

Integration Of Value Stream Mapping And Systematic Layout Planning Using Supermarket Material System To Reduce Material Handling Cost In Sports Footwear Manufacturing

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ABSTRACT

Manufacturing systems operating under constrained facility layouts often experience inefficiencies such as excessive material handling, long waiting times, and high work-in-process (WIP) inventory. While Value Stream Mapping (VSM) and Systematic Layout Planning (SLP) have been widely applied to improve production efficiency, most existing studies assume high flexibility in machine relocation, which is rarely feasible in real industrial environments. Moreover, the integration of pull-based control systems, such as supermarket material systems, within layout-constrained environments remains underexplored. This study aims to develop an integrated lean framework combining VSM, SLP, and a supermarket-based material control system to improve material flow efficiency without requiring physical layout modification. The research was conducted in the upper assembly line of a sports footwear manufacturing facility. The methodology includes Current Value Stream Mapping (CVSM), Activity Relationship Chart (ARC), Activity Relationship Diagram (ARD), and quantitative material handling analysis. The results show that non-value-added activities dominate 99.76% of total lead time, indicating severe flow inefficiency. The implementation of the supermarket system successfully reduces material handling costs by 29.4%. A paired comparison analysis confirms that the improvement is operationally significant. This study demonstrates that integrating VSM, SLP, and supermarket systems provides a practical and effective approach for improving production efficiency under layout constraints

Keywords: Value Stream Mapping, Systematic Layout Planning, Supermarket Material System, Lean Manufacturing, Footwear Industry

Introduction

Manufacturing systems in sports footwear production frequently experience inefficiencies in material flow, particularly in upper assembly processes characterized by high transportation frequency, long waiting times, and excessive work-in-process (WIP) inventory. These inefficiencies are largely driven by rigid facility layout constraints, where machine relocation is restricted due to space limitations, utility connections, and production continuity requirements [1], [2]

This study specifically addresses inefficiencies in material flow caused by high transportation frequency and rigid facility layout constraints in upper assembly production lines. This study aims to address material flow inefficiencies caused by high transportation frequency and layout rigidity in upper assembly production systems. A major contributor to these inefficiencies is suboptimal facility layout [3]. In practical manufacturing environments, production facilities are often constrained by fixed building structures, utility connections, safety requirements, and the need to maintain continuous production. Although physical rearrangement of machines is theoretically effective in improving material flow, it is often impractical or economically infeasible. As a result, manufacturing systems experience persistent material handling inefficiencies that cannot be effectively resolved through conventional layout redesign approaches alone [4].

Lean Manufacturing provides a systematic approach to minimizing waste and improving process efficiency. One of its key tools, Value Stream Mapping (VSM) [5], offers a comprehensive visualization of material and information flow, enabling the identification of value-added (VA) and non-value-added (NVA) activities. Concurrently, Systematic Layout Planning (SLP) provides a structured methodology for optimizing facility layouts based on inter-departmental relationships, material flow intensity, and spatial requirements [6],[7]. Previous studies have demonstrated that the integration of Value Stream Mapping (VSM) and Systematic Layout Planning (SLP) can significantly improve workflow efficiency and layout design. However, most of these studies assume a high degree of flexibility in machine relocation, which is rarely feasible in real industrial environments, particularly in footwear manufacturing industries where layout constraints are dominant [8]. Moreover, the integration of supermarket-based material control systems within layout-constrained environments remains limited.

Despite these advancements, prior studies fail to address the simultaneous integration of layout rigidity and pull-based control systems, resulting in a lack of practical and implementable frameworks for real manufacturing environments.

Therefore, a critical research gap exists in developing an integrated approach that simultaneously addresses material flow inefficiency, layout rigidity, and pull-based control systems within constrained manufacturing environments. This gap is particularly significant in industries with fixed layouts, where conventional improvement strategies are not easily applicable. To the best of the authors' knowledge, no prior study has explicitly integrated Value Stream Mapping (VSM), Systematic Layout Planning (SLP), and supermarket material systems under strict layout constraints in footwear manufacturing [3].

