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A Framework to Enhance Green Factories by Applying Lean Production Concepts: A Case Study

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Abstract

In the last decades, competition between several industries to deliver high-quality products is marginally increasing in terms of costs and performance. Lean is one of those activities that focuses on reducing costs by eliminating non-value-added activities. This factory faces various wastes in its production process, including defects, waiting, unnecessary inventory, overprocessing, unnecessary motion, overproduction, and transportation. This study uses a lean manufacturing approach, Value Stream Mapping, to identify and minimize waste, enhance production time efficiency. Meanwhile, green manufacturing is an approach that seeks to achieve measurable and significant environmental improvements. In this research, we study the causal relationship between lean and green manufacturing. We apply several lean tools to enhance the efficiency of a mixed-product production line used in vehicle assembly. A future state VSM incorporating Kanban pull systems, supermarket buffers, and 5S workplace organization was developed and validated. Through the study, we found out that lean and green have a strong relationship in terms of waste elimination, resource efficiency, and environmental impact reduction, where the implementation of lean tools simultaneously achieves both operational excellence and sustainability objectives. Quantitative results demonstrate a lead time reduction from 178.453 to 15.883 days (a 91.099% decrease). These percentages have a direct effect on the flow of materials and information, save raw materials for other uses, free up people to work on other products, and change the amount of electricity used, the amount of water used in cooling systems for injection processes, and the amount of inventory in warehouses. In the end, they affect the percentage of defective products.

Keywords

Value Stream Mapping, Non-Value-Added, Kanban Pull Systems, Environmental Impact

1. Introduction

1.1. Background and Motivation

The modern manufacturing landscape is characterized by intense global competition, rapid technological advancement, and increasing pressure for corporate social responsibility. Historically, the pursuit of operational efficiency and cost reduction, often driven by the principles of Lean Manufacturing (LM), has been a primary focus for firms seeking a competitive edge [1]. LM, rooted in the Toyota Production System, is fundamentally a systematic approach to identifying and eliminating waste (Muda) in all forms, thereby improving quality, reducing lead times, and lowering costs [2].

However, the 21st century has introduced a critical, non-negotiable dimension to this operational calculus: environmental sustainability. Global climate change, resource depletion, and stringent environmental regulations have necessitated a paradigm shift, compelling organizations to integrate ecological considerations into their core business strategies [3]. This dual imperative—the drive for operational leanness and the commitment to environmental stewardship—has led to the emergence of the "Lean-Green" philosophy.

1.2. Problem Statement

As earlier mentioned, we study the effect of lean on lowering carbon foot print.

The analyzed factory produces various products that feeding for car manufacturing, specially had been selected a specific product that is the more seller, TFR90 of fixed features for Chevrolet pickup trucks, the plant produces about 15,000 parts of TFR90 monthly with a total value of (1,800,000) Egyptian pounds.

Currently, the factory employs (31) people. the production in the plant takes place in a one-shift system, three-shift system and is divided into four lines:

Injection line_work takes place 6 days a week, and the shift lasts 8.5 h (8:00-4:30); during the shift there are two breaks, one for 30 min at the beginning of the day and one for 30 min from (12:00 to 12:30), the second shift lasts 8.5 h (4:00-12:30); during the shift there are two breaks, one for 30 min at the beginning of the shift and one for 30 min from (8:00 to 8:30) and the third shift lasts 8.5 h (12:00-8:00); during the shift there are two breaks, one for 30 min at the beginning of the shift and one for 30 min from (4:00 to 4:30);

Metal forming line_work takes place 6 days a week, and the shift lasts 8.5 h (8:00-4:30); during the shift there are two breaks, one for 30 min at the beginning of the day and one for 30 min from (12:00 to 12:30);

Electric Working line (Harness)_work takes place 6 days a week, and the shift lasts 8.5 h (8:00-4:30); during the shift there are two breaks, one for 30 min at the beginning of the day and one for 30 min from (12:00 to 12:30);

Final Assembly line_work takes place 6 days a week, and the shift lasts 8.5 h (8:00-4:30); during the shift there are two breaks, one for 30 min at the beginning of the day and one for 30 min from (12:00 to 12:30).

The implementation of such a work system results from the specificity of the operation of devices installed on the lines.

The material for the production of the TFR90 is beaded plastic imported from aboard, some from recycling the defected products, rolled sheet metal with a specific width, thickness of sheet and weight of the roll, rolled sheets from copper with a specific width, thickness of sheet and weight of the roll, electric wires from copper with a specific diameter and finally other complementary parts assist in the assembly process.

The average time of order fulfillment for a material in a plant is (3) months. Therefore, the company prepares monthly demand forecasts, which are reviewed every (1) months.

The company's customers place orders for the next month no later than on the 25th of the previous month. Verification of orders is possible every day. The estimated monthly demand for the plant's production is about 15,000 parts, while deliveries to customers are made (daily) by trucks with an average capacity of (750) parts.

Production orders for individual departments are generated based on the received customer orders, the level of inter-operational stocks, the level of stocks of finished products, and the expected level of shortages.

1.3. Research Objectives

This research paper aims to address the identified gap by achieving the following objectives:

To define and conceptualize the "Green Effect" of Lean Manufacturing, establishing a clear theoretical link between core LM principles (e.g., Value Stream Mapping, 5S, Just-in-Time) and environmental performance indicators.

To empirically investigate the extent to which the adoption of integrated Lean-Green practices influences a firm's environmental performance, specifically focusing on reductions in waste, energy, and material consumption.

To analyze the mediating role of environmental management systems and organizational culture in maximizing the synergistic benefits of the Lean-Green integration.

To propose a conceptual framework for the successful implementation of Lean-Green strategies that ensures simultaneous improvements in operational efficiency and environmental sustainability.

1.4. Significance of the Study

This study holds significant theoretical and practical implications. Theoretically, it contributes to the growing body of literature on sustainable operations management by providing a robust framework for understanding the causality and synergy between Lean and Green paradigms. It moves beyond anecdotal evidence to offer empirical validation of the "Green Effect," thereby enriching the theoretical foundation of the Lean-Green concept. Practically, the findings will provide managers and policymakers with actionable insights and a clear roadmap for implementing integrated Lean-Green strategies. By demonstrating the tangible environmental and economic benefits, this research encourages wider adoption of these practices, fostering a more sustainable and competitive manufacturing sector.

lean manufacturing is known to minimize waster hence minimizing carbon foot prints and enhancing green manufacturing. Two questions remain unanswered:

How lean manufacturing can enhance green manufacturing?

To what extend can lean improve green factories?

Hence, in this research we try to answer these two questions. The rest of the paper is organized as follows; first we conduct a literature review. Then in Section 3 we explain the used methodology and the case study. In section 4 we discuss the results. Finally, we provide the concluding remarks.

2. Literature Review (Table 1)

Table 1. Literature review over integrated lean and green manufacturing.

