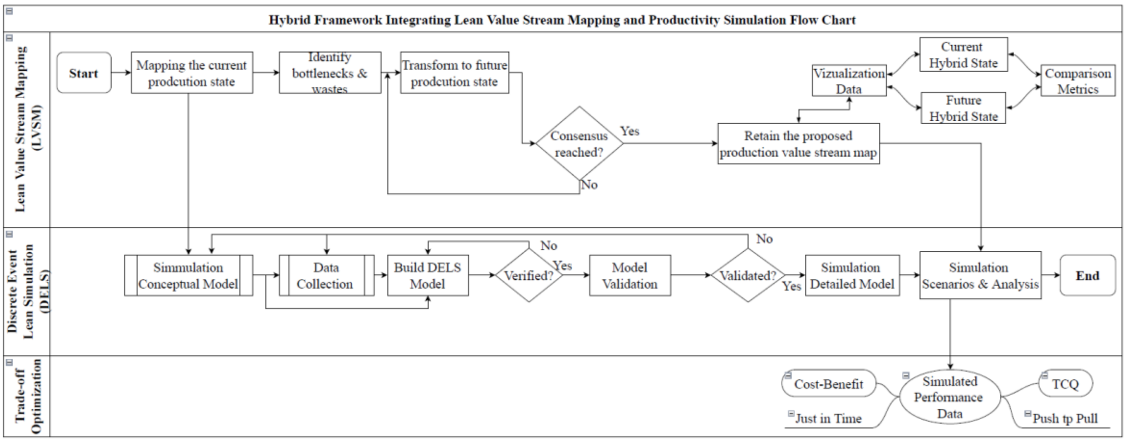

Figure 2: Hybrid Framework Flowchart

A WINDOW PRODUCTION CASE STUDY

A qualitative case study involving a window and door manufacturing company (referred to herein as “ABC plant”) was selected to test and validate the proposed hybrid framework. The main criteria governing this case study were to reduce lean waste, increase productivity, and dynamically optimize manufacturing trade-offs for push-pull and JIT production systems by enhancing the effectiveness of LVSM using a dynamic model created using a simulation-based approach. At the time of the case study, this ABC plant was under increasing pressure due to internal and external factors to ramp up production and throughput of Sealed Units (SUs) to meet customer demand. Accordingly, ABC plant's desired future state and productivity expectations included the following:

- Production of 45 SUs/day, based on current and future market needs (baseline production throughput is 28 SU/day).
- Order-to-manufacturing lead time of 10 days (baseline lead time is 13.57 days).

The proposed hybrid framework was implemented to measure and record the LVSM, DELS, and trade-off optimization outputs compared to the current baseline metrics based on the desired future state. The non-value-added activities, eight wastes, and bottlenecks were determined using the conventional VSM analysis tool. In ABC plant’s current state, windows are fabricated through several workstations, as described in Figure 3, where a combination of machines and workers are allocated in a hybrid push-to-pull and JIT production system. Each window undergoes a set of operations, including cutting, welding, cleaning, hardware installation, final assembly, glazing, quality check, and packaging before being shipped to the customer.

