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Enhancing production efficiency through value stream mapping and simulation in the automotive industry

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ABSTRACT

Lean manufacturing and Value Stream Mapping (VSM) have long helped automotive companies uncover waste and streamline production. However, most studies treat VSM and simulation in isolation or focus on a single product line, leaving a gap in how to integrate them dynamically. This paper addresses these gaps by introducing the Multi-Machine Activity (MMA) approach to group-related tasks and operators into coherent cells for simultaneous analysis. This study aims to improve production efficiency by integrating VSM and discrete-event simulation via the MMA approach. We mapped current and future states of two steering-column assembly lines, collected cycle-time and inventory data, and validated improvement scenarios using simulation. The results show that non-value-added time reduces from 7.56 to 2.69 days for the guided model, and from 5.88 to 2.43 days for the non-guided one, while cutting lead time by over 60%. The contribution of the paper is threefold: we formalize MMA as a theoretical tool for dynamic VSM; we demonstrate its capabilities in a dual-model comparison; and we quantify total bottleneck elimination, thereby advancing lean-simulation integration theory. Finally, these findings confirm that the proposed approach enhances decision-making. These results pave the way to explore the integration of Industry 4.0 with lean techniques.

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1. Introduction

The automotive industry faces relentless pressure to deliver higher quality, lower costs, and shorter lead times. Lean manufacturing has become a cornerstone for eliminating waste and fostering continuous improvement [1], [2]. Value Stream Mapping (VSM) offers a visual framework for identifying non-value-added activities, while Discrete Event Simulation (DES) enables virtual experimentation with process changes before implementation.

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Several studies have explored the integration of VSM and DES in manufacturing, but most treat VSM as a static diagram, overlooking the dynamic interactions among operators and process variability [3], [4]. Moreover, existing implementations focus on a single product variant, limiting insights into how lean improvements perform across multiple product types. What is missing is a formal theoretical construct that unifies VSM and simulation into a single, dynamic framework.

In this context, this paper aims to introduce Multi-Machine Activity (MMA) as a novel analytical unit that groups co-located tasks and operators for simultaneous VSM and DES analysis. We apply the MMA approach to two variants of steering-column assembly within the same plant. Our objectives seek to develop and formalize the MMA construct within VSM theory, validate the MMA-VSM integration through Arena simulation for both product lines, quantify the elimination of bottlenecks, the reduction in non-value-added time, and the improvement in lead time.

2. Literature review

Today, the continuous search for practical solutions to improve the sustainability and competitiveness of industries has increased. Manufacturing faces increasingly complex challenges due to the integration of new technologies and high process variability. According to Soltani et al. [5], one of the main problems identified in production systems is identifying and minimizing waste along the value chain. The VSM is considered an essential tool within the lean philosophy for its ability to identify waste [6], [7]. Also, Hussain and Figueiredo [8] showed that grouping products allowed visualizing and improving processes. Ghosh and Lever [9] demonstrated in their VSM application a 50% reduction in process steps.

The future state map represents an optimized version of the production process, aligning production with customer demand. In addition, takt-time is an essential element for balancing workloads and reducing lead times [10]. However, its implementation faces significant barriers. Martínez-Cerón et al. [11] pointed out that, although VSM is simple and effective, its implementation may require support from other lean tools. Achmadi et al. [12] exemplified this approach by showing how VSM allowed mapping the flow of materials and information in a production process, promoting continuous improvements. Masuti and Dabade [13] documented their application in an excavator manufacturing company, with identification of rework and long setup times. Along these lines, Camacaro-Peña et al. [14] combined VSM with other lean techniques, such as Total Productive Maintenance (TPM), addressing problems related to lack of training and operational efficiency. Similarly, Aadithya et al. [15] implemented VSM in the manufacturing industry, integrating it with the Fuzzy TOPSIS method for the prioritization of lean tools in improving production flow. Gaikwad and Sunnapwar [16] reviewed the operational and environmental performance of integrating Lean, Green issues, and Six Sigma.

The VSM approach is not only useful in repetitive processes but can also be adapted to more complex production environments (see [17]). Stadnicka and Litwin [17] proposed an extended methodology by integrating VSM with System Dynamics Analysis (SDA). The quantitative impact of VSM has also been evaluated in recent studies. For example, El Kihel et al. [18] showed how VSM can be adapted to analyze the downstream supply chain in the automotive industry. In addition, VSM has evolved to include environmental and energy metrics to provide a more comprehensive perspective in terms of sustainability [19]. Hartini et al. [20] combined VSM with sustainability indicators on its environmental and social impact. Noto and Cosenz [21] proposed a Dynamic Value Stream Mapping (DVSM) including System Dynamics (SD) modeling to overcome the static nature and capture dynamic variations.

Similarly, simulation has been widely used to complement VSM, allowing a more accurate evaluation of improvement scenarios before implementation. Abideen and Mohamad [22] demonstrated the integration of VSM with DES. Zahraee et al. [23] identified bottlenecks and balancing production lines. In addition, Chud et al. [24] highlighted the usefulness of e-VSM to evaluate improvement proposals before their actual implementation. The combination of VSM with simulation has been shown to be especially effective in service systems [25].

Recently, the integration of VSM techniques with Industry 4.0 has spurred considerable research (see [26]), which investigated the combination of hybrid simulation with value stream mapping. Its goal is to comprehend changes in materials, processes, and information flows. Mariappan et al. [27] created a VSM model that can monitor manufacturing setups in real time by integrating with lean tools and Industry 4.0. Babaeimorad et al. [28] used an Industry 4.0 conceptual model and a mathematical model to suggest an optimal parallel machine-scheduling problem with preventive maintenance. Bozanic et al. [29] proposed a multi-criteria decision-making model to rank lean organization systems management approaches for maintenance. Liu et al. [30] suggested an integrated method that combines dynamic value stream mapping with hybrid simulation, considering variations in multi-product flows.