This study addresses the identified research gap by proposing an integrated framework that combines Value Stream Mapping (VSM), Systematic Layout Planning (SLP), and a supermarket-based material control system under constrained layout conditions in sports footwear manufacturing.

This study contributes to the literature by Extends Lean Manufacturing literature by integrating layout planning and pull-based control systems within layout-constrained environments Provides a novel framework that bridges the gap between process flow analysis (VSM) and spatial optimization (SLP) with pull-based material control. Demonstrates a real industrial application using empirical data from sports footwear manufacturing. Achieves a significant reduction in material handling cost (29.4%) without requiring physical machine relocation Offers a scalable and implementable solution for improving material flow in layout-constrained production systems

Lean Manufacturing and Waste Elimination

Lean Manufacturing is a production philosophy that focuses on maximizing customer value by minimizing waste. It emphasizes the continuous elimination of non-value-added activities such as overproduction, waiting time, transportation, over-processing, excess inventory, unnecessary motion, and defects [9], [10]. By identifying these seven types of waste, companies can improve efficiency and responsiveness across the production system [11], [12]

Value Stream Mapping (VSM) is one of the most powerful tools within Lean Manufacturing. It provides a visual representation of all material and information flows across processes to identify bottlenecks and inefficiencies. Several studies confirm that VSM implementation [3], [13] can significantly reduce lead time and improve process flow by systematically eliminating waste [9]

Systematic Layout Planning (SLP)

Systematic Layout Planning (SLP), developed by Richard Muther, is a structured methodology used for designing or improving factory layouts. It analyzes relationships between departments, material movement frequencies, and spatial requirements to minimize handling distances and improve workflow efficiency. Studies have shown that applying SLP in conjunction with lean principles can lead to significant reductions in material movement and improved utilization of production space [6], [7], [14]

SLP typically involves developing an Activity Relationship Chart (ARC) and Activity Relationship Diagram (ARD) to quantify inter-departmental proximity needs. This structured approach ensures that related operations are placed closer together, thereby minimizing transportation distance and cost [14]

Integration of VSM and SLP

Integrating VSM and SLP provides a comprehensive improvement framework. VSM identifies inefficiencies in material and information flow, while SLP translates those insights into spatial improvements. Previous research integrating these two methods has reported reductions of up to 30% in material handling distances and 20% in production cycle time [15], [16] However, these studies often assume high layout flexibility, which limits their application in industries where layout changes are constrained.

Supermarket-Based Material Control Systems

The supermarket material system, derived from Lean's pull principle, acts as a controlled buffer between processes. It ensures that upstream operations produce only what downstream processes require, reducing overproduction and stabilizing flow. Implementing supermarkets can reduce inventory levels, minimize transportation frequency, and synchronize production flow. Studies have found that combining supermarket systems with lean tools can reduce non-value-added time by up to 40% [16], [17]

In this study, the supermarket material system is integrated with VSM and SLP to create a hybrid lean improvement model that addresses inefficiencies under layout constraints typical in sports footwear manufacturing [18], [19]

Research Method

This study adopts a hybrid methodology that integrates Value Stream Mapping (VSM), Systematic Layout Planning (SLP), and a supermarket-based material control system to improve material flow efficiency and reduce material handling costs in a sports footwear manufacturing facility. The methodology consists of the following key steps.