Author/Source	Key Methodology	Main Findings
Abualfaraa *et al.* [4]	Quantitative survey analysis of Saudi manufacturing SMEs.	Awareness of lean-green benefits is growing; combined strategies lead to greater operational and environmental performance than green practices alone.
Junior *et al.* [5]	Literature review and simulation of the Lean and Green (L&G) model.	L&G synergy enhances performance; adoption is hindered by lack of government/industry commitment and qualified staff, while top-down support is critical.
Ikatrinasari *et al.* [6]	Value stream analysis and implementation of SMED (Single-Minute Exchange of Die).	SMED reduced lead time by 15% (from 1,742.5 to 1,477.5 minutes); energy savings achieved through SMED and equipment upgrades (LEDs, AC optimization).
Dungani Rudi *et al.* [7]	Development of an L&G model (Men, Material, Machine, Money, Environment) and simulation.	L&G fundamentals help beginners understand synergy; barriers include lack of knowledge and expertise, especially in SMEs.
Jbira *et al.* [8]	Qualitative observation and conceptual analysis.	Lean and green initiatives are often complementary, but potential conflicts exist where green practices might clash with lean business objectives.
Yehia *et al.* [9]	Environmental assessments and process modernization (Marble industry case study).	Modernizing equipment and processes enhances efficiency; waste-free and green philosophies are strongly connected; specific measures like tree barriers and renewable energy reduce pollution.
Dong *et al.* [10]	Development of a 4M1E model optimized with backpropagation (BP) algorithms.	Traditional static models are insufficient; adaptive BP algorithms enable dynamic, real-time analytical models for continuous lean-green improvement.
Choudhary *et al.* [11]	Case study using Value Stream Mapping (VSM), Root Cause Analysis (RCA), and Green Integrated VSM (GIVSM).	GIVSM reduced lead time by 63% and carbon footprint by 77%; highlighted the potential conflict where higher production efficiency may increase total energy demand.
Yadav *et al.* [12]	Conceptual framework for Green Lean Six Sigma (GLSS).	GLSS minimizes environmental impact while improving quality and profitability; teamwork and management commitment are the most critical facilitators.

Continued

Lyna [13]	Integration of Lean Six Sigma (LSS) with environmental strategies and Industry 4.0/5.0 technologies.	GLSS supports the circular economy; Industry 4.0 (IoT/CPS) enables real-time data-driven decisions; measurement requires environmental, economic, and social KPIs.
Mohan *et al.* [14]	Systematic framework combining DMAIC with Green Lean Six Sigma (GLSS).	GLSS uses 3R principles to enhance productivity and well-being; identifies challenges in developing countries like India (lack of experience/technology).
Lintang *et al.* [15]	Process Activity Mapping (PAM) and Future State Environmental VSM (Batik production).	Reduced cycle time by 3.9% and energy use by 14%; emissions dropped by 63% by switching fuel sources (firewood to gas).
Ridwan Alief *et al.* [16]	Green Value Stream Mapping (Antenna production line).	Reduced manufacturing lead time by 1,953 seconds; increased value-added time ratio from 76.78% to 87.62%.

3. Methodology

3.1. Lean Tool Integration Strategies

3.1.1. Current State

Value Stream Mapping (VSM) is a tool in lean manufacturing that is commonly used for mapping the entire flow of both information flow and material flow. VSM can be used to outline a product's production line, including materials and information from each workstation. Furthermore, a VSM utilized for categorizing waste types. Figure 1 illustrates the fundamental symbols of Value Stream Mapping.

The Value Stream Mapping (VSM) analysis of the TFR90 electrical connector assembly process reveals a complex, multi-stage manufacturing operation with

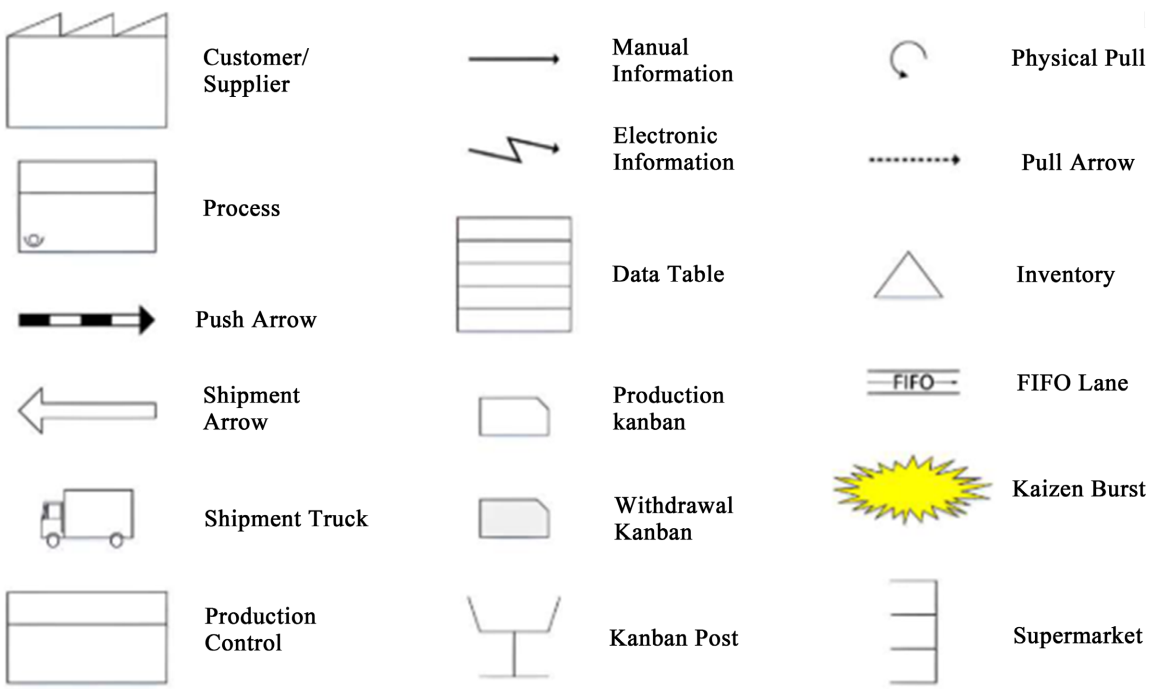


Figure 1. Standardized symbols for VSM [17].

significant opportunities for optimization. The current process involves multiple injection molding, metal forming, assembly, and quality control operations distributed across numerous machines and workstations. The analysis identifies key bottlenecks, capacity constraints, and waste areas that can be addressed through systematic lean manufacturing improvements.

My faculty dean let me tour the factory. Factory divisions include injection, metal forming, galvanization, harness, assembly, and inventory. Many visits to the facility were made to coordinate with HR in organizing department head meetings throughout three months. Start with the injection department and classify all machinery used to inject components for a car's rear light.

The injection department engineers collected data while loading machines onto components. After communicating with the metal forming department's operations manager, the days for loading the machines with the car's rear light's metal components were determined. The archive and the appropriate engineer collected data on multiple presses of various sizes for this phase.
To examine how the metal forming department produces metal goods, the galvanizing department was visited. Technicians assessed galvanizing production. The electrical harness assembly area was next inspected, and this sector's machinery and manufacturing capacity were inventoried.

The assembly department was then visited to evaluate all assembly steps and production capabilities. Each visit examined the waste percentage for all departments and found their reasons. We studied ways to recycle and reintegrate defective components into injection operations in small amounts. Some is sold to convert it to cash.