Table 1 presents a comparative overview of relevant VSM studies alongside the present work.

While a number of studies have demonstrated the practical benefits of combining VSM and simulation, as shown in Table 1, the theoretical contribution of the paper is based in the following three key aspects: i) We introduce MMA (Multi-Machine Activity), a novel approach that groups co-located tasks and operators into a single analytical unit. This MMA approach improves the traditional, static VSM by capturing the dynamic interactions and resource constraints of complex production systems. ii) By integrating simulation with VSM, it provides a formal alternative for testing and refining lean improvement hypotheses, closing a critical gap in lean theory between conceptual insight and more solid validation. iii) Bridging lean and Industry 4.0 domains, by studying how digital simulation functions as both a validation engine and a continuous-improvement enabler. This integration advances theory by showing that digital simulation does not simply support lean practices but actively co-evolves them, opening new avenues for research on digital-lean systems.

The remainder of the paper is structured as follows: the methodology is detailed in Section 2. The results are presented in Section 3. Finally, section 4 concludes the paper.

3. Materials and methods

3.1 Case company

The study was conducted at XYZ, a Tier-1 supplier of steering systems and driveline components in India. The plant employs over 200 staff and has eight assembly and machining lines. It operates two shifts per day and maintains a weekend maintenance

Table 1. Literature review

Study	VSM + Simulation Integration	Product Scope	Dynamic Framework	Main Contribution
F. A. Abdulmalek & J. Rajgopal [1]	Static VSM + DES	Process sector	No	Benchmark simulation case study
G. Gurumurthy & R. Kodali [3]	Static VSM + DES	Single production line	No	Lean system design via simulation
S. Kumar et al. [10]	Hybrid VSM sequencing	Manufactu-ring organizations	Partial	Performance enhancement via optimal VSM tool sequencing
Martínez Cerón et al. [11]	VSM as a management tool	Various industries	No	Cross industry VSM application framework
F. Achmadi et al. [12]	VSM + Ranked Positional Weight	Defense industry	No	Assembly process optimization
D. Stadnicka & P. Litwin [17]	VSM + System dynamics integration	Manufactu-ring line modeling	No	System dynamics enhanced VSM for line analysis
F. Cavdur et al. [25]	Simulation ba-sed VSM (case study)	Service systems	No	Lean service system design via VSM and simulation
W. D. P. Ferreira et al. [26]	Static VSM + Agent based approach	Industry 4.0 contexts	No	Agent based framework for I4.0 VSM
R. C. S. Mariappan et al. [27]	Static VSM + AI based modeling	Single production line	Partial	Intelligent VSM for Industry 4.0 adoption
S. Babaeimorad et al. [28]	Static VSM + Optimi-zation scheduling	Industry 4.0 production	Partial	Integrated production and preventive maintenance scheduling
D. Božanić et al. [29]	Static VSM + MABAC decision making	Technical maintenance	No	DIBR II–MABAC model for ranking lean system techniques
M. Liu et al. [30]	Static VSM + Hybrid Simulation (DVSM HS)	Multi variant production	Partial	Real time shop floor improvement via dynamic VSM–hybrid simulation
Present study	MMA+VSM + DES	Multi variant production	Yes	Dynamic VSM–simulation framework via the MMA concept

day. The facility holds TS 16949, ISO 9001, and ISO 14001 certifications. XYZ produces two steering columns with two variants, the guided W-501 model and the non-guided W-501 model, with a monthly installed capacity of 11,640 units.

The line combines manual and automatic operations, implying a semi-automatic process. Eighteen processes are required to assemble the guided W-501 model, while 16 processes are needed for the non-guided W-501 model. In total, 49 parts are used from 30 different suppliers. The line's workflow is designed in cells, where the same operator can perform multiple tasks within a group of operations. Currently, the layout of machines and stations generates a zigzagging process flow, with irregular movements of both materials and operators. This design increases transport and movement times, resulting in process waste. In addition, some stations have cycle times that exceed the takt time, causing delays between activities. Long lead times were also found to be high, which negatively affects process efficiency. To optimize its operations, the company seeks to streamline the process flow, reduce cycle times, reduce in-process inventory levels, and eliminate unnecessary transports and movements.

3.2 VSM implementation methodology

For this study, a lean manufacturing technique, specifically the Value Stream Map (VSM), was implemented in a complex automotive component assembly line. The tool was used to improve production flows and overall efficiency. The proposed process consisted of the following steps:

(1) Selection of the process. For this step, it is important to gather data on the process, such as cycle times, inventory levels, defect rates, and customer requirements.

(2) Initial analysis and Gemba walkthroughs. To gather data, a cross-functional team composed of personnel from different hierarchical levels was formed and conducted Gemba walkthroughs to observe the workflow in its operational context. During this procedure, tools such as the "Five Whys" and "5W2H" were used to identify specific problems. Table 2 summarizes the composition of the cross-functional team.

(3) Elaboration of the current state. In this phase, the corresponding VSM of the current state

Table 2. Cross-functional team

Designation	Department	Hierarchical Level	Role in Study
Head of Production	Operations	Senior Management	Oversaw project scope and resource allocation
Head of Manufacturing Engineering	Manufacturing Engineering	Senior Management	Provided engineering insight and validated cycle-time data
Head of Quality	Quality Assurance	Senior Management	Identified quality-related wastes and rework sources
Head of Production Planning & Control (PPC)	Production Planning & Control	Senior Management	Coordinated customer orders and material-flow data
Team Leader (Manager)	Manufacturing Engineering	Middle Management	Led VSM drafting and data-collection protocols
Team Leader (Manager)	Production Planning & Control	Middle Management	Managed information-flow mapping and forecasting
Assistant Team Leader (Supervisor)	Operations	First-line Management	Coordinated shop-floor schedules during Gemba walks
Assistant Team Leader (Supervisor)	Quality Assurance	First-line Management	Assisted in quality data gathering and defect tracking
Operator	Assembly Line	Shop-floor Staff	Participated in time studies and validated cycle-time measurements
Operator	Assembly Line	Shop-floor Staff	Supported material-flow observations and inventory counts
External Expert	–	External Consultant	Facilitated methodological design and simulation modeling
External Expert	–	External Consultant	Guided analytical framework development and theoretical formalization

of the production line was developed. This map included complete documentation of all stages of the production line, from receipt of raw materials to delivery to the end customer, as well as the relevant processes and work cells.