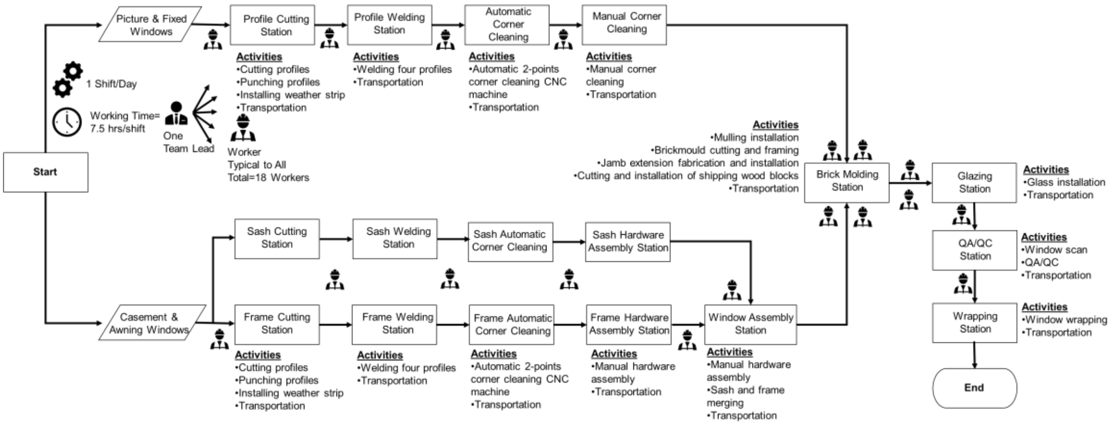

Figure 3: Sequence of Operations

LEAN VALUE STREAM MAPPING (LVSM)

Manufacturing systems do not usually operate in a linear manner because the number of workers varies from one day to another, predictability and performance deviate from the baseline, and unplanned breakdowns disrupt the process. The first activity in mapping a current process state is to select the product and its customizability options. Then, the typical process operations are mapped using LVSM to fully support better understanding of the overall process and to flag potential bottlenecks and sources of waste. Mapping the current state is an important step toward realizing the desired future state as a result of implementing appropriate process improvement measures identified in reference to the current-state map. In the present case, the inputs for this activity were imported from the company's ERP and Material Requirements Planning (MRP) systems.

The current-state map for the selected window manufacturing line using VSM notation (Rother and Shook, 2003) is shown in Figure 4. The calculations carried out in preparing the current-state map revealed that the value-added time of the process is 449.96 min while the production lead time is 13.57 working days. The process efficiency ratio was found to be 0.07 (or 7%), giving a clear indication that the selected window manufacturing process contains a variety of non-value-added activities. Next, the takt time was calculated using Equation 1, which assume a 7.5 hr (450 min) workday (excluding scheduled breaks) and that daily customer demand is 40 SUs/day

$$Takt\ Time = \frac{Total\ Daily\ Operating\ Time}{Total\ Daily\ Customer\ Demand} \quad (1)$$

The takt time was found to be 11.25 min/SU. The current-state map, it should be noted, represents a push-pull system combined with JIT production. The analysis revealed that operations such as profile cutting, profile welding, and automatic corner cleaning yielded cycle times lower than the takt time, while other operations yielded cycle times higher than the takt time as illustrated in Figure 4.

After visualizing and analyzing the current-state map and consulting with the management team, six different scenarios were proposed. The productivity improvement scenarios summarized in Table 1, were implemented in the simulation model with team consensus using pre-determined metrics to derive the future-state map.