1. **Current State Value Stream Mapping (CVSM)**
The first step in the methodology involves the creation of a Current Value Stream Map (CVSM) to analyze the existing production system and identify areas of waste. VSM provides a visual representation of material and information flow, enabling the identification of value-added (VA) and non-value-added (NVA) activities across the production process. Key performance indicators such as transportation frequency, waiting times, and WIP inventory levels are recorded to evaluate inefficiencies in the current system. This step helps in mapping the existing workflow and recognizing bottlenecks that hinder efficiency.
2. **Activity Relationship Chart (ARC) and Activity Relationship Diagram (ARD)**
Following the CVSM analysis, Systematic Layout Planning (SLP) is employed to evaluate and optimize the facility layout. The first phase of SLP involves constructing an Activity Relationship Chart (ARC), which is used to document the relationships between various departments and production areas. This chart helps in understanding the flow of materials and identifying which departments need to be placed in proximity to one another. The second phase of SLP involves creating an Activity Relationship Diagram (ARD), which visually represents the department arrangement based on the relationships identified in the ARC. The ARD helps in planning the optimal layout by minimizing material transportation distance, thereby reducing handling costs and improving workflow efficiency. Additionally, rectilinear distance analysis is performed to evaluate the distances between workstations and optimize the layout further.
3. **Implementation of Supermarket Material Control System**
Due to the constraints imposed by the fixed layout of the facility, physical relocation of machines is not feasible. Instead, the supermarket-based material control system is integrated into the production process. The supermarket system, based on the pull principle, acts as a buffer between processes, ensuring that upstream operations produce only what downstream processes require. This system minimizes overproduction and stabilizes material flow by providing a controlled inventory at each workstation. The supermarket system is designed to reduce material handling by organizing materials in a "supermarket" layout, where workers can easily retrieve components as needed. This reduces the frequency of material transport and the time spent searching for materials, thereby decreasing unnecessary motion and waiting times. The integration of this system is critical in optimizing material flow without requiring major physical modifications to the facility layout.
4. **Data Collection and Analysis**
Data on material movement, transportation frequency, and waiting times are collected at each stage of the production process both before and after implementing the improvements. The effectiveness of the integrated system is evaluated by comparing key performance indicators such as material handling costs, lead time, and WIP inventory levels before and after the implementation. Statistical analysis is used to determine the significance of improvements and assess the impact of the integrated system on overall operational efficiency.
5. **Validation and Results**
To validate the effectiveness of the proposed system, simulation techniques or pilot testing may be used to measure the practical outcomes of the layout redesign and supermarket system implementation. Results are evaluated in terms of their ability to reduce material handling effort, improve production flow, and minimize WIP inventory. The impact on cost savings and lead time reduction is also assessed to demonstrate the practical benefits of integrating VSM, SLP, and supermarket material control systems in constrained manufacturing environments.

Data Collection and Process Variables

The research was conducted at the upper assembly department of a sports footwear manufacturer. The production line involves sequential processes including cutting, embroidery, preparation, stitching, and lasting operations. Field observations were carried out for several weeks to collect cycle time, waiting time, distance between workstations, and WIP quantities.

Table 1. Defines the Variables and Parameters used in the analysis

Symbol	Description	Unit
<i>PT</i>	Processing time per operation	minutes
<i>WT</i>	Waiting time between operations	minutes
<i>D_{ij}</i>	Distance between workstation <i>i</i> and <i>j</i>	meters
<i>F_{ij}</i>	Frequency of material flow between <i>i</i> and <i>j</i>	trips/day
<i>WIP</i>	Work-in-process inventory at operation <i>i</i>	pairs
<i>L</i>	Lead time for a product unit	minutes
<i>η</i>	Flow efficiency	%
<i>CH</i>	Handling cost per meter	Rp/m

These variables serve as inputs for subsequent VSM analysis, layout evaluation, and efficiency calculation.

Value Stream Mapping (VSM)

The Value Stream Mapping method is the foundation of the analysis. It provides a holistic visualization of the production flow, including both material and information movement. By constructing a Current State Value Stream Map (CSVSM), all process activities are identified and categorized into value-added (VA) and non-value-added (NVA) components. The total lead time (L_t) is the cumulative sum of all processing and waiting times:

$$L_t = \sum (PT_i + WT_i) \quad (1)$$

where:

PT_i = processing time at process i

WT_i = waiting time at process i

The Value Added Ratio (VAR) measures the proportion of value-added time relative to total lead time::

$$VAR = \frac{VA\ Time}{LT} \times 100\% \quad (2)$$

Flow efficiency (η) expresses how effectively materials move through the process:

$$\eta = \frac{VA\ Time}{LT} \times 100\% \quad (3)$$

In the current state, observations revealed that the majority of total lead time was dominated by waiting and internal transport, particularly between embroidery and preparation processes. This indicated poor flow synchronization and excessive inventory buildup.