(4) Detection and evaluation of waste. Based on the analysis of the current state, the main problems of the line were identified, which included:
   a. Cycle times superior to the takt time
   b. Considerable time spent on activities that are not value added.
   c. Large quantity of inventory.

(5) Elaboration of the Future State Value Stream Map. Based on the results of the previous state, some lean manufacturing tools were implemented to optimize processes and improve efficiency. The adopted actions include:
   a. Cycle time reduction: simplification of tasks and redistribution of resources.
   b. Application of 5s: improve the organization of the workspace and reduction of search and transport times.
   c. Flow leveling: workload balancing between stations.
   d. Kanban implementation: efficient inventory management to avoid overproduction.
   e. Continuous flow optimization: elimination of flow barriers to reduce waiting times and improve synchronization between stages.

(6) Simulation models. To validate the improvements, discrete simulation models were developed in the simulation software Arena to evaluate both the current and future states. Arena version 16.1 is chosen due to its comprehensive process and resource modules, and built-in statistical reporting tools. Its specialized assembly-line features and intuitive graphical interface make it the most suitable choice.

(7) This analysis confirmed the benefits of the proposal before its implementation in the future VSM.

Once all the key activities of both processes are identified, the current value stream map was drawn up. In this VSM map, the activities corresponding to the guided W-501 model (represented in blue color) and the non-guided W-501 model (represented in red color) were distinguished, as shown in Figure 1.

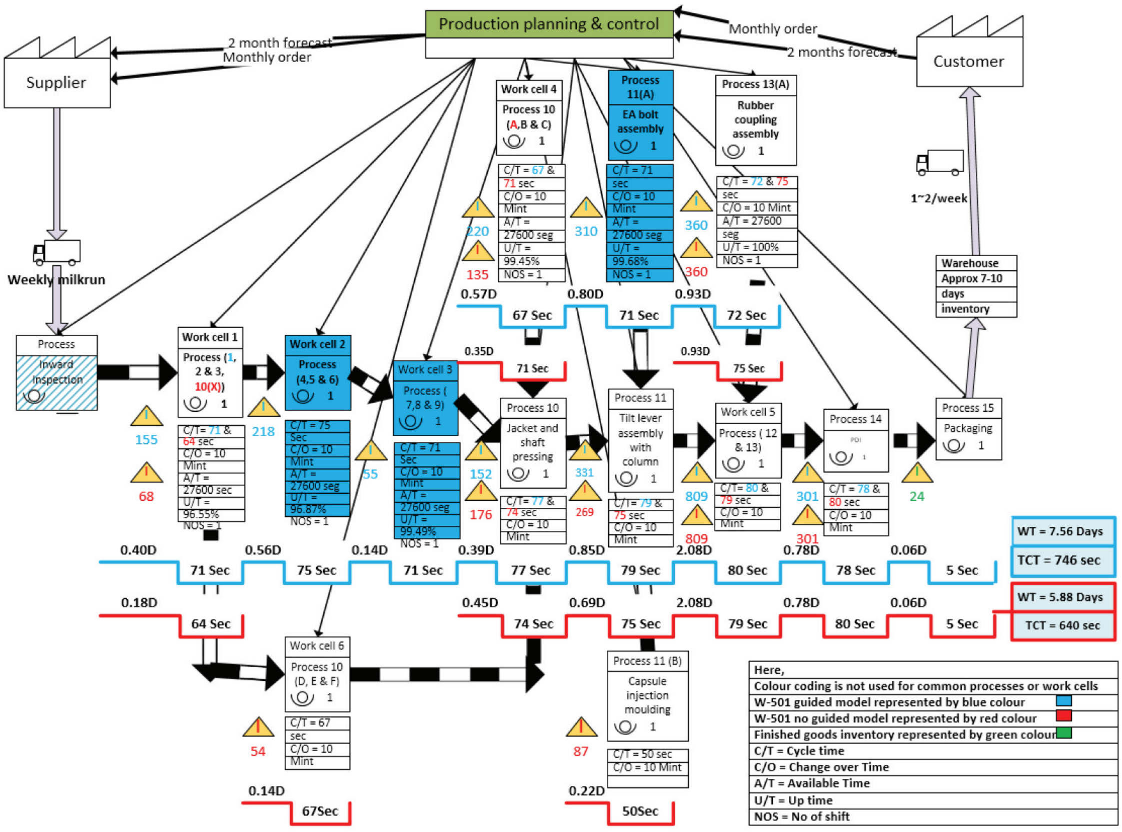

Figure 1. VSM for the current state [*source: authors own work*]

4. Results

4.1 Assessment of the current state

A key element of this study was the use of simulation modeling using the Arena software. Specific models were developed for the plant's two assembly lines. Detailed data such as cycle times, equipment availability, defect rates, operating shifts, inventory levels, and utilization rates were integrated into each simulation model. As an illustration, Figure 2 shows part of the simulation modules corresponding to the current state of the guided W-501 model line. These simulations were the base for identifying bottlenecks and evaluating waste levels.

