

## **The Role of Lean Manufacturing and Robotic Cells in Improving Productivity and Efficiency in Small and Medium-Sized Enterprises (SMEs) Within the Machining Industry.**

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**Abstract:** SMEs are an important part of the manufacturing industry, yet many SMEs lack the productivity and competitiveness of large manufacturers because they are still using traditional, labour-intensive processes or inefficiently designed systems to do business. The purpose of this study was to outline a structured approach to combine lean manufacturing principles with robotic automation to increase productivity, improve the consistency of processes, and maximize the use of available resources in SMEs that operate machining processes. Current State Analysis revealed an extremely low match of demand to production capacity with the system producing a mere 27,846 units/month with a demand of 40,000 units/month, resulting in a shortage of 30.4%. Many processes within the system were characterised by a high number of non-value-added activities such as manual loading/unloading, waiting, and re-handling and high numbers of operator fatigue related to high density of manufacturing (650 sq. ft.) and inconsistent quality. The development of a flow oriented robotic cell layout provided the opportunity to optimize the layout, automate the material handling processes and implement the use of Poka-Yoke and Jidoka mechanisms. Using the new cell layout, operational performance improved significantly with cycle time being reduced by 12.5%, productivity increased by 30%, and floor space reduced by 43%. In addition, the operator dependency for the new robotic cell layout was reduced from three operators per shift to one operator per shift thus improving the efficiency of the process and reducing variability due to operator fatigue. Lean principles allowed for the elimination of non-value-added activities and the improvement of process flow, while the automation provided a consistent output and improved safety. Thus, the evidence indicates the use of a lean-first and an automation-next strategies provide viable and scalable solutions for SMEs that desire sustainable improvements in productivity, quality, and overall cost efficiency.

**Keywords:** Lean Manufacturing, Value Stream mapping, Cycle Time, Productivity, Poka-Yoke

### **1. Introduction:**

The manufacturing sector consists of many small and medium enterprises ("SMEs"). SME's are extremely significant in the production of jobs and production through manufacturing. However, many SMEs demonstrate low degree of productivity, and therefore, SMEs typically have a lack of effectiveness in resource utilization and inconsistencies in quality due to their dependence upon traditional methods and the significant use of labour-intensive methods in production. Manual operations, unoptimized layouts and non-integrated processing will increase the number of non-value-added operations and increase cycle times, and also create discrepancies between demand and capacity. The inability for SMEs to meet the increase in customer demand is primarily based on the extent of their process inefficiencies rather than the limits of their resource capabilities. This study demonstrates a significant gap between

production capacity and demand at the machining system under investigation; and therefore, SMEs are faced with the following challenges: (1) excessive manual handling activities; (2) excessive fatigue operators; (3) process variation; and (4) inefficient layout. Thus, by understanding the need for a systematic improvement of the above challenges, SMEs must implement improvement methodologies.

One methodology used to eliminate waste and improve flow and productivity is lean manufacturing. The Value Stream Map ("VSM") is one tool used in lean manufacturing provides organizations with the means to define their current state and identify sources of waste, as well as assists organizations in designing a new "future" state using the same process. In highly involved repetitive and operator dependent environments, simply implementing lean processes will not equalize the output of the operation with demand. Rather, the combination of lean principles and implementing forms of automation, specifically robotic systems, has provided many organizations with the ability to improve production quality, stability, and production throughput. Lean-Automation Integration is a more recent development in the market place. This methodology first focuses on eliminating waste, and then implements a level of selective automation prior to further productive utilizing the new level of productivity to maximize efficiencies and the return on investment. The current research expands upon that concept by incorporating a Robo Cell Lean/Automated Integrated Framework for enhancing the machining systems of small-to-medium enterprises (SMEs).