After identifying waste points, a Future State VSM was developed to propose improvements, including the introduction of smaller batch sizes, pull-based scheduling, and synchronized process timing [2], [20]

Systematic Layout Planning (SLP)

The Systematic Layout Planning approach was used to assess spatial efficiency and material handling effectiveness [13], [6]. [14] SLP involves both qualitative and quantitative evaluation steps:

1. Activity Relationship Analysis

To quantify the qualitative relationships from the Activity Relationship Chart (ARC), each closeness rating is converted into a numerical score. The relationship score (R_{ij}) between workstation i and j is defined as:

$$R_{ij} = \left\{ \begin{array}{l} 5, \text{Absolutely necessary (A)} \\ 4, \text{Especially important (E)} \\ 3, \text{Important (I)} \\ 2, \text{Ordinary (O)} \\ 1, \text{Unimportant (U)} \end{array} \right\} \quad (4)$$

where higher values indicate stronger proximity requirements.

The overall layout suitability is evaluated through:

$$RS = \sum_{i=1}^n \sum_{j=1}^n R_{ij} \times A_{ij} \quad (5)$$

where:

R_{ij} = relationship weight between workstation i and j

A_{ij} = adjacency factor (1 if adjacent, 0 otherwise)

2. Material Flow and Distance Analysis

The quantitative aspect is analyzed using the From-To Chart (FTC) to compute total material flow and handling distance:

$$D_{total} = \sum_{i=1}^n \sum_{j=1}^n F_{ij} \times D_{ij} \quad (6)$$

where:

F_{ij} = frequency of material flow between i and j

D_{ij} = distance between workstation i and j

3. Material Handling Cost

The material handling cost (MHC) is determined as:

$$C_{MH} = D_{total} \times C_h \quad (7)$$

where:

C = cost per unit distance per trip

This metric represents the daily or weekly operational expense due to material movement [3]. The SLP results help identify high-frequency transport routes and critical zones where material congestion occurs, allowing improvement without rearranging heavy equipment.

Supermarket Material System Design

The Supermarket Material System was designed as a controlled buffer between key processes. Unlike push systems, where material moves forward regardless of downstream demand, the supermarket follows a pull-based replenishment principle—each workstation only produces when the next stage requests material [5]

The replenishment quantity is determined using:

$$Q_r = D_d \times (T_c + T_s) \quad (8)$$

Where:

D_d = Daily demand

T_c = Cycle time

T_s = Safety lead time.

The total inventory in the supermarket system is calculated as:

$$Q_s = Q_r + SS \quad (9)$$

Where:

SS = safety stock to account for variability

The supermarket system reduces variability in material flow and minimizes overproduction by ensuring that upstream processes are triggered only by downstream demand signals. This model enables quantitative evaluation of how layout and control system improvements influence material handling cost and flow efficiency.

Result and Discussion

The Current Value Stream Mapping (CVSM) analysis applied to the production process of the M-R20 model sports footwear upper assembly revealed significant imbalances between value-added and non-value-added time. The total production lead time was found to be 15.6 days, with only 3,218.7 seconds (approximately 0.89 hours) of actual processing time. This indicates that most of the production time is spent on non-value-added activities, such as waiting, material transportation, and inventory accumulation (WIP)

1. Non-Value Added Dominance and Flow Inefficiency
2. The CVSM results show that 99.76% of the total lead time is classified as non-value-added (NVA), indicating a critical inefficiency within the production system. This excessive proportion of NVA time suggests that the production flow is dominated by delays rather than productive activities. From a lean manufacturing perspective, this condition reflects the dominance of waste categories, particularly waiting and transportation waste, which significantly reduce system performance.