The production of units has an effective working time of 460 minutes per shift. The customer needs 11,640 units per month; when converted to daily units, this leads to a requirement of 388 units per day. On the other hand, the takt time, necessary to meet the demand, is 71 seconds. With the help of the simulation carried out with the Arena software, the non-value-added activities were determined, which accumulated 7.56 days for the guided W-501 model and 5.88 days for the non-guided W-501 model. These times are significantly higher when compared to the value-added activities of the line. The analysis shows that the process ratio is critical since it is only 0.36% and 0.39% for the W-501 guided and W-501 unguided models, respectively. This indicates that the non-value-added activities are considerably higher compared to the value-added activities. To visualize in more detail both the value-added and non-value-added times of the current VSM are presented in Table 3.

Certain process steps in the guided W-501 model were identified as bottlenecks limiting the capacity needed to meet the daily demand of 388 units. To ensure that this demand can be satisfied, the lines need major improvement since several processes drastically reduce the production capacity. In particular, Process 10, Process 11, Process 13A, Process 14, Work cell N2, and Work cell N5 are the bottlenecks of the line since they surpass the takt time of 71 seconds. Hence, the goal of producing 388 units is not achieved due to the existence of multiple bottlenecks. In the current state, the line can produce only 345 units since its production capacity is defined by the slowest process that in this case is defined by the Work cell N5. Table 4 shows the cycle time, utilization, and daily production from the simulation model of the current state for model W-501 guided.

Regarding the simulation results of the current VSM of the unguided W-501 model, several bottleneck processes were identified. In particular, processes 10, 11, 13A, 14, and Work Cell N5, present a cycle time greater than the cadence defined by the takt time. This highlights the fact that major improvements are needed in the line. Given the existence of several bottlenecks, this line can only produce 345 units, a quantity that is far from the objective of 388 units per day. Relevant indices of the line are shown in Table 5.

The simulation of the current state of both lines reveals that, on average, 345 units can be produced

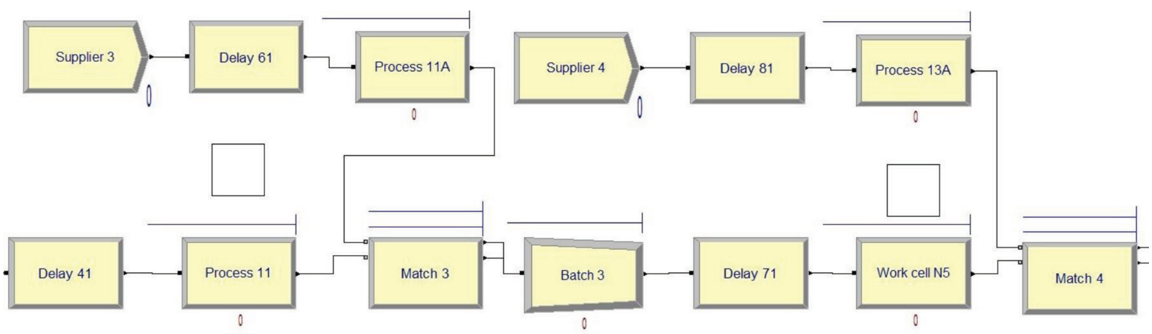

Figure 2. Simulation model for the guided W-501 model [*source: authors own work*]

Table 3. Indices of the current state

	Value added time (sec)	Value added time (min)	Non-value added time (sec)	Non-value added time (min)	Non-value added time (days)	Process ratio
Line W-501 guided	746	12.433	208776	3479.6	7.56	0.36%
Line W-501 non-guided	640	10.667	162398	2706.63	5.88	0.39%

Table 4. Simulation results of the current VSM of the guided W-501 model

	Average cycle time (sec)	Average cycle time (min)	Time required to meet daily demand (sec)	Utilization %	Daily production
Process 10	77	1.28	29876	108.25%	358.44
Process 11	79	1.32	30652	111.06%	349.37
Process 11A	71	1.18	27548	99.81%	388.73
Process 13A	72	1.20	27936	101.22%	383.33
Process 14	78	1.30	30264	109.65%	353.85
Process 15	5	0.08	1940	7.03%	5520.00
Work cell N1	71	1.18	27548	99.81%	388.73
Work cell N2	75	1.25	29100	105.43%	368.00
Work cell N3	71	1.18	27548	99.81%	388.73
Work cell N4	67	1.12	25996	94.19%	411.94
Work cell N5	80	1.33	31040	112.46%	345.00

Table 5. Simulation results of the current VSM of the non-guided W-501 model

	Average cycle time (sec)	Average cycle time (min)	Time required to meet daily demand (sec)	Utilization %	Daily production
Process 10	74	1.23	28712	104.03%	372.97
Process 11	75	1.25	29100	105.43%	368.00
Process 11B	50	0.83	19400	70.29%	552.00
Process 13A	75	1.25	29100	105.43%	368.00
Process 14	80	1.33	31040	112.46%	345.00
Process 15	5	0.08	1940	7.03%	5520.00
Work cell N1	64	1.07	24832	89.97%	431.25
Work cell N4	71	1.18	27548	99.81%	388.73
Work cell N5	79	1.32	30652	111.06%	349.37
Work cell N6	67	1.12	25996	94.19%	411.94

per day, which is equivalent to satisfy only 88.92% of the daily demand. In addition, the simulation results serve to visually identify process bottlenecks. In this regard, Figure 3 presents an operator balance chart of the production system, where we note that 11 processes surpass the takt time of 71 seconds (red line). These bottlenecks directly impact the system's ability to satisfy customers´ demand, and their elimination is the main goal of the study.

We complement the results with Table 6, which shows the total process time in the system, which includes both value-added and non-value-added activities. The simulation results indicate that the guided W-501 model needs 5.29 days to complete a unit, while the unguided W-501 model requires 4.40 days. These times are considerably high and represent an urgent necessity to improve the current production system.