Lean manufacturing has become widely accepted as a viable approach to enhancing productivity; eliminating waste; and otherwise enhancing operational efficiencies within a manufacturing system. The concept of lean manufacturing originated from the work of Womack and Jones, and is based upon the principle of creating value through the elimination of waste in a systematic fashion [1]. Subsequent research established that when implemented successfully, lean is regarded as an integrated system consisting of a variety of tools and techniques that together can enhance the performance of a manufacturing operation [2]. Unfortunately, for SMEs, the successful implementation of lean manufacturing typically presents challenges due to a lack of financial resources; limited experience; and resistance from within the organization. Various studies examine the identified critical success factors necessary for the effective implementation of lean manufacturing, and include; the commitment of leadership; employee involvement; and integration with the strategic vision of the organization [3].

Value Stream Mapping (VSM) is one of the most popular lean tools for identifying inefficiencies in a manufacturing operation and for developing improved material and information flow. Developed by Rother and Shook, VSM provides a visual representation of the flow of material and information within a process, thereby allowing the organization to clearly identify which activities add value and which do not [4]. The research surrounding the use of VSM in manufacturing operations has emphasized the utility of VSM for identifying and eliminating waste while guiding continuous improvement initiatives [5]. A number of studies have documented successful applications of VSM in SMEs and have reported the achievement of reduced cycle time; reduced inventory; and reduced production lead time associated with the application of VSM [6-8]. Although lean implementation has many benefits, it may not fully solve problems related to process variability or operator dependency, especially in labour-intensive facilities. Cultural resistance, a lack of strategic vision, and improper tool selection are major barriers to a lean manufacturing implementation [9,10]. In

highly manual environments, operator dependent activities lead to cycle time and quality inconsistency, which will lower overall system reliability. These findings suggest that there is significant impact from non-value-added activities, such as manual handling and rework, on productivity within SMEs.

Automation has become a key enabler of improved manufacturing performance by eliminating human interaction and providing greater process consistency. Automation has been shown to enhance productivity through continuous operation, variability reduction, and better product quality [11]. Industrial robotics have gained traction due to lower cost and greater flexibility. Robotic systems provide greater operational efficiency, reduce dependence on human labour, and improve safety [12-14]. The integration of lean manufacturing with automation is becoming a popular holistic methodology for implementing system perfection. The definition of Lean Automation combines waste reduction and advanced technology to attain perfect performance [15]. Lean principles serve as a basis for implementing Industry 4.0 technology effectively; adopting a "lean-first-then-automate" strategy provides superior results [16-18]. Facility layout and cellular manufacturing are also important contributors to manufacturing efficiency. Optimized facility layouts minimize material handling costs, increase flow efficiencies, and improve effective space utilization [19]. Cellular manufacturing methods have demonstrated the ability to reduce lead time and increase productivity by decreasing the unnecessary movement of employees, and through better coordination of processes [20,21].

Poka-Yoke and Jidoka are two of the most important quality improvement methods for ensuring process reliability and reducing defects. Poka-Yoke, introduced by Shigeo Shingo, is a method of designing error-proof devices that prevent defects from being produced [22]. Jidoka allows machines to detect abnormal conditions and stop automatically; this process improves quality and reduces rework [23,24]. The literature indicates that individual studies have been conducted on lean manufacturing, value stream mapping (VSM), automation, and facility layout optimization; however, there is a need for comprehensive frameworks that integrate all these methodologies into a practical, scalable solution. While the existing studies provide solid theoretical support for integrated methodologies, there is a lack of comprehensive examples of successful real-world implementation of integrated methodologies to address productivity, effective space utilization, operator dependency, and improvement in quality at the same time in SMEs. This represents a gap that needs to be addressed by the integrated Lean-Automation methodology proposed in this research.

## **2. Problem Definition:**

The Manufacturing Sector relies heavily on Small and Medium Enterprises (SMEs), but many SMEs are dependent upon traditional labour-intensive production techniques thus restricting productivity, quality and efficiency of processes. This investigation is carried out at NETMECH FOUNDERS Pvt. Ltd. (Maharashtra-India).