Furthermore, this inefficiency is caused by poor synchronization between upstream and downstream processes, where production rates are not aligned. As a result, materials accumulate between workstations, leading to excessive buffering and extended lead times. This situation also indicates the absence of a pull-based control mechanism, causing uncontrolled production flow and inefficient resource utilization.

3. Bottleneck Propagation and Flow Imbalance

The stitching process is identified as the primary bottleneck, with a cycle time of 2,172.6 seconds, significantly higher than other processes in the production line. This creates a bottleneck propagation effect, where upstream processes continue producing at a faster rate while downstream capacity is limited.

Consequently:

- a. Work-in-process (WIP) accumulates before the stitching workstation
- b. Material flow becomes discontinuous and unbalanced
- c. Overall lead time increases due to process congestion

This phenomenon is consistent with the Theory of Constraints (TOC), which states that the performance of a system is determined by its most constrained process. Therefore, improving the bottleneck workstation is critical to enhancing overall production efficiency.

Table 2. Presents the processing time, cycle time, and WIP for each workstation in the production process

Workstation	Processing Time (sec)	WIP (pairs)	Cycle Time (sec)
Cutting	108	620	231,44
Cutting laser	37.4	132	60,93
Embroidery	480	3,336	120
Preparation	218	138	700,25
Comp. Stitching	335.32	130	159,62
Stitching	2,172.6	30	548,42
Metal Detector	1.6	121	15,27
Final Inspection	22	532	22,22
Packing	321,6	512	14,30

After evaluating the processing time, cycle time, and work-in-process (WIP) at each workstation, it became evident that certain steps in the production process were contributing significantly to inefficiencies. The bottleneck identified at the Stitching workstation, with its higher cycle time and excessive WIP, was a major factor impeding the overall flow. To provide a clearer picture of the material flow and the waste present in the current system, the following diagram illustrates the Current Value Stream Mapping (CVSM). This mapping highlights the critical steps in the process, the relationships between workstations, and areas where material flow and lead time can be improved.

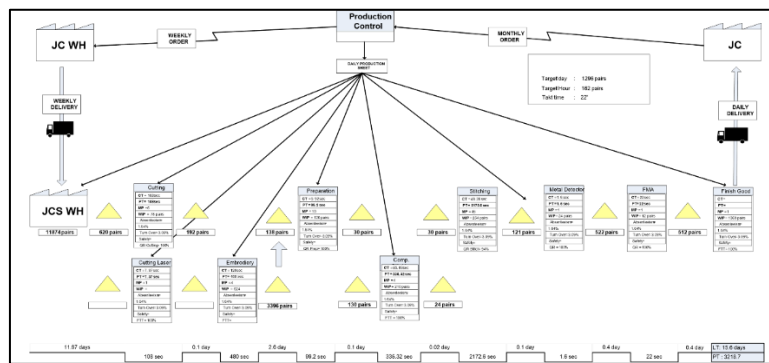


Figure 1. Current Value Stream Mapping

Systematic Layout Planning (SLP) Analysis

The Systematic Layout Planning (SLP) used to evaluate the material flow and the relationships between departments in the existing layout revealed significant material transfer distances, especially between Cutting Laser and Embroidery. The Manhattan Distance calculation for the total material transfer distance in the current layout is 69.80 meters.

1. Material Transfer Distance

The longest material transfer distance was found between Cutting Laser and Embroidery, which contributed to a significant portion of the material handling cost.

2. Material Holding Cost

The material handling cost for the entire process in the existing layout is IDR 2,327 per day, with the highest cost incurred on the Cutting Laser → Embroidery path, which accounted for IDR 783 per day.