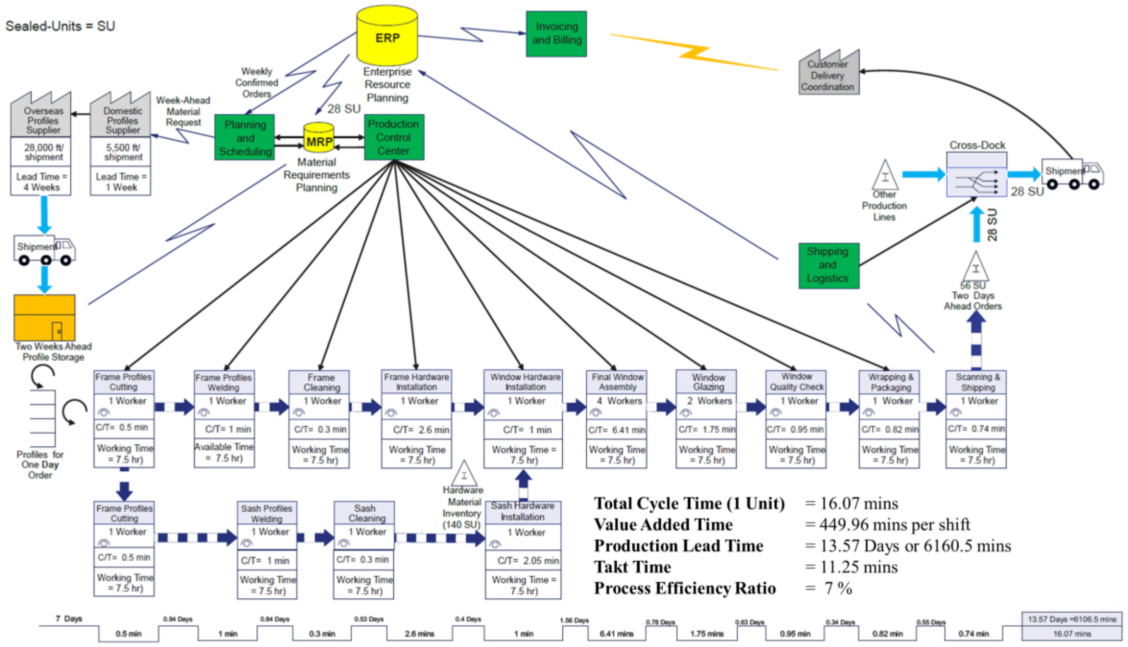

Figure 4: Lean Value Stream Map (Current State)

Table 1: Proposed Improvement Scenarios

Scenario #	Scenario Description
1	Implement 1D linear hardware installation process by changing the current production flow
2	Reduce window hardware search time by installing advanced hardware storage lighting bins
3	Improve the final assembly by installing semi-automated workstations
4	Reduce glazing search time by using smart glass organizing carts
5	Combination of Scenarios 1,2,3, and 4
6 A/B	Scenario 5 combined with a line balancing measure (i.e., adding/reallocating two workers

DISCRETE-EVENT LEAN SIMULATION (DELS) MODEL

The initial step in designing and developing a simulation model is to reflect the process's built and current state. In the present case, LVSM was the primary input in developing the simulation model. After visualizing the current state of the production line and analyzing its sequence of operation, allocated resources, cycle and takt times, bottlenecks, and waste sources, and setting out assumptions, the simulation model was built using the data collected from the ERP and MRP systems. A database for the simulation model containing all the relevant information was created using Microsoft Access and this database was then linked with Simphony.NET. The case study involved some inherent complexity due to mass customization and variations in operations leading to cycle time fluctuations, in turn, to different attributes being simulated.

The case study target was set to five days of production, June 5, 6, 7, 8 and 09, 2021. The simulation running time was 7.5 working hours, representing one working shift per day. The designed model was tested, verified, and validated using various methods and approaches to track the total number of SUs produced per day. All the tests indicated that the simulated model is close to reality and represents the current state with an average variance of just 6%, lower than the established simulation model threshold of 10%. After validating the simulation model, the six scenarios were simulated, and their results were compared to the baseline productivity rates as shown in Table 2.

Table 2: Scenarios Productivity Comparison

Productivity (SU/Hr)	LVSM			DELS			LVSM & DELS
Scenarios	Current	Future	Diff. (%)	Current	Future	Diff. (%)	Diff. (%)
Baseline	3.51	-	-	3.73	-	-	6%
1	-	3.77	8%	-	3.96	6%	5%
2	-	3.75	7%	-	3.81	2%	2%
3	-	3.96	13%	-	4.18	12%	6%
4	-	3.78	8%	-	3.86	4%	2%
5	-	3.88	11%	-	4.61	24%	19%
6A	-	4.29	22%	-	5.76	51%	34%
6B	-	3.24	-8%	-	3.46	-7%	-1%

TRADE-OFF OPTIMIZATION

Multi-objective optimization problems typically deal with conflicting target key performance indicators (KPIs) wherein an increase or decrease in one KPI will affect another KPI. Trade-off optimizations, meanwhile, is an essential tool that measures the change in KPI objectives relative to changes in others and then optimizes the values to provide the decision-maker with the best fit improvement by which to move from the current state to the future state. In this research, the economic trade-offs of the various improvement scenarios were calculated in order to validate the best fit scenario in terms of its capacity after LVSM and DELS were used.