The simulation models facilitated the identification of the relevance of implementing and adapting lean manufacturing tools and techniques to reduce process times and achieve the takt time, as well as eliminating or minimizing existing bottlenecks. The obtained results from the simulation of both models in the current state are presented in Table 7.

4.2 Assessment of the future state

The analysis of the simulation results of the current VSM for the W-501 and W-501 models revealed several inefficiencies and wastes that directly impact system performance. Among the most significant problems are the presence of multiple bottlenecks at critical stages of the process, excessive inventory buildup in certain processes, and process times that do not meet the requirements necessary to satisfy demand denoted by the takt time.

Based on this analysis, several improvement strategies were designed and included in the future VSM, and a second set of simulations was performed to

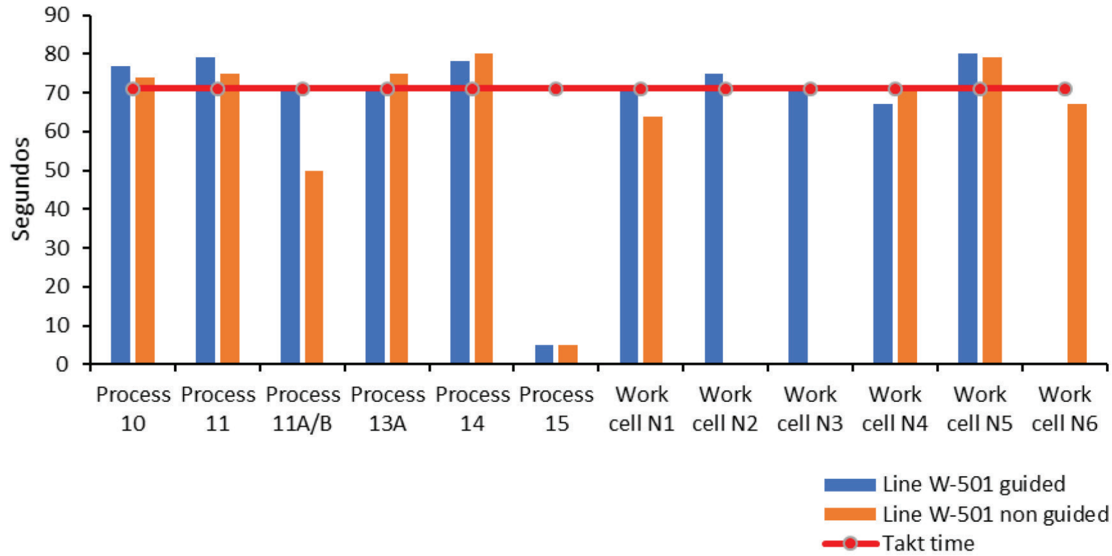

Figure 3. Operator balance chart of the current state [*source: authors own work*]

Table 6. Time in system of the current state

	Time in system (sec)	Time in system (min)	Time in system (days)
Line W-501 guided	146119.05	2435.32	5.29
Line W-501 non-guided	121472.86	2024.55	4.40

Table 7. Simulation results of the current state

	Value added (days)	Non-value added (days)	Production lead time (days)
Line W-501 guided	0.3	7.56	5.29
Line W-501 non-guided	0.2	5.88	4.40

evaluate their impact. These improvements include:

a) Line balancing by leveling to evenly distribute the workload to reduce bottlenecks.
b) Workflow structuring with Kaizen events focused on eliminating waste, reducing cycle times, and improving efficiency.
c) Introduction of a Kanban system to better manage inventories, reducing backlogs.
d) Optimization of work cells through standardization, increasing production consistency, and improving productivity.
e) Automation in critical manual processes, such as inspection and packaging stages.
f) Application of TPM, maximizing unplanned downtime.
g) Simplification of material transport routes, eliminating redundant movements, and reducing downtime.
h) Reconfiguration of final assembly stations.

Figure 4 presents the suggested changes within the future VSM.

The simulation models developed with the Arena software for the future state of the guided W-501 model include all the proposed improvements. As an illustration, Figure 5 presents part of the Arena modules for the W-501 model.

The future state simulation models lead us to observe that there is a significant reduction in the non-value-added time, besides a reduction in the value-adding time due to the use of several lean methods. In the guided W-501 model, the time that does not add value decreased to 2.69 days, while in the non-guided W-501 model, it was reduced to 2.43 days, reflecting a considerable improvement in both lines. Additionally, the process ratio increased to 0.94% for the guided W-501 model and 0.90% for the W-501 model, which implies the reduction of the non-value-added operations. Further details of these simulation outputs are shown in Table 8.