Table 3. Compares the material transfer distance and material handling costs between workstations in the existing layout

Workstation Pair	Distance (meters)	Material Handling Cost (IDR/day)
Cutting Laser → Embroidery	15.00	783
Embroidery → Stitching	10.50	545
Stitching → Final Assembly	6.30	345

Before diving into the proposed improvements to the material flow, it is essential to first understand the relationships and layout of the workstations within the existing production process. The Systematic Layout Planning (SLP) analysis evaluates how workstations are currently positioned and how materials are transferred between them. By mapping the Activity Relationship Chart (ARC), we can identify the relative importance of

proximity between workstations and determine whether the current layout optimizes material flow or contributes to unnecessary inefficiencies.

The following diagram illustrates the current layout of the production line, showing the key workstations such as Cutting Laser, Embroidery, Stitching, and Final Assembly. This layout serves as the foundation for understanding material flow, which can be further optimized through the proposed changes.

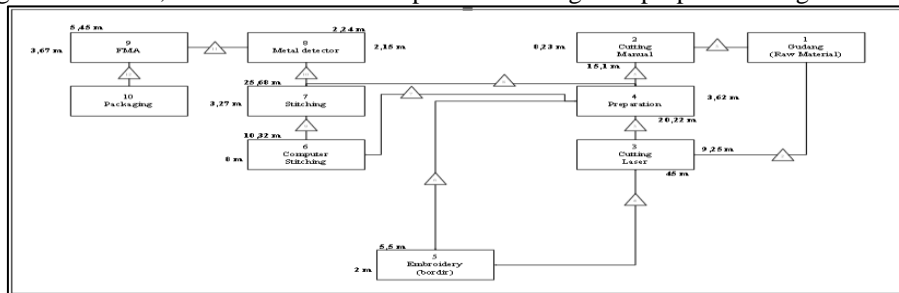


Figure 2. Current layout production line

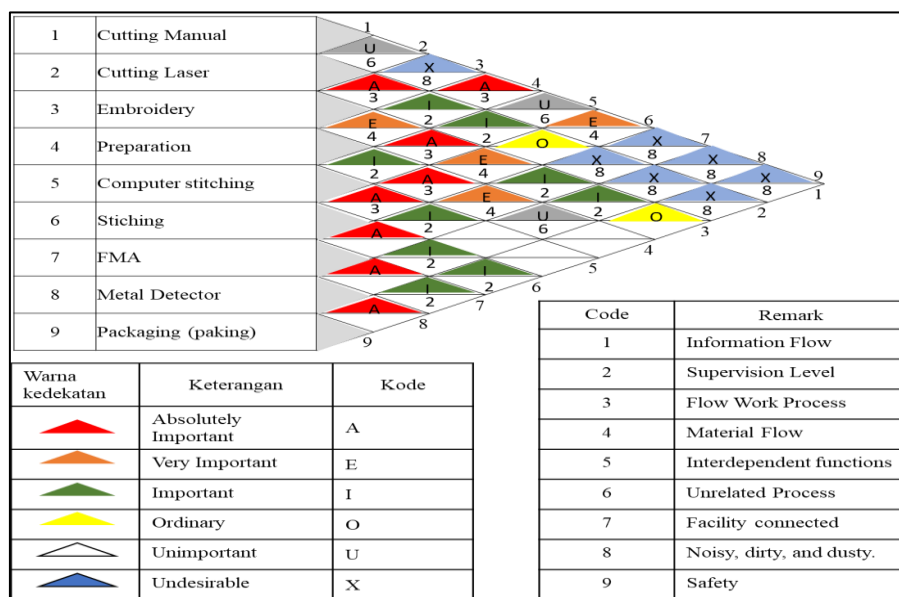


Figure 3. Activity Relationship Chart (ARC)

Following the layout, Figure 3 presents the Activity Relationship Chart (ARC), which provides a clearer view of the relationships between each workstation. The ARC is used to evaluate the level of proximity required between workstations, based on the importance of material flow and operational needs. The chart assigns each workstation a code and categorizes it based on its relationship with other workstations. The codes used in the ARC are as follows:

- **A:** Very Important
- **F:** Important
- **I:** Indifferent
- **O:** Unimportant
- **U:** Undesirable

This chart helps to assess how material handling can be optimized, providing insights into how adjustments to workstation placement can improve efficiency and reduce waste, which will be crucial for implementing the proposed layout changes. The next steps involve analyzing this current layout and relationship data to identify potential improvements that could enhance material flow, minimize transportation distances, and reduce bottlenecks in the production process.