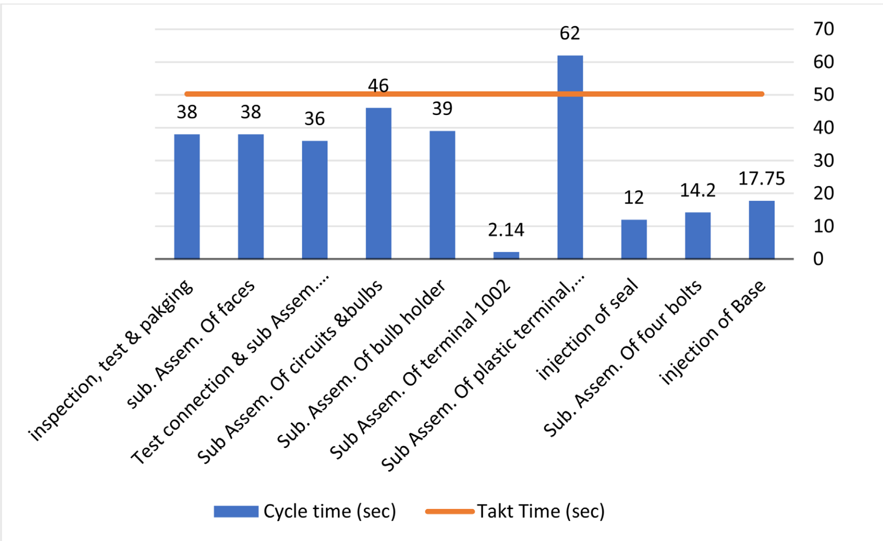


Figure 2. Cycle time of assembly operations.

As shown in **Figure 2**, it was a bottleneck in the sub assembly stage of plastic terminal, spring and dust panoply. It was proposed to parallel two stages of the subassembly stage of plastic terminal, springs, dust panoply. This facilitates the material flow during the assembly operations.

Figure 3 was captured from the factory, there were three probabilities of correction action that would take place with the defects found in the final assembly stage. Firstly, if the defect wasn't in front of view for the customer, it would pass to the palletizing stage. secondly if the defect was in front of view for the customer, it would be rejected and not pass to the palletizing stage. So, the defected product would be recycled as small ratio was used with raw material for plastic injection of other parts. Thirdly if the defect was in front of view for the customer, it would be rejected and scraped.

Figure 3. Three probabilities of correction action at final assembly stage.

This Pareto diagram clearly demonstrates the 80/20 principle in quality management.

56% of all defects come from a single cause: Fracture in the face, 83.3% of all defects come from just 3 defect types, focusing on the vital few yields maximum improvement benefit Fracture defects (67.8%) are the priority focus area, eliminating top 3 defects would reduce total defects by 83%.

As shown in Figure 4. the fracture in the faces was the highest amount in the defects so it should go back to injection stage to detect injection parameters, inspect the mold cavity and eject pins.it was found that the melting point temperature was high so, it affects semi-crystalline structure of the mold. And so, on there is a fishbone diagram showing causes of the facture in the faces.

Root Cause Analysis (RCA) Identification

Fishbone Diagram of Face Fracture in TRF90

The fishbone diagram is utilized to classify the causes of the problem. Based on interviews and root cause analysis, Fracture of the Face in TRF90 occurs due to several causes, namely man, methods, materials, and measurements.

Based on the fishbone Figure 5, it can be seen the major causes that occur in Fracture of the face in TRF90. Man is caused by lack of machine operator training; machine is caused by machine maintenance and machine failure during processing; methods are caused by inefficient machine maintenance procedures and poor maintenance scheduling; materials are caused by improper storage of materials;

environment is caused by poor weather conditions and inappropriate humidity temperatures.

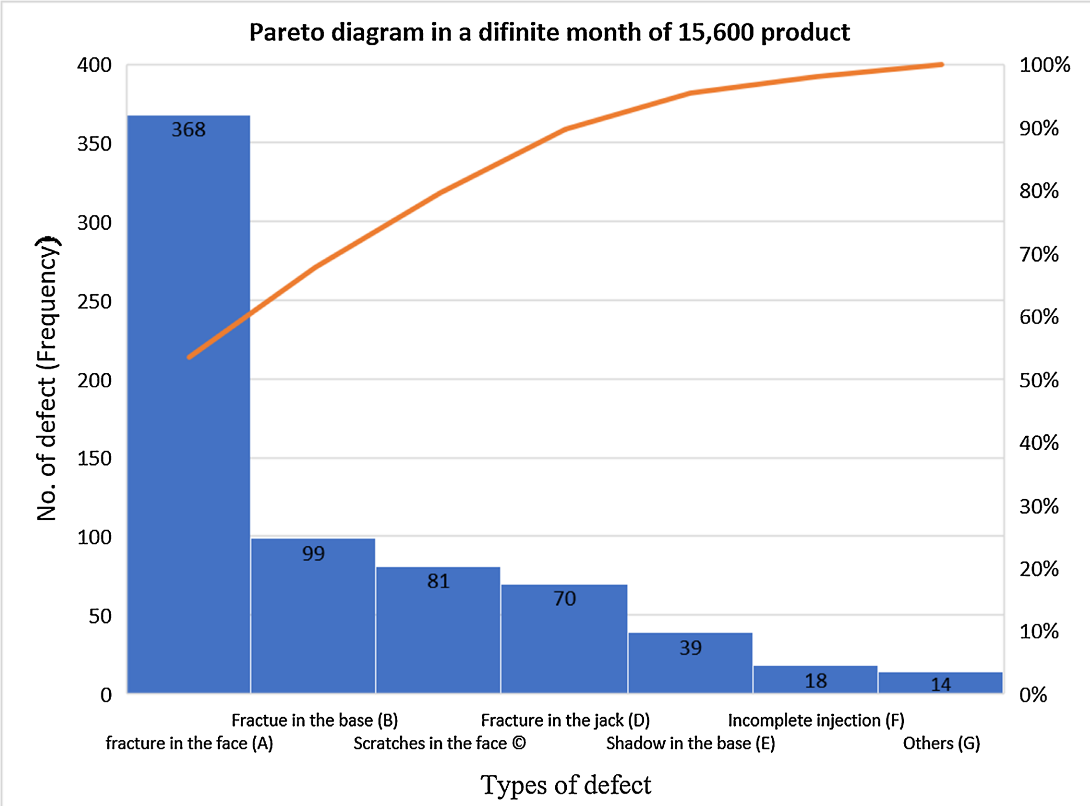


Figure 4. Pareto diagram of defects at final assembly stage through a definite month.

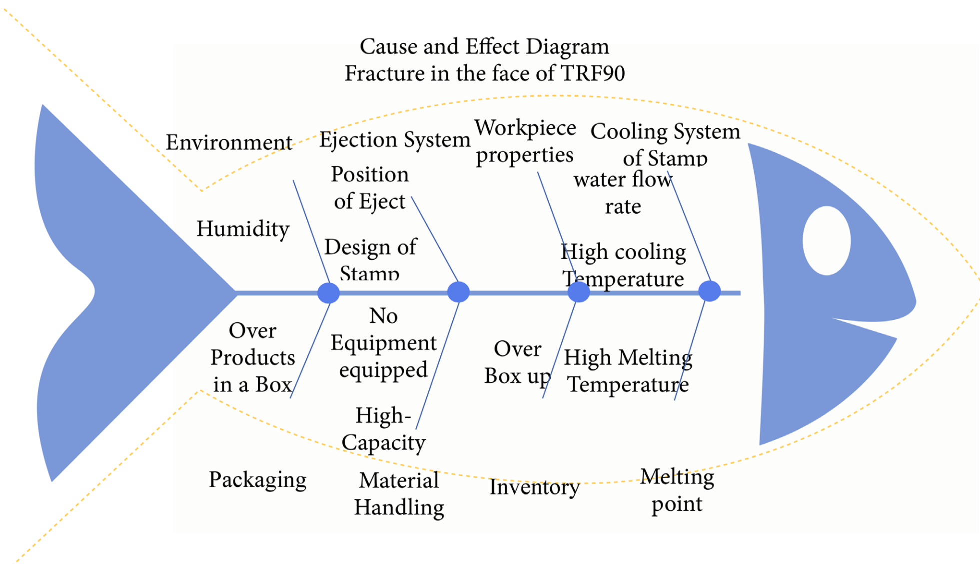


Figure 5. Fracture of the face in TRF90 fishbone diagram.