Return on Investment (ROI)

In this research, ROI was implemented as an indicative analysis tool to decrease the uncertainty in selecting the best proposed productivity improvement scenarios from a financial perspective. Equation 2 is used to calculate the scenarios ROI.

$$ROI = \frac{V_I - C_I}{C_I} \quad (2)$$

where V_I = current value of the improvement in dollars, and C_I = cost of the improvement in dollars.

Cost-Benefit Analysis (CBA)

The Cost-Benefit Ratio expressed as Aggregated Cost-Benefit Ratio (ACBR), which quantitatively analyzes the comprehensive performance of the proposed improvement scenario, reveals the monetary value for the purpose of evaluating the comprehensive improvement performance of a given scenario, as illustrated in Equation 3.

$$\text{Aggregated Cost Benefit Ratio (ACBR)} = \frac{\sum EB}{\sum AC}\ x\ \sum_{i=1}^{n} \frac{C_F}{(1+r)^i},\ 0\ \leq\ \text{ACBR}\ \leq\ 1 \qquad (3)$$

where ∑EB represents the expected benefits, ∑AC represents the associated costs, C_F is the cash flow in dollars, r is the discount rate between 0 and 1, and i is the time of cash flow between 0 and 1.

Time-Cost-Quality (TCQ)

Researchers have introduced a variety of mathematical models for time-cost-quality (TCQ) trade-off analysis to tackle optimization under uncertainty. Equation 6 shows that if TCQ is a positive value, the improvement scenario will result in a higher concurrent trade-off that improves quality after implementation, while, if TCQ is a negative value, then the improvement scenario will result in a lower concurrent trade-off that improves quality after implementation.

$$TCQ\ Trade-Off\ Ratio = \frac{T_S}{T_B} x \frac{C_S}{C_o} x \frac{Q_I}{Q_B} \qquad (6)$$

where TCQ ranges between 0 and 1, T_S = time saved in minutes, T_B = baseline time in minutes, C_S = cost saved in dollars, C_B = baseline cost in dollars, Q_I and Q_B = improvement and baseline quality, respectively, between 0 and 1.

RESULTS AND DISCUSSION

The goal for this scenario productivity analysis is to find the bottleneck of the production line and determine the proper solutions to eliminate it. However, it should be noted that by performing changes in one station, another station may become a potential bottleneck. Therefore, this research takes into consideration this possibility and provides feasible solutions given the current manufacturing capacity while also not creating any new bottlenecks. After running and validating the simulation, bottlenecks are identified and some future-state scenarios are tested with the goal to reduce or eliminate their impact on the manufacturing line, always aiming for productivity improvement and line balancing. By comparing the production line's current state (using LVSM) with the future state (using DELS), the productivity rate for each improvement scenario was calculated. The comparison between scenarios is presented in Figure 5.

Given the case study constraints, limitations, and assumptions, Scenario 6A was found to be the best fit in terms of overall metrics with 63% productivity improvement. The company's current daily demand at the time of the study was 28 SUs/day, and, according to our analysis, the company could increase its throughput by an additional 15 SUs/day by implementing Scenario 6A. However, this improvement would come with a cost burden for implementation that would, in terms of ROI, entail a three-month payback period. Next, all improvement scenarios were compared to the LVSM and the DELS baseline. It was found that, by combining scenarios 1, 2, 3, and 4 (i.e., Scenario 5), ABC plant would boost its productivity from 3.73 SUs/day to 4.61 SUs/day resulting in seven additional SUs compared to the baseline productivity rate. However, this scenario would have a higher ROI compared to scenario 6A.