Fig. 1 Photographic view of component (As cast, First Side machining, Second Side Machining)

Investigation was done on a component shown in Fig. 1 (Details of components are not mentioned as per instructions from the company). The machining operations basically involves turning and facing operations for both sides. As a result of the old Machining System (manual production capacity = 27,846 units), there exists a restriction in the current SME manufacturing supply chain ("Supply Chain") to meet customer demand (demand = 40,000 units/month), creating a shortfall of 12,154 units (30.4% gap). The Supply Chain had a gap in the ability to fulfill market demand due to production inefficiencies; as opposed to constraints to resources."

Furthermore, the most prevalent form of Non-Value-Added Activities ("NVAA") were present in the existing Machining Systems i.e. Loading/Unloading parts, RH-Handling parts, waiting on operator while machining. These activities contribute to excess Cycle Time, Reduced Consistent Output, and Poor Flow. In addition, due to the requirement of the operator to utilize manual clamping in the machining process, there was also no predictability (or Variability) in part quality, leading to rejected parts and delays caused by the separation of machining. From an operational standpoint, the old Machining Systems had an efficiency of (OEE  $\approx$  85%) and depend on operator performance rather than the capabilities of the machines themselves. Demand located outside capacity constrains the system as well as non-value-added activities, dependence on operators, variation in processes, and inefficient layout. These constraints indicate the need for a structured approach to eliminate waste, improve flow and productivity, and achieve sustainable and safe manufacturing operations through the integration of lean manufacturing and automated technologies.



**Fig.2 Manual machining layout with congested workspace, poor material flow, and operator-dependent handling causing motion waste and ergonomic issues.**

Fig.2 shows the manual machining setup characterized by a linear machine arrangement with limited accessibility and congested working space. The narrow walkway between machines creates excessive movement of the operators and poor flow of material. The area highlighted in yellow shows the manual loading/unloading zone where the operator handles the same part multiple times to load/unload it, creating motion waste and waiting, which contributes to the operator's ergonomic workload. Likewise, the lack of a structured layout design creates inefficient use of space, operator fatigue, and potentially unsafe working condition.

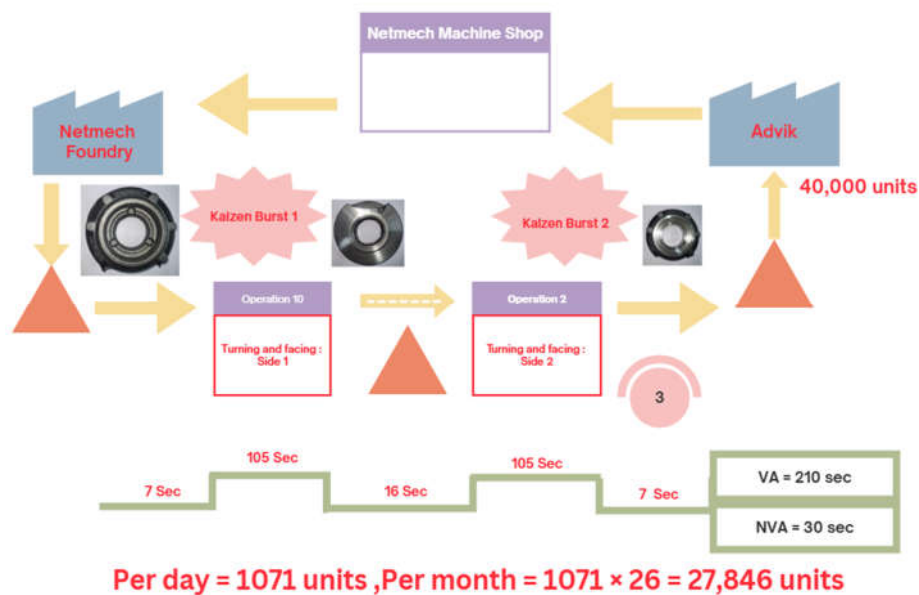


Fig.3 Current State Map

The current state map shown in Fig.3 depicts the manual machining process as it takes place at NETMECH and the associated workflows. The components of the process flow from foundry to machine in two operations—turning and facing of Side One and Side Two. The process was disjointed; therefore, there was an increased amount of time required to wait for one of the operations to finish and to handle the parts manually for transit between these operations. The total cycle time for the complete machining cycle was 120 seconds, 105 of which were for the machining and 15 seconds were for loading/unloading.