Process flow analysis

As shown in the **Figure 6**, This pie chart illustrates the fundamental principle of lean manufacturing: manufacturing processes are dominated by waste (99.99%), with only a tiny fraction of time actually adding value (0.0082%).

Figure 7 reveals that Final Assembly & Packaging dominates the production process, accounting for nearly 77% of all value-added time. This makes it the primary focus for improvement efforts.

Figure 8 illustrated that the Injection Molding Section is exceptionally well-balanced with no bottlenecks and 5.8× excess capacity. This is an ideal production section from a line balance perspective.

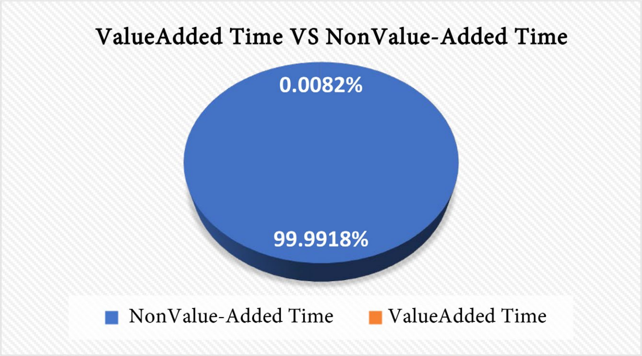


Figure 6. Value-added time vs nonvalue-added time pie chart through current VSM.

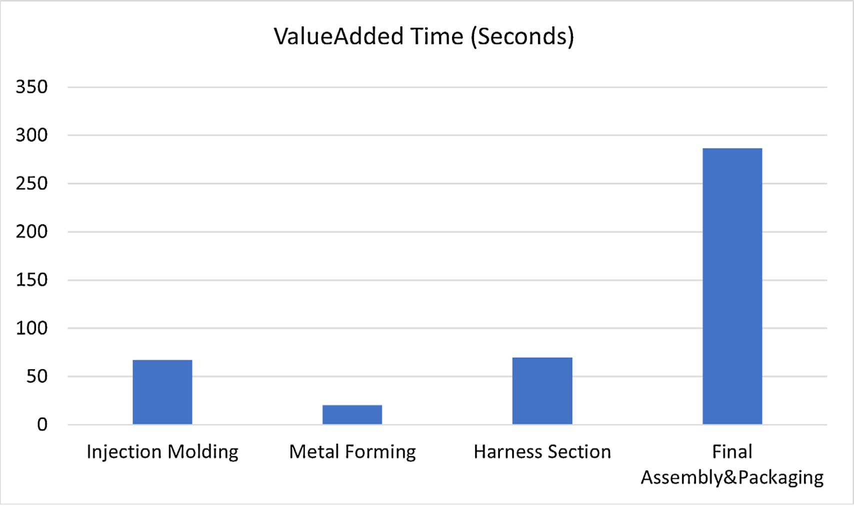


Figure 7. Value-added time at current value stream map.

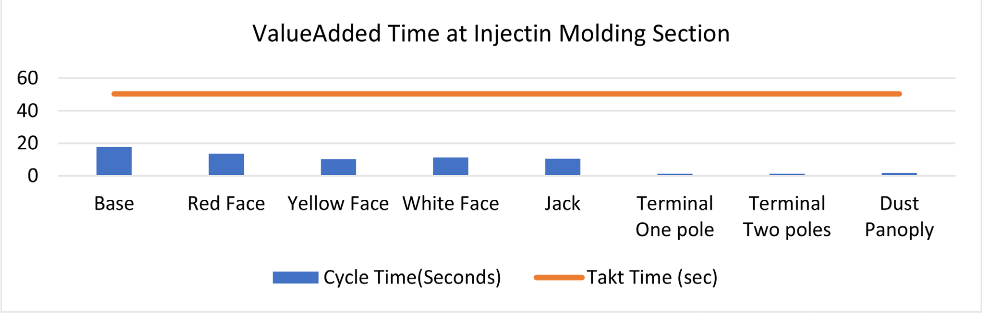


Figure 8. Value-added time at injection molding section at current VSM.

However, this creates a strategic challenge such as Injection molding produces far faster than downstream sections can consume, Risk of overproduction and WIP accumulation, requires pull-based production control (Kanban), Opportunity to reduce batch sizes and lead time.

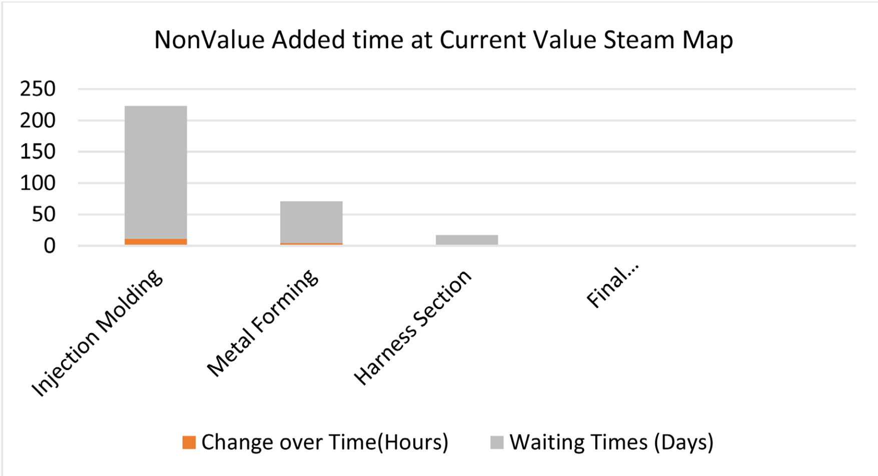


Figure 9. Nonvalue-added time at current value stream map.

As shown in the **Figure 9**, the nonvalue added time at the different stage of manufacturing TRF90. Changeover time and waiting time are two distinct sources of waste that must be eliminated. During the change of injection Molds, the machine breaks down, creating a bottleneck in operations that adversely impacts the environment due to energy consumption during this period. Where waiting time originates from work-in-progress (WIP), it involves the reservation or holding onto of raw materials in the form of semi-finished goods. The implementation of a Kanban pull system and Single Minute Exchange of Die (SMED) was discussed.

The Metal Forming Section is exceptionally well-balanced with no bottlenecks and 19x excess capacity. This is an ideal production section from a line balance perspective. However, this creates a strategic challenge: Metal forming produces far faster than downstream sections can consume, Risk of overproduction and WIP accumulation, requires pull-based production control (Kanban), and Opportunity to reduce batch sizes and lead time (**Figure 10**).

So, we need to Implement Kanban pull system to prevent overproduction, reduce batch sizes to improve lead time and flexibility, Shift focus to bottleneck sections (Harness and Final Assembly), Use excess capacity for preventive maintenance and continuous improvement.