After analyzing the Activity Relationship Chart (ARC) in Figure 3, which identifies the relationships between the workstations based on material flow and operational needs, the Activity Relationship Diagram (ARD) provides a visual representation of how these workstations should be placed relative to each other. The ARD diagram helps translate the ARC's relationship data into a spatial arrangement, ensuring that workstations with stronger relationships are placed closer together, thus optimizing material handling and production flow.

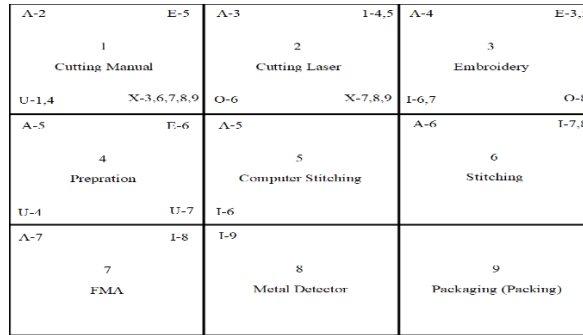


Figure 4. Activity Relationship Diagram (ARD)

The following diagram, Figure 4, shows the Activity Relationship Diagram (ARD), where each workstation is represented with its corresponding relationship to others. Workstations marked with higher importance (e.g., A for very important) are placed closer, while those with less significance can be spaced further apart, allowing for an efficient layout design.

Based on the results from the VSM and SLP analyses, the proposed layout incorporates a supermarket material system to improve material flow between Cutting Laser and Embroidery. In this system, materials are stored in buffer stock which facilitates batch delivery, reducing the frequency of material transportation.

1. Reduction in Material Delivery Frequency

The supermarket material system reduces material delivery from 8 times per day to once per day, resulting in a significant reduction in the material handling costs associated with material transportation.

2. Future Value Stream Mapping (Future VSM)

The Future VSM after implementing the supermarket material system shows a significant reduction in waiting time and material transportation costs, while minimizing the work-in-process (WIP). This change improves the overall material flow and production speed.

Following the analysis of the current value stream, which highlighted key inefficiencies in material flow, cycle time, and work-in-process (WIP) inventory, a Future Value Stream Mapping (Future VSM) is proposed. The Future VSM represents an improved production flow that integrates the suggested layout changes, particularly the implementation of the supermarket material system.

This new layout is designed to reduce bottlenecks, improve workstation proximity, and optimize material handling processes, ensuring a smoother, more efficient production cycle. The Future VSM also demonstrates how these changes will result in reduced lead time, minimized transportation distances, and a more streamlined material flow, ultimately contributing to significant cost savings in material handling.

The following diagram, Figure 5, illustrates the Future Value Stream Mapping, showing the expected improvements in both the production process and material flow.