The system operated at an average of 85% efficiency, producing 1,071 units per day, or 27,846 units per month, and falls short of the required demand of 40,000 units. The map identifies several Kaizen ‘bursts’ that depict problem areas in the process, including excessive manual handling, operator fatigue, and inconsistent quality due to burrs on the parts.

The majority of the time, in the process (approximately 30 seconds), was made up of non-value-added activities (e.g., waiting, re-handling, and movement between machines). In (the current state), the system required three operators per shift to be able to perform the machining operations, which created a high reliance on hourly labour and fatigue. Additionally, the layout occupied 650 square feet of floor space, creating motion waste and inefficiencies in the flow of material.

In conclusion, the current state represented a disjointed labour-intensive process with a high percentage of non-value-added time, variability in the processes, and limited productivity; therefore, it is apparent that there is a need for lean interventions and automated solutions.

### **3. Implementation of the Lean-Automation Integrated Framework to Create a Robotic Cell**

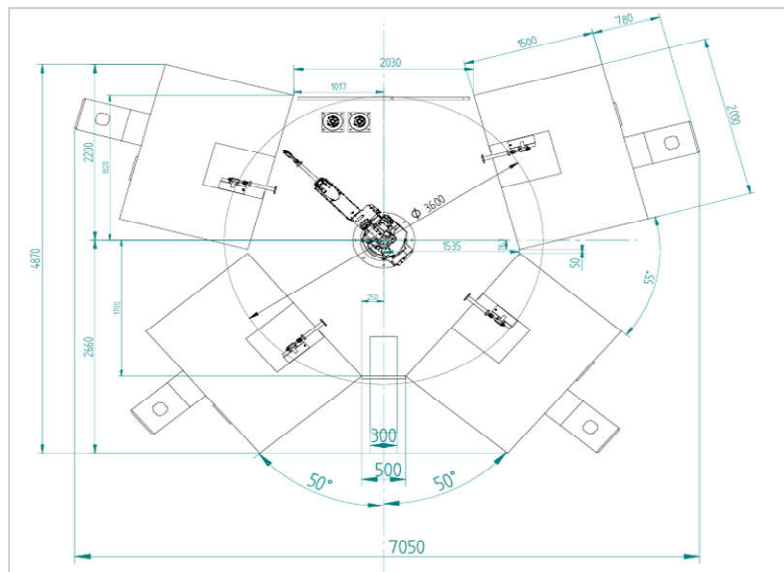
In order to address the lack of efficiency in the current machining operation, a process improvement method that leverages the principles of Lean and automation has been developed to increase productivity, remove non-value-added processes, improve process flow, and provide a safe working environment which is shown in Fig.4 and discussed in sub sequent sections.



**Fig.4 Lean-Automation Integrated Robotic Cell**

### 3.1.Optimizing Flow Oriented Robot Cell Layout and Design

An evaluation of the original layout revealed a lack of efficiency due to poor use of space, excessive manual handling, and inadequate flow of materials through the current 650 SF layout.



**Fig. 5 Robot Cell Layout and Design**

The flow oriented robotic cell layout (see Fig. 5) was subsequently developed to solve these issues, resulting in a compact circular configuration with the robot located centrally, and the production area reduced from 650 SF to 368 SF (a 43% savings in area).