The metal forming section is a strength to leverage, not a problem to fix. The real opportunities for improvement lie in the Harness Section (20% bottleneck) and Final Assembly Section (80% critical bottleneck).

Figure 11 clearly illustrates a lean manufacturing bottleneck situation where one operation (Sub. Assembly of Plastic Terminal, Spring & Dust Panoply) is constraining the entire production line. The operation exceeds takt time by 20%, preventing the line from meeting customer demand. Addressing this bottleneck through process improvement, line balancing, or capacity addition is the highest priority for improving harness section performance.

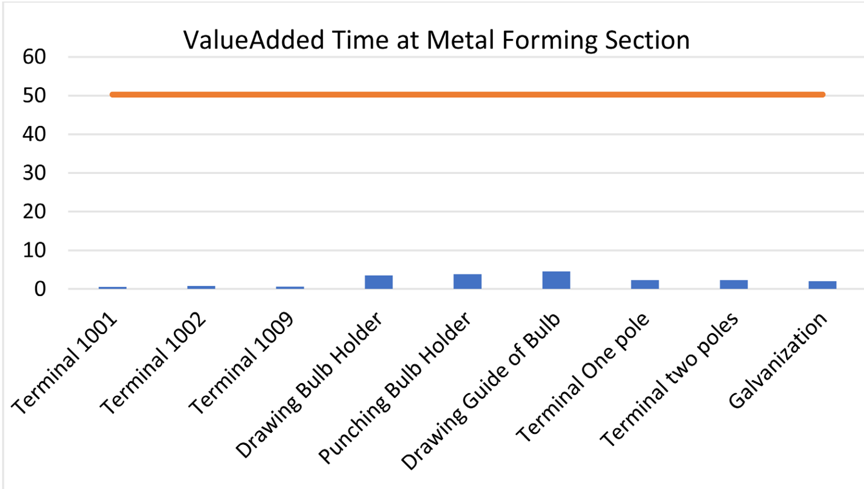


Figure 10. Value-added time at metal forming section at current VSM.

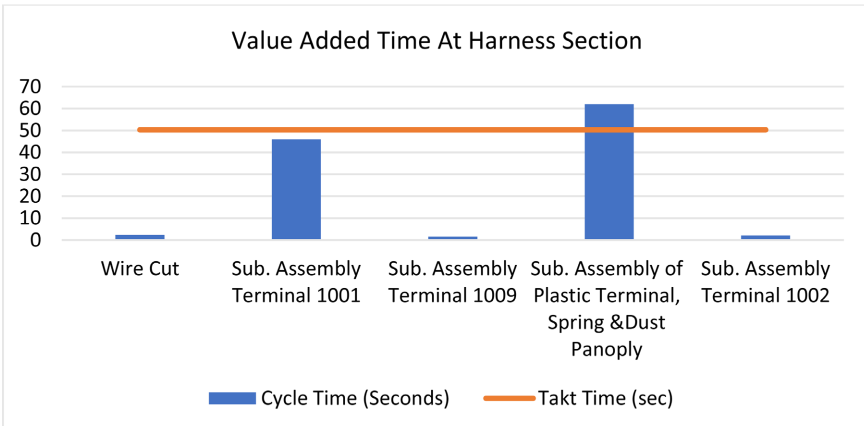


Figure 11. Value-added time at harness section at current VSM.

The Palletizing operation is a CRITICAL BOTTLENECK in the final assembly section, operating at 80% above takt time. This operation is preventing the entire production line from meeting customer demand, with a capacity shortfall of 44%. (**Figure 12**).

So, we need to conduct detailed root cause analysis of palletizing inefficiency, implement process optimization to reduce cycle time to 50 seconds, if optimization insufficient, add parallel palletizing station or automation. This is a higher priority bottleneck than the harness section due to its severity (80% vs. 20% excess time) and direct impact on final production throughput.

3.1.2. Future State

Value added time at current state map at: Value Added (VA) is Activities that directly improve the product's quality or function and contribute to the final

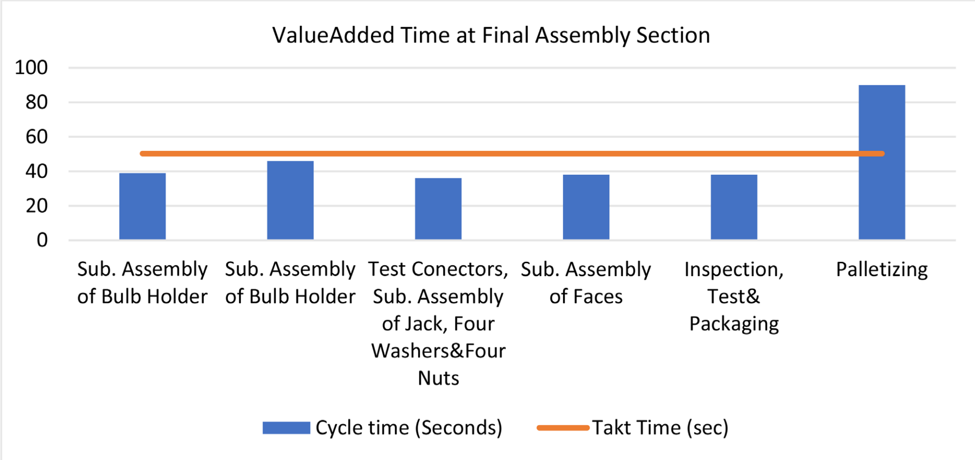


Figure 12. Value-added time at final assembly section at current VSM.

value desired by the customer.

1) injection molding = C/T for Base + C/T for Red face + C/T for Yellow face + C/T for White face + C/T for jack + C/T for terminal one-pole + C/T for terminal Two-pole + C/T for dust panoply = 17.5 + 13.5 + 10.25 + 11.25 + 10.5 + 0.25 + 0.25 + 0.75 = 67.5 Seconds.

2) Metal forming = C/T for T1001 + C/T for T1002 + C/T for T1009 + C/T for Drawing bulb holder + C/T for punching bulb holder + C/T for drawing guide of bulb + C/T for T. one-pole + C/T for T. two poles + C/T for galvanization = 0.54 + 0.77 + 0.6 + 3.5 + 3.85 + 4.5 + 2.3 + 2.3 + 2 = 20.36 seconds.

3) Harness = C/T for wire cut + C/T for sub. Assem. T.1001 + C/T for sub Assem. T1009 + C/T for sub Assem. Of plastic terminal, spring and dust panoply + C/T for sub Assem. Of T. 1002 = 2.4 + 1.46 + 1.64 + 62 + 2.14 = 69.64 seconds.

4) Final Assembly = C/T for sub Assem. Bulb holder + C/T for sub Assem. circuits and bulbs + C/T for test connection, sub Assem. Of jack, four washers and four nuts + C/T for sub Assem. Of faces + C/T for inspection, test &packaging + C/T for palletizing = 39 + 46 + 36 + 38 + 38 + 90 = 287 seconds.

Non-Value Added (NVA) is Activities that do not enhance product quality or function and only consume time and resources without benefiting the customer.

NVA at current state map = 178.439 Days, NVA at future state map = 15.87 Days.