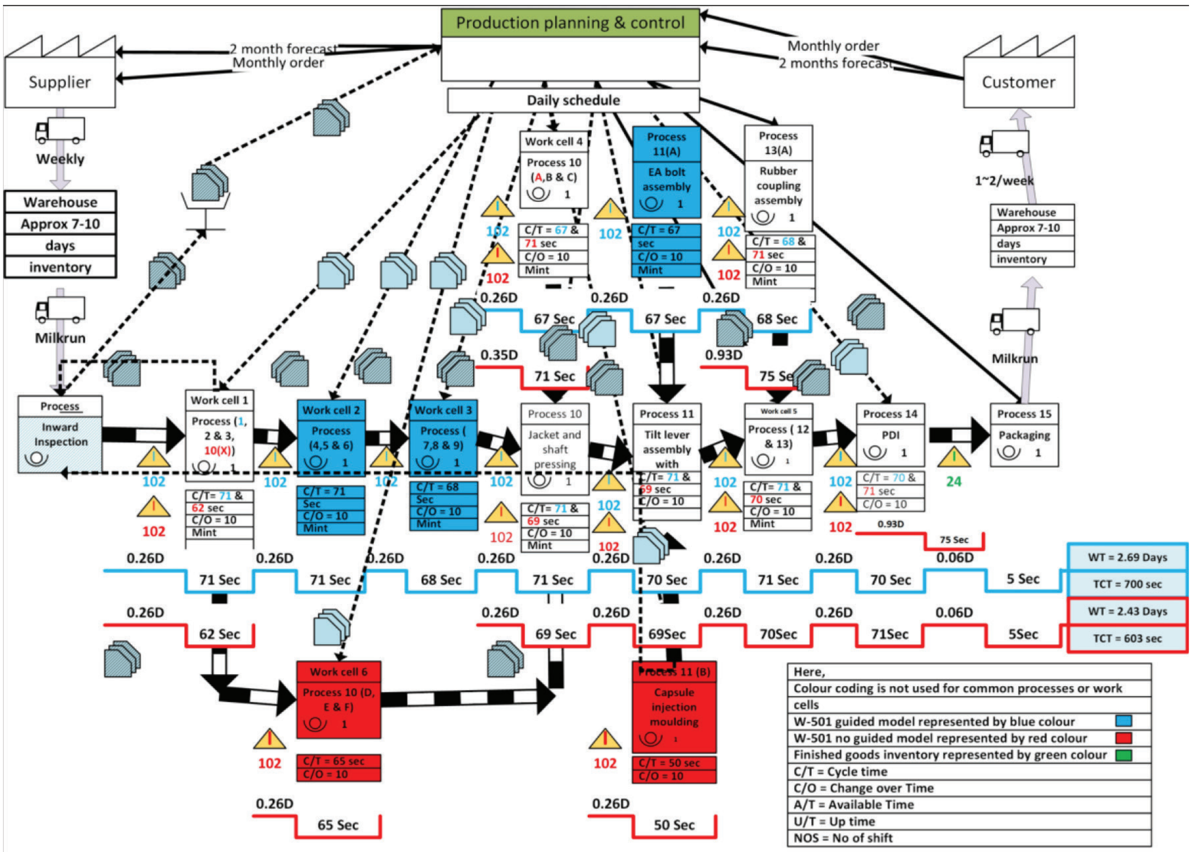

Figure 4. Future state value stream map [*source: authors own work*]

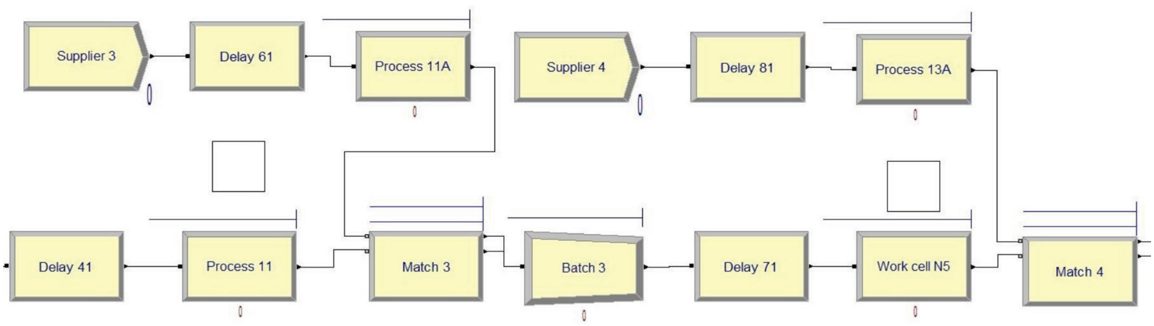

Figure 5. Future state simulation of the guided W-501 model [*source: authors own work*]

Table 8. Indices of the future state

	Value added time (sec)	Value added time (min)	Non-value added time (sec)	Non-value added time (min)	Non-value added time (days)	Process ratio
Line W-501 guided	700	11.67	74267	1237.78	2.69	0.94%
Line W-501 non-guided	603	10.05	67011	1116.85	2.43	0.90%

Through the lean improvements implemented in the future state, it was possible to significantly mitigate the problems related to bottlenecks. In the current state, eleven activities were detected that exceeded the takt time. However, in the future state, a reduction in cycle times and a more balanced workload were achieved. This allowed us to observe that in the future state, no activity exceeds the takt time. Table 9 presents the cycle time, utilization, and daily production of the future state of line-guided W-501, where we note that all the processes satisfy the takt time of 71 seconds. Hence, no bottlenecks are observed in the future state, and the goal of producing 388 units per day is also achieved.

Table 9. Simulation results of the future state of the guided W-501 model

	Average cycle time (sec)	Average cycle time (min)	Time required to meet daily demand (sec)	Utilization %	Daily production (units)
Process 10	71	1.18	27548	99.81%	388.73
Process 11	71	1.18	27548	99.81%	388.73
Process 11A	67	1.12	25996	94.19%	411.94
Process 13A	68	1.13	26384	95.59%	405.88
Process 14	70	1.17	27160	98.41%	394.29
Process 15	5	0.08	1940	7.03%	5520.00
Work cell N1	71	1.18	27548	99.81%	388.73
Work cell N2	71	1.18	27548	99.81%	388.73
Work cell N3	68	1.13	26384	95.59%	405.88
Work cell N4	67	1.12	25996	94.19%	411.94
Work cell N5	71	1.18	27548	99.81%	388.73

Table 10 presents the average cycle time, utilization, and daily production of the future state non-guided W-501 line. From the simulation results, we note that there are no bottlenecks in this future state and that this line achieves a production rate of 388 units per day.

Figure 6 presents the operator balance chart of the current and future VSM for line-guided W-501. We note that by implementing the lean techniques previously described in this section, we eliminated the 11 bottlenecks of the line. This improvement serves to attain the goal of production in terms of the quantity of units produced per day.

Figure 7 illustrates the operator balance chart for the non-guided W-501 model, showing that all the bottlenecks detected in the current state are eliminated. This yields to attain the production goals of the firm.