The new layout offers:

- Reduced manual handling
- Decreased congestion of function areas
- Increased flow and visibility of materials
- Increased ergonomics and workplace safety

### 3.2. Automating the Loading and Unloading of Parts

The primary bottleneck in the manual system was the handling of parts that were reliant on manual loading and unloading processes which caused operator fatigue, variability, and waiting times. Consequently, an automatic robotic handling system was created to load and unload parts.

Key elements of the automation process are:

- Fixed load/unload stations
- Robotic arms will transfer parts
- Loading/unloading will be synchronized with machine cutting application cycle

Since the introduction of the automatic handling system, the process has eliminated manual handling, reduced cycle time variability, and provided for a steady continual output of products.

The future state design clearly demonstrates the fact that automation has dramatically reduced the wasted motion associated with the operation and provided a more stable working environment.

### 3.3.Implementation of Jidoka (Built In Quality) and Poka-Yoke (Error Proofing)

To eliminate quality issues associated with the manual handling processes, error-proofing and built in quality controls were incorporated into the system.



**Fig. 6 Contact type Poka Yoka used for robot cell door. After door open steel rod contact lose with sensor and red light C alarm start and robot movement stop.**

Some of the major implementations include:

- Safety interlock system-Contact type safety device has been installed at the door of the robotic cell, and when the door is opened, the contact of the devices is opened, an alarm sounds, and the robotic arm will stop immediately. This is shown in Fig.6.
- Conveyor Sensors-Sensors will monitor the total number of parts on a conveyor and prevent the robotic arm from loading too many parts on a conveyor shown in Fig.7.
- Clamping Poka-Yoke Mechanism. The pusher type system used during the first side machining and second side machining will ensure proper position and seating of components.
- Indexing Mechanism. The indexing mechanism will ensure proper positioning/orientation and movement of components between the machining operations.



**Fig.7 Conveyor sensor used if conveyor full with parts sensor detect that and then robot not kept parts on conveyor.**

The above elements resulted in:

- To eliminate any misaligned or improperly clamped components
- To reduce the number of defects and rework.
- To provide for a more reliable and consistent process

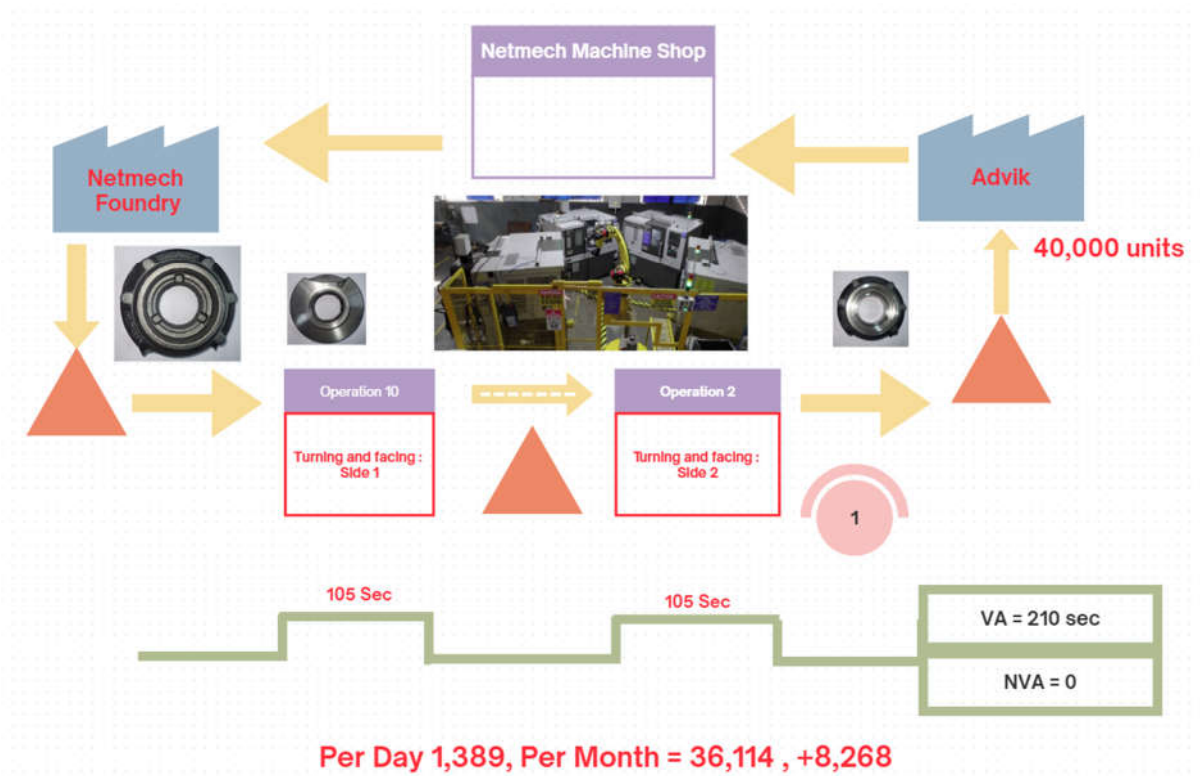
### 3.4.Value Stream Mapping (VSM) of Lean Robotic Cell Integration