Lead time expectation refers to the greatest duration permitted by the client from the receipt of the order till the material is delivered to them.

$$\begin{aligned}\text{Leadtime reduction}(\%) &= \frac{\text{Leadtime after lean} - \text{lead time before lean}}{\text{leadtime before lean}} \\ &= \frac{15.883-178.453}{178.453} = \frac{162.57}{178.453}\times 100 = 91.099\%\end{aligned} \tag{1}$$

Cycle time is the total elapsed time required to complete a specific task or produce a single unit from start to finish.

$$\begin{aligned}\text{Overall production efficiency} &= \frac{\text{Value Added Time}}{\text{Total Cycle Time}} \times 100 \\ &= \frac{\frac{395.09}{3600\times7.5}}{178.439+\frac{395.09}{3600\times7.5}} \times 100 \\ &= \frac{0.01463}{178.439+0.01463} \times 100 \\ &= 0.0082\% \left(\text{Current}\right)\end{aligned} \tag{2}$$

$$\begin{aligned}\text{Overall production efficiency} &= \frac{\frac{355.09}{3600\times7.5}}{15.87+\frac{355.09}{3600\times7.5}} \times 100 \\ &= \frac{0.01314}{15.87+0.01314} \times 100 \\ &= 0.0827\% \left(\text{Future}\right)\end{aligned}$$

4. The Lean Tools

4.1. Supermarket Buffers

Supermarkets serve as inventory buffers when processes experience disruptions. Supermarkets mitigate bottlenecks while incurring inventory carrying cost. Optimal supermarket sizing equilibrates flow stability with inventory costs, necessitating the consideration of: 1) unpredictability in upstream process cycle time, 2) patterns of downstream process demand, 3) replenishment lead time, and 4) inventory carrying costs.

- **Injection stage:**

  Base, $\bar{d}$ = 12,107, Acceptance risk = 10 percent, so service level 90.

  Because only demand is variable (*i.e.* has a St. dev.) Using a service level of 0.9

  You obtain Z = + 1.28

  A reorder point (ROP) is the specific, predetermined inventory level at which a business must place a new order to replenish stock. Setting this threshold prevents stockouts (running out of product) while avoiding the excess holding costs of over-ordering.

$$\text{So,}\quad \text{ROP} = \bar{d} \times LT + Z\sigma_d\sqrt{LT} \tag{3}$$

where, $\bar{d}$ = Average dialy or weekly demand, LT = Lead time in days or weeks, σ_d = Standard variation of demand in days or weeks.

$$\text{ROP} = 12107 \times \frac{1}{26} + 1.28 \times 9113 \times \sqrt{\frac{1}{26}} = 2753 \text{ units}$$

$$\begin{aligned}\text{Takt time} &= \frac{\text{Available time per day}}{\text{customer demand per day}} \\ &= \frac{75\times60}{12107/26} = \frac{450}{465} = 0.967 \text{ min/unit}\end{aligned} \tag{4}$$

$$\sigma = 9113 \text{ unit/month}$$

$$\text{Leadtime of order} = 1.5 + 7.5 + 7.5 = 16.5 \text{ hrs.} = \frac{16.5}{22.5} = 0.733 \text{ days}$$

$$\text{Safety stock} = 20\%\text{demand rate} = 20\% \times 600 = 120 \text{ units} \tag{5}$$

Safety Stock, material held to satisfy demand in cases where actual demand is higher than expected, or where the next cycle is late in starting.

$$\begin{aligned} \text{ROP} &= \text{Expected demand during Leadtime} + \text{Safety stock} \\ &= 440 + 120 = 560 \text{ units} \end{aligned} \tag{6}$$

This number represents the alarm siren for initiating the production of an additional batch of base, red face, white face, yellow face, and jack items.

$$\text{Safety stock} = 20\% \text{ demand rate} = 20\% \times 1800 = 360 \text{ units}$$

ROP = Expected demand during Leadtime + Safety stock = 1320 + 360 = 1680 units

This number serves as the alarm siren for the initiation of production for another batch of dust panoply items.

The reorder point for other items in the injection and metal forming sections has not been established due to the minimal changeover time of the machines in both sections, and the requirement of a clamping device for securing the metal roll in the metal forming section. hence enhancing cash flow and diminishing inventory holding expenses.

All the recommendations and bottleneck that were discussed before are implemented in the future value steam mapping as shown in **Figure 13**.

4.2. SMED

Single Minute Exchange of Die, is a key Lean Manufacturing technology that cuts setup time and waste. Successful SMED implementation increases modification frequency, inventory reduction, flexibility, and product quality. Using single-digit minute intervals, convert as many internal positions as possible into external roles to execute them without disrupting operations. Modern manufacturing must increase efficiency and reduce environmental effect.

This study analyses the environmental sustainability benefits of using SMED in a Mold installation process, linking time, energy, and carbon footprint reduction. Green Effect is the beneficial environmental results attained through implementation of sustainable engineering practices, technologies, or systems that reduce resource consumption, minimize waste and emissions, enhance energy efficiency, and reduce the overall environmental footprint while maintaining or enhancing technical and economic performance (**Table 2**).

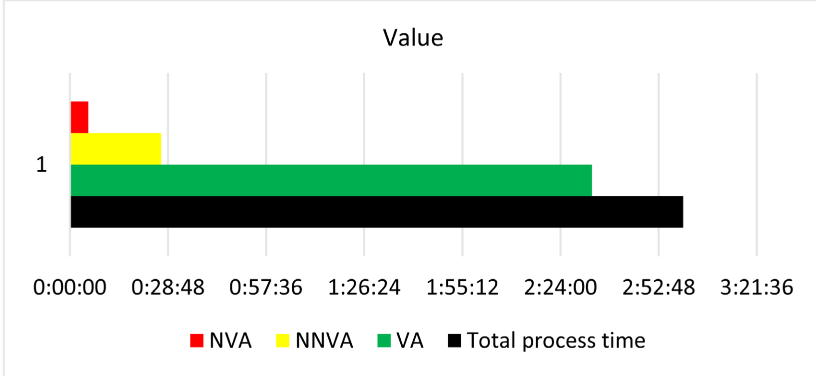
Necessary But Non-Value Added (NNVA) is Activities that do not add value but are essential to ensure smooth production flow, such as inspections, documentation, and use of standard equipment (**Table 3**).

Table 2. SMED analysis sheet of the process of changing the base injection mold.