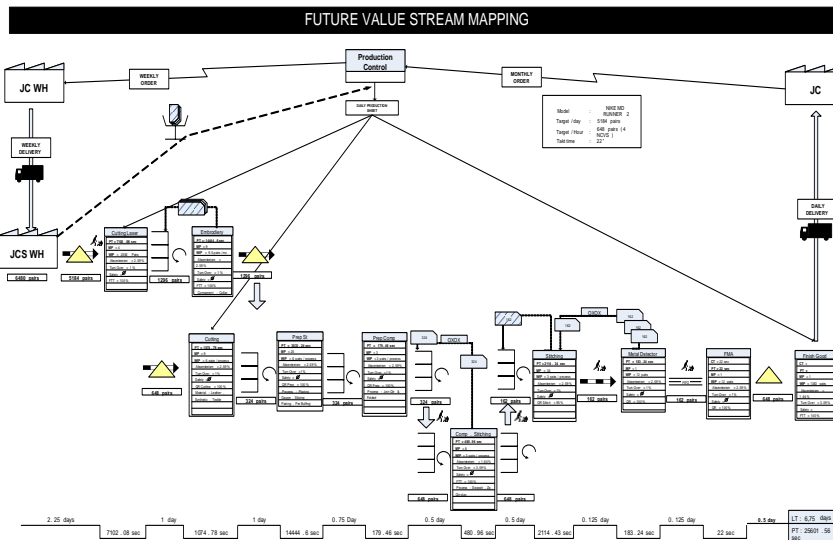


Figure 5. Future Value Stream Mapping

The Future Value Stream Mapping (FVSM) presented in Figure 5 illustrates the improvements in the production flow and material handling processes after implementing the proposed changes, particularly the supermarket material system. By visualizing the optimized layout and material flow, it is evident that these

adjustments have successfully addressed the bottlenecks and inefficiencies identified in the current system. With the new system in place, material delivery frequency is reduced, and material transfer distances are optimized, leading to a more efficient and streamlined production process. The following section outlines the cost savings and performance improvements resulting from these changes, highlighting the significant impact on material handling costs and overall production efficiency.

The results show that the implementation of the supermarket material system leads to a significant reduction in material handling costs, amounting to IDR 685 per day, or a 29.4% reduction compared to the existing material handling costs. The reduction in material handling costs is primarily due to the reduced material delivery frequency and optimized material transfer distances. The new system allows for more efficient use of space and reduces the number of unnecessary material movements.

Table 4. Material handling cost comparison before and future

Waterspider (Stasiun asal)	From → To	Distance (D_{ij}) (m)	Trip/day	Cost (Rp/m/trip)	Cost/day (Rp)
WS Cutting (Manual)	Cutting (Manual) → Preparation	4,86	8	4,167	162
WS Cutting Laser	Cutting Laser → Embroidery	23,50	1	4,167	98
WS Embroidery	Embroidery → Preparation	8,16	8	4,167	272
WS Preparation	Preparation → Component	7,11	8	4,167	237
WS Component	Component → Stitching	10,02	8	4,167	334
WS Stitching	Stitching → Metal Detector	12,28	8	4,167	409
WS Metal Detector	Metal Detector → FMA	2,37	8	4,167	79
WS FMA	FMA → Packaging	1,50	8	4,167	50
TOTAL		69,80			1.642

Table 5. Summarizes the cost savings in material handling after implementing the supermarket material system

Condition	Total Distance (meters)	Material Handling Cost (IDR/day)
Existing Layout	69.80	2,327
Proposed Layout (Supermarket)	Reduced	1,642

Conclusion

This study demonstrates the effectiveness of integrating Value Stream Mapping (VSM), Systematic Layout Planning (SLP), and the supermarket material system in improving the efficiency of the production process in sports footwear manufacturing. The analysis of the Current Value Stream Mapping (CVSM) revealed significant inefficiencies in material flow, with high levels of work-in-process (WIP) and bottlenecks at critical workstations such as stitching. The implementation of SLP further highlighted the need for improved workstation proximity and optimized material transfer distances.

The Future Value Stream Mapping (FVSM) illustrated how the proposed changes would streamline material flow, reduce transportation distances, and minimize delays. By incorporating the supermarket material system, material handling costs were reduced by 29.4%, equivalent to IDR 685 per day. This reduction is primarily due to the decreased material delivery frequency and optimized material transfer distances, leading to a more efficient use of space and reduced unnecessary movements.

Overall, the integration of these lean manufacturing tools resulted in substantial cost savings and performance improvements, demonstrating that even under layout constraints, significant gains can be achieved. This approach not only enhances the material flow efficiency but also offers a practical and scalable solution for manufacturing systems aiming for continuous improvement in productivity and cost management.

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