The implementation of the aforementioned lean improvements generated a significant benefit in the reduction of time in the system for both lines. On the one hand, the indicator of the time in system for the guided W-501 model was reduced to 1.92 days, while for the non-guided W-501 model, it decreased to 1.66 days. These results show a significant reduction compared to the current state indicators, highlighting the effectiveness of the implemented actions. More details of the times in the system corresponding to the future state can be found in Table 11.

Key performance metrics for both assembly lines, comparing current and future states, are summarized in Table 12.

As shown in Table 12, all objectives of the study were satisfied, the bottlenecks of the line were eliminated, waste of NVA time was reduced by over 58%, lead times decreased by over 60%, and daily output

Table 10. Simulation results of the future VSM of the non-guided W-501 model

	Cycle time average (sec)	Average cycle time (min)	Time required to meet daily demand (sec) demand (sec)	Utilization %	Daily production (units)
Process 10	69	1.15	26772	97.00%	400.00
Process 11	69	1.15	26772	97.00%	400.00
Process 11A	50	0.83	19400	70.29%	552.00
Process 13A	71	1.18	27548	99.81%	388.73
Process 14	71	1.18	27548	99.81%	388.73
Process 15	5	0.08	1940	7.03%	5520.00
Work cell N1	62	1.03	24056	87.16%	445.16
Work cell N4	71	1.18	27548	99.81%	388.73
Work cell N5	70	1.17	27160	98.41%	394.29
Work cell N6	65	1.08	25220	91.38%	424.62

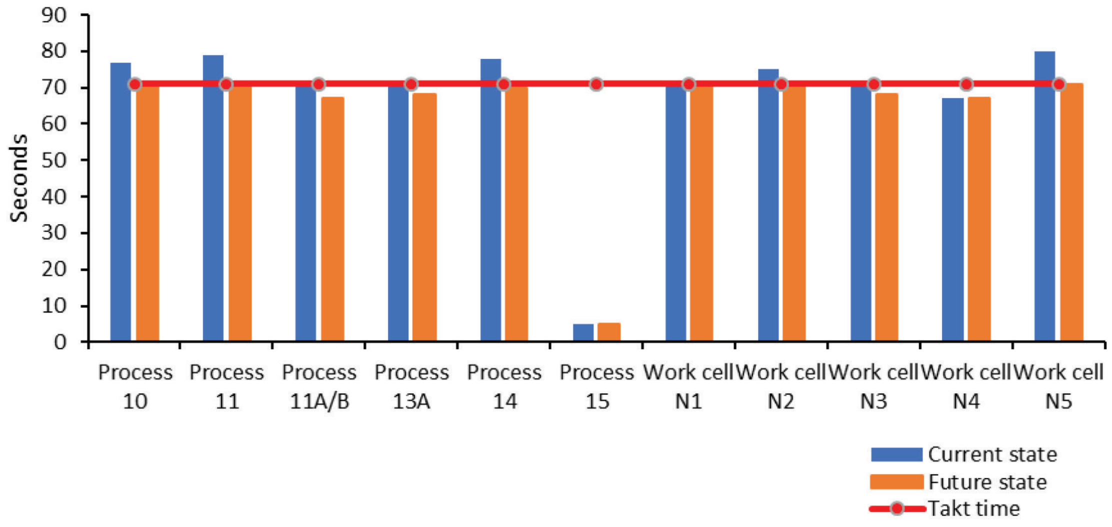

Figure 6. Operator balance chart of the future VSM for the guided W-501 model [*source: authors own work*]

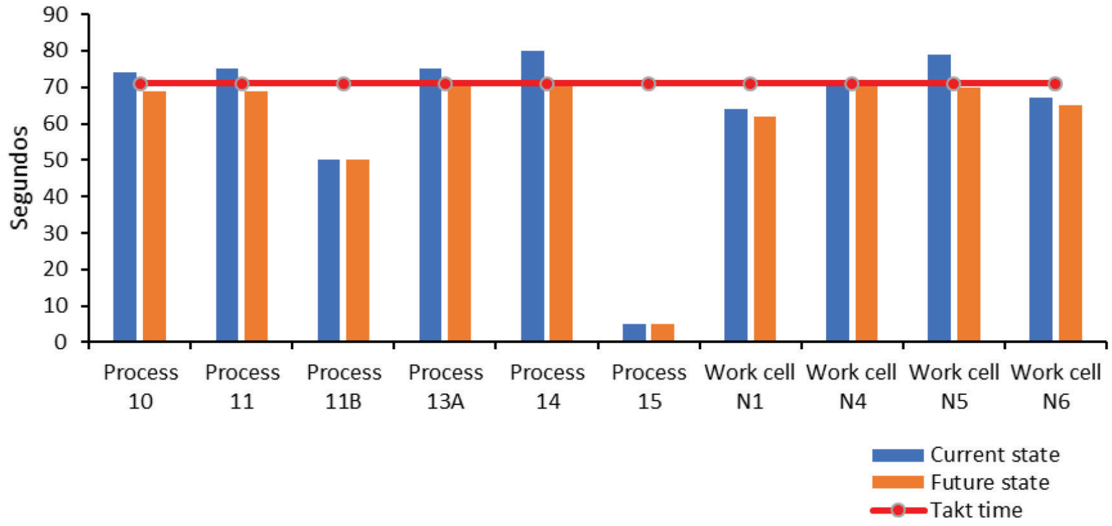

Figure 7. Operator balance chart of the future state for the non-guided W-501 model [*source: authors own work*]

Table 11. Time in system of the future state

	Time in system (sec)	Time in system (min)	Time in system (days)
Line W-501 guided	53098.69	884.98	1.92
Line W-501 non-guided	45695.42	761.59	1.66

Table 12. Summary of key performance indicators

Metric	W-501 guided (current state)	W-501 guided (future state)	W-501 non-guided (current state)	W-501 non-guided (future state)
Value-added time (days)	0.03	0.02	0.03	0.02
Non-value added time (days)	7.56	2.69	5.88	2.43
Production lead time (days)	5.29	1.92	4.40	1.66
Process ratio (%)	0.36%	0.94%	0.39%	0.90%
Daily production (units/day)	345	388.7	345	388.7

increased to 388 units to meet customer demand. Figure 8 illustrates the value-adding time comparison of both lines, providing a clear visualization of the improvements achieved.