OPERATOR			TIME (min)		
STEP	INTERNAL/ EXTERNAL	DESCRIPTION	TIME START	TIME STOP	TIME
1	I	Getting out the last product from machine	0:00:00	0:01:34	01:34
2	I	Retracting core back	0:01:34	0:05:05	03:31
3	I	Removing water hoses (MTC)	0:05:05	0:06:07	01:02
4	I	Removing core hydraulic hoses	0:06:07	0:19:32	13:25
5	I	Removing hot runner cables	0:19:32	0:19:32	00:00
6	I	Mold close	0:19:32	0:20:12	00:40
7	I	Nozzle backward	0:20:12	0:20:32	00:20
8	I	Fixing mold lock	0:20:32	0:20:32	00:00
9	I	Fixing crane's lock	0:20:32	0:20:50	00:18
10	I	tighten crane wire	0:20:50	0:21:23	00:33
11	I	Unlock mold clamps	0:21:23	0:31:53	10:30
12	I	Remove machine nozzle	0:31:53	0:35:28	03:35
13	I	Remove old mold	0:35:28	0:38:09	02:41
14	I	Unlock crane's lock	0:38:09	0:38:30	00:21
15	I	Connecting wire to new mold (crane)	0:38:30	0:38:30	00:00
16	I	Color change 1	0:38:30	0:47:18	08:48
17	I	Placing the mold in machine	0:47:18	1:03:18	16:00
18	I	centering mold	1:03:18	1:12:25	09:07
19	I	fixing mold to machine	1:12:25	1:43:00	30:35
20	I	Remove crane's lock	1:43:00	1:44:33	01:33
21	I	Connecting hot runner and turn it on	1:44:33	1:44:33	00:00
22	I	Mold open	1:44:33	1:46:33	02:00
23	I	connecting water hoses (water distribution manifold)	1:46:33	2:03:02	16:29
24	I	adjusting high pressure + loading mold data	2:03:02	2:11:00	07:58
	I	Color change 2	2:11:00	2:17:00	06:00
26	I	Nozzle fixing	2:17:00	2:17:00	00:00
27	I	connecting nozzle heater	2:17:00	2:25:22	08:22
28	E	Checking mold gates	2:25:22	2:30:45	05:23
29	I	Start up	2:30:45	2:59:59	29:14
TOTAL TIME = 180 Min					
Number of defects = 11					

Table 3. Analysis of work category sheet.

VA		NNVA	
Description	Duration	Description	Duration
Getting out the last product from machine	01:34	Remove machine nozzle	03:35
Retracting core back	03:31	Color change 1	08:48
Removing water hoses (MTC)	01:02	Color change 2	06:00
Removing core hydraulic hoses	13:25	Nozzle fixing	00:00
Removing hot runner cables	00:00	connecting nozzle heater	08:22
Mold close	00:40	Total	26:45
Nozzle backward	00:20	NVA	
Fixing mold lock	00:00	Description	Duration
Fixing crane's lock	00:18	Checking mold gates	05:23
tighten crane wire	00:33	Total	05:23
Unlock mold clamps	10:30		
Remove old mold	02:41		
Unlock crane's lock	00:21		
Connecting wire to new mold (crane)	00:00		
Placing the mold in machine	16:00		
centering mold	09:07		
fixing mold to machine	30:35		
Remove crane's lock	01:33		
Connecting hot runner and turn it on	00:00		
Mold open	02:00		
connecting water hoses (water distribution manifold)	16:29		
adjusting high pressure + loading mold data	07:58		
Checking mold gates	05:23		
Start up	29:14		
Total	2:33:14		



This substantial enhancement is anticipated to augment machine availability, elevate output capacity, and diminish operational costs related to downtime (Table 4).

Table 4. Comparison of the change over time before and after SMED implementation.

Metric	Current State	After SMED	Reduction
Total Process Time	174.9 min	83.8 min	52.0%
Machine Downtime (Internal)	169.5 min	68.1 min	59.8%
External Preparation Time	5.4 min	15.7 min	+190.7%

4.2.1. Analysis of the Current State: Mold Installation Procedure

Present Activity Distribution:

Total Process Duration: 174.9 minutes.

Internal Activities (Machine Downtime): 169.5 minutes (96.9% of overall procedure duration).

External Activities (Machine Operation): 5.4 minutes (3.1% of overall process duration).

This disparity signifies considerable prospects for enhancement by transitioning internal operations to external ones and optimizing the remaining duties.

4.2.2. SMED Implementation Strategy: Attaining a 50% Reduction

A multi-faceted strategy aimed at achieving a 50% decrease in overall changeover time, emphasizing conversion and optimization, is offered.

1) Separation of Internal and External Activities

Numerous functions presently conducted internally can be transitioned to external tasks. This entails pre-staging, pre-heating, and organizing tools and materials while the machine continues to produce the preceding batch. Internal activities define the activity elements when the machine is turned off or stops operating. Meanwhile, external activity is an activity element that is obtained when the machine is on or operating (Table 5).

2) Optimizing Internal Operations

For internal activities, substantial time savings can be realized through enhanced technologies, methodologies, and organizational strategies. The subsequent Table 6 delineates the suggested optimization initiatives and their anticipated effects:

Table 5. Changing internal activities to external.

Step	Current Classification	Description	Duration (min)	Proposed Classification	Rationale
15	Internal	Connecting wire to new mold (crane)	0.0	External	Can be done while the previous mold is being removed or new mold is staged.
16	Internal	Color change 1	8.8	External	Material preparation (e.g., pre-mixing, pre-drying, staging new material) can occur before machine stop.
25	Internal	Color change 2	6.0	External	Similar to Color change 1, material preparation can be externalized.
27	Internal	Connecting nozzle heater	8.4	External	Pre-heating the nozzle or using quick-connect pre-heated nozzles can be done externally.
28	External	Checking mold gates	5.4	External	Already external, no change.

Table 6. Time reduction efforts for internal activities taken.

Target Activity	Current Duration (min)	Proposed Improvement	Estimated Reduction Factor	New Duration (min)
Fixing mold to machine (Step 19)	30.6	Quick-release clamping systems (e.g., hydraulic, magnetic)	60%	12.2
Start up (Step 29)	29.2	Standardized start-up sequence, pre-heated mold, optimized parameters	55%	13.1
Removing/Connecting Hoses (Steps 3, 4, 23)	1.0, 13.4, 16.5	Multi-coupling connectors	55%	0.4, 6.0, 7.4
Placing/Centering Mold (Steps 17, 18)	16.0, 9.1	Standardized mold guides, precise machine positioning	50%	8.0, 4.5
Unlock mold clamps (Step 11)	10.5	Quick-release clamping systems	50%	5.3
Other General Steps	Variable	Improved tooling, 5S, operator training	45%	Variable

An investigation of Single-Minute Exchange of Die (SMED) applied to the mold installation procedure for the Rear Lamp Base (Machine 530/2). The main goal was to attain a 50% decrease in the overall changeover duration. The systematic implementation of SMED principles, which involves the segregation and transformation of internal and external activities, along with the optimization of residual internal tasks, indicates a possible 52.0% reduction in total process time, lowering the changeover duration from 174.9 minutes to 83.8 minutes.

Upon implementing SMED on M/C530/2, this methodology can be extended to other machines within the injection molding area to achieve the outcomes identified in subsequent value stream mapping.

This chart demonstrates the powerful impact of SMED (Single-Minute Exchange of Die) implementation. the 52.1% reduction in changeover time is a major lean manufacturing achievement that significantly improves production efficiency, flexibility, and financial performance.