Meanwhile, it was found that removing two workers from the production line (i.e., Scenario 6B) would decrease daily productivity and increase the economic trade-off. The highest ACBR was that of Scenario 6A at 0.406. Although this scenario has a higher initial cost than the other scenarios, the financial benefit ultimately attainted is also considerably higher, with the total annual estimated savings of approximately $422,000.

As with ACBR, the highest is that of Scenario 6A at 0.254, meaning that this scenario entails more labor resources and a higher degree of automation, but also higher quality.

Table 3. Trade-off Optimization Results

Scenarios	**1**	**2**	**3**	**4**	**5**	**6-A**	**6-B**
Estimated cost ($)	$26,000	$8,000	$55,000	$6,000	$95,000	$115,000	$75,000
Current time (Mins) LVSM	3.60	1.00	6.41	0.75	11.76	9.41	15.68
Proposed time (Mins) DELS	1.58	0.20	4.41	0.35	6.54	5.23	8.72
Total time saving (Mins)	2.02	0.80	2.00	0.40	5.22	4.18	6.96
Total time saving (%)	56%	80%	31%	53%	44%	44%	44%
Productivity Rate (SU/Hr)	3.957	3.808	4.181	3.864	4.610	5.763	3.458
Difference from Baseline Productivity (3.733 SU/Hr)	0.22	0.07	0.45	0.13	0.88	2.03	-0.28
SU per day on 7.5 hrs shift (Baseline = 28 SU/day)	29.68	28.56	31.36	28.98	34.58	43.22	25.93
Average times a worker perform the activity /day (Ea.)	28	28	28	28	28	28	28
Average time workers spend on the activity (mins/day)	100.80	28.00	179.48	21.00	329.28	263.42	439.04
Savings in time (mins/day)	56.56	22.40	56.00	11.20	146.16	182.70	109.62
Current No. of Workers (Ea.)	1	1	4	2	8	10	6
Worker full burden rate ($/hr)	$38.00	$38.00	$38.00	$38.00	$38.00	$38.00	$38.00
Savings ($/day)	$36	$14	$142	$14	$740	$1,157	$416
Savings ($/year)	$13,074	$5,178	$51,781	$5,178	$270,298	$422,341	$152,042
ROI	1.989	1.545	1.062	1.159	0.351	0.272	0.493
ACBR (Months)	≈ 24	≈ 19	≈ 13	≈ 14	≈ 4	≈ 3	≈ 6
TCQ	0.126	0.050	0.124	0.025	0.325	0.406	0.244

CONCLUSION

This research investigated two productivity improvement tools for assisting decision-makers in evaluating productivity improvement scenarios prior to implementation: traditional lean value stream mapping and discrete-event lean simulation. The two tools were integrated into a hybrid decision-making framework to reduce lean manufacturing waste, increase throughput and productivity, and dynamically optimize economic trade-offs for push-pull and JIT production systems. The proposed framework was found to overcome the constraints and limitations of traditional lean value stream mapping by incorporating simulation. The robust hybrid framework was implemented in a case study to test its applicability and feasibility in the context of mass customization systems to demonstrate how simulation-based analysis can facilitate the transformation of the production system from the current state to the future state. Various productivity improvement scenarios were applied to a window production line. The results demonstrated the framework's validity in simulating and visualizing the impact of the different improvement scenarios on overall productivity, and therefore its value in assisting decision-makers in evaluating alternatives prior to implementation as part of a continuous transformation program.

Trade-off optimizations were then applied in order to assess each scenario from an economic perspective, demonstrating the utility of the framework supporting decision-makers in identifying the best fit improvement scenario. The framework was designed as a generative decision-making tool and was applied to different product streams under certain limitations and assumptions. Future work will include the development of a genetic algorithm to assess the trade-off optimization and Pareto analysis to evaluate competing objectives and measure their impact before implementation.

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