Figure 9 shows the reduction in the non-value-added activities and production lead time of both lines, demonstrating the benefits of the proposed approach.

5. Conclusion

Traditional Value Stream Mapping generates powerful diagnostic visuals but fails to capture the dynamic, resource-driven complexity of modern production lines. Our research addresses this gap by introducing the Multi-Machine Activity (MMA) approach, which unifies VSM with simulation into one coherent, dynamic multi-product framework. In this paper, we set out with three clear objectives, all of which have been achieved: i) Formalize the MMA concept within lean theory, enabling VSM to represent both material and information flows dynamically. ii) Validate MMA-VSM integration: we constructed current and future simulation scenarios that demonstrate the seamless integration of VSM mapping and simulation. iii) Quantify performance benefits: Our simulation results lead to a complete bottleneck removal, where eleven overloaded processes were reduced below the takt-time. Also, it was

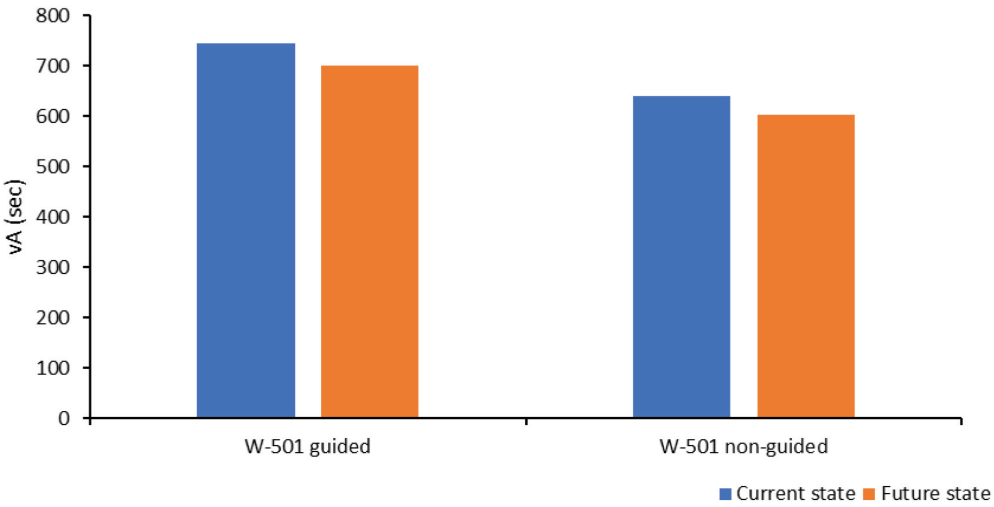

Figure 8. Value added time comparison [*source: authors own work*]

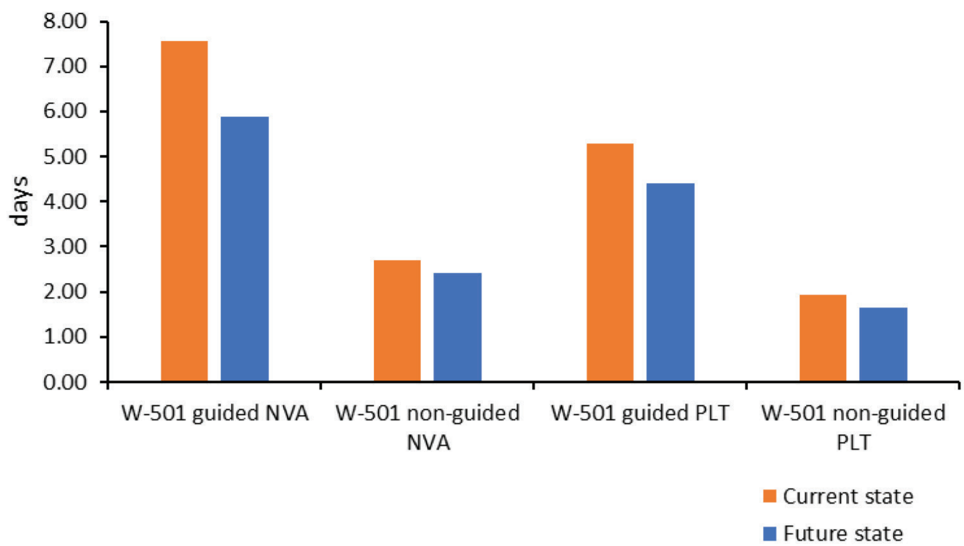

Figure 9. Non-value added time and production lead time comparison [*source: authors own work*]

achieved a major waste reduction, where non-value-added time dropped by 64.4% in the guided line and 58.7% in the non-guided line. Further, daily output increased from 345 to 388 units, fully meeting customer demand.

Regarding the originality of the research, this study embeds a formal MMA construct into VSM for a multi-product line, conducts a direct dual-model comparison, and achieves full bottleneck elimination through lean–digital integration. Theoretically, our approach extends process-flow theory, and practically, it offers a blueprint for rapid, low-cost lean transformations in complex, mixed-model environments.

While our integrated VSM–simulation approach demonstrated clear improvements in production lead time and waste reduction, several limitations must be considered, since this study assumes constant daily demand, fixed machine availability, and defect rates based on historical averages. Future work could integrate stochastic demand patterns, time-dependent failure distributions, and operator learning curves to capture more accurately the real-world dynamics.

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