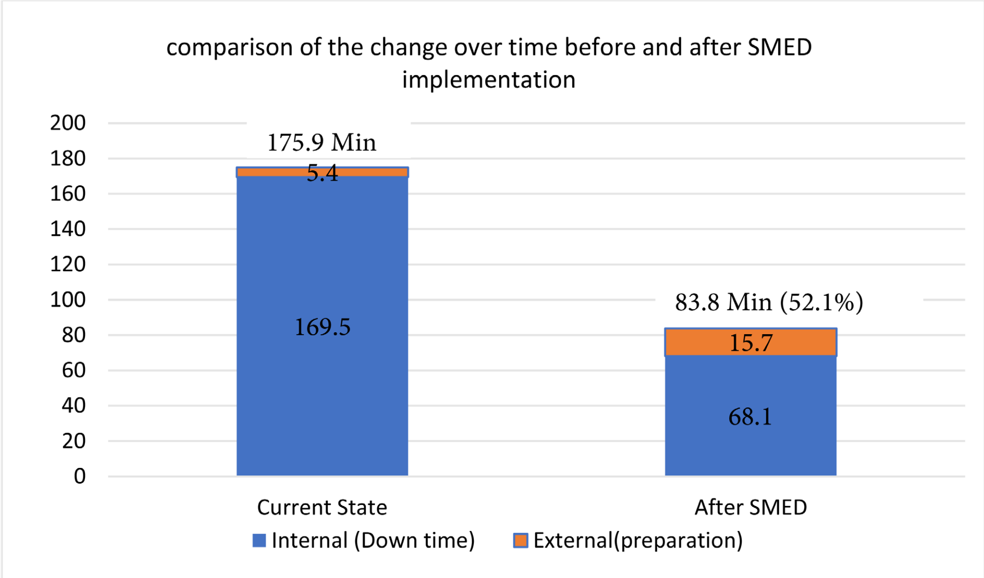


Figure 13. Comparison of the change over time before and after SMED implementation.

4.2.3. Quantitative Analysis of Energy and Carbon Footprint

1) Energy Consumption Model

During changeover, even when not actively producing, injection molding machines consume substantial energy to maintain operational readiness (e.g., heating barrels, hydraulic systems, control systems). Equation (7) showed that the energy consumption (E) during machine downtime can be modeled as:

$$E = P_{idle} \times T_{downtime} \tag{7}$$

where, E is the energy consumed in kWh. P_{idle} is the average power consumption of the machine during idle/changeover state in kW. $T_{downtime}$ is the duration of machine downtime (internal changeover time) in hours.

For a 530-ton injection molding machine, the average power consumption during idle/changeover (P_{idle}) is estimated at 29.25 kW (65% of an average 45 kW production power).[18]

2) Carbon Footprint Calculation

Equation (8) showed that the carbon footprint (CF) associated with electricity consumption is calculated by multiplying the energy consumed by a relevant CO_2 emission factor:

$$CF = E \times EF_{CO2} \tag{8}$$

where, CF is the carbon footprint in kg CO_2. E is the energy consumed in kWh.

EF_{CO2} is the CO_2 emission factor for electricity generation in kg CO_2/kWh. A representative global average emission factor of 0.475 kg CO_2/kWh is used for this analysis [19].

3) SMED Impact on Environmental Metrics

The SMED implementation directly reduces $T_{downtime}$, which in turn decreases E and subsequently CF. The percentage reduction in energy and CO_2 emissions is directly proportional to the percentage reduction in internal changeover time, assuming P_{idle} and EF_{CO2} remain constant.

4) Energy and Carbon Footprint Reduction

Based on the established models, the energy consumption and CO_2 emissions were calculated for both the current and proposed states: (Table 7)

Table 7. Comparison of the energy consumption and CO_2 emissions before and after SMED implementation.

Metric	Current State	After SMED	Savings per Changeover	Percentage Reduction
Internal Downtime	169.5 min	68.1 min	101.4 min	59.8%
Energy Consumption	82.64 kWh	33.20 kWh	49.44 kWh	59.8%
CO_2 Emissions	23.48 kg	9.43 kg	14.05 kg	59.8%

These results demonstrate a direct and proportional relationship between the reduction in internal changeover time and the reduction in energy consumption and CO_2 emissions. The 59.8% reduction in internal downtime translates directly to a 59.8% reduction in energy consumption and CO_2 emissions during the changeover period.

5) Annual Environmental Impact

Assuming 150 changeovers per year (e.g., 3 changeovers per week for 50 weeks), the annual environmental benefits are substantial:

Annual Energy Savings: 49.44 kWh/changeover × 150 changeovers/year = 7416 kWh/year and Annual CO_2 Reduction: 14.05 kg CO_2/changeover×150 changeovers/year = 2107.5 kg CO_2/year≈2.107 metric tons CO_2/year. This annual CO_2 reduction is equivalent to avoiding the emissions from driving a gasoline-powered passenger vehicle for approximately 5366 miles. [20] The anticipated environmental advantages of attaining a 25% decrease in changeover durations for a group of seven injection molding machines. This research quantifies energy savings and carbon dioxide (CO_2) emission reductions, offering a comprehensive overview of the beneficial effects on operational sustainability.

6) Principal Conclusions from 25% Decrease

Total Monthly Energy Savings, A 25% reduction in changeover times for all machines is anticipated to conserve 239.85 kWh of electricity monthly. Total Monthly CO_2 Emissions Decreased: This energy conservation results in a reduction of 113.93 kg of CO_2 emissions each month. Total Annual Energy Savings, the segment is projected to conserve 2878.20 kWh of electricity annually due to decreased changeover periods. Total Annual CO_2 decrease: The annual decrease in carbon footprint resulting from these initiatives is 1.37 metric tons of CO_2.

7) Machine-Specific Contributions to Savings:

As SMED was implemented to M/C 530/2, it was implemented to the other machine in the injection section. Table 8 summarizes the energy and CO_2 saved through one month.

Table 8. Comparison of the change over time, Monthly Energy Saved and Monthly CO_2 saved before and after SMED implementation of other machines used for producing different parts of the identified product.

Machine	Tonnage	Baseline C/O Time (hr.)	Reduced C/O Time (hr.)	Monthly Energy Saved (kWh)	Monthly CO_2 Saved (kg)
M/C 260	260	2.00	1.50	73.13	34.74
M/C 140/1	140	1.00	0.75	27.30	12.97
M/C 180/1	180	1.00	0.75	35.10	16.67
M/C 140	140	1.00	0.75	27.30	12.97
M/C 90/1	90	1.00	0.75	17.55	8.34
M/C 90/2	90	1.00	0.75	17.55	8.34
M/C 90	90	1.00	0.75	17.55	8.34

These savings are derived from reducing the non-productive idle time during which machines still consume energy.

5. Conclusions

This study proves that Lean Manufacturing's "Green Effect" is real and has quantifiable benefits. The TFR90 case study shows that systematic lean manufacturing projects simultaneously achieve: Operational Excellence, Cut lead time by 91.099%, improved quality, and increased efficiency. Environmental Sustainability, 39.07 percent carbon footprint reduction, better resource use, and reduced waste. Financial Performance, Waste minimization decreases costs, boosts cash flow, and enhances competitiveness.

Integration of Lean and Green manufacturing changes operations. Lean-Green views efficiency and sustainability as mutually reinforcing goals that drive competitive advantage in an environmentally concerned global economy. Organizations that successfully implement integrated Lean-Green strategies will achieve superior financial performance and operational efficiency and become leaders in sustainable manufacturing, meeting the expectations of increasingly environmentally conscious customers, regulators, and stakeholders. Lean Manufacturing is Green when environmental considerations are considered throughout the value stream. Waste minimization and continued development may provide any manufacturing organization a meaningful and verifiable "Green Effect".

Environmental Management Systems (EMS) mediates how sustainability programs impact the environment. Thus, mean that Lean Green integration encourages organizations to establish structured environmental policies and EMS improves resource consumption, waste management, pollution prevention, and regulatory compliance. Thus, Green Effect improves. Organizational culture is the common values, attitudes, conventions, and behaviors that affect employees. A sustainability-oriented culture encourages employees to Support environmental initiatives, participate in continuous improvement, reduce waste, Share green knowledge and adopt environmentally responsible behaviors.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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