A Value Stream Map (VSM) analysis of the existing process allowed for an optimized future state design, as outlined in the future state map. The future state map included: integrated first-side and second-side machining, continuous flow via robotic handling, and the elimination of non-value-added activities. After the optimised process was implemented, the following results were obtained: value added time of 210 seconds, elimination of non-value-added time (i.e. 0), and balanced operations with synchronised flow. The implementation of several Key Performance Indicators (KPIs) demonstrated the following measurable improvement to process performance:

Kaizen 1 - layout optimisation, optimised, and fixed loading locations (see Addendum C for details)

Kaizen 2 - automated material handling (see Addendum C for details)

The KPIs above led to reduced waste associated with motion, improved safety, and increased visibility into the process.



**Value Stream Mapping (VSM) of Lean Robotic Cell Integration**

### 3.5.Performance and Productivity Improvements

The implementation of the lean-automation framework has led to a significant improvement in performance.

Parameter	Manual System	Robo System	Improvement
Cycle Time	120 sec	105 sec	↓ 12.5%
Production/Shift	357	462	+105
Daily Production	1,071	1,389	+318
Monthly Production	27,846	36,114	+8,268
Productivity	—	—	↑ 30%
Operators	3 per shift (9 total)	1 per shift (3 total)	Reduced
Space	650 sq. ft.	368 sq. ft.	↓ 43%

The novelty of the System includes

- Waste elimination of waiting and motion
- Significant reduction of rework and over-processing
- Significant reduction of operator fatigue
- Improved process efficiency and space utilization

### 3.6.Financial Impact and Profitability

Evaluation of the Proposed System shows positive Economic Validity-

Automated Lean System:

- Total Machining Revenue: ₹4,41,000.00
- Final Profit per Month: ₹2,65,600

The Cost Structure for the system includes labor, maintenance, tooling, consumables and utilities. Although profit increased for this investment in automation due to increased production, the biggest contribution to this profit increase was the reduction in Operational Waste.

### 3.7.New Optimized Robotic Cell Layout

A radical redesign of the conventional linear machining arrangement to a compact, flow-oriented, cellular machining system has occurred through the optimized robotic cell layout. With the new cellular manufacturing system, CNC machines are oriented radially from a centrally located robotic arm; creating the ultimate environment for efficient material handling and synchronized operations that reduce the core inefficiencies in the current manufacturing process.

One of the main advantages of the new layout will be reduced distances travelled by material and movement of operators between machines. The existing manual loading/unloading and

inter-machine travel create significant motion and waiting waste. However, the new centralized robotic system minimizes distance travelled by material by allowing for direct transfer of materials from one machine to the next while working inside a defined working envelope. This reduces non-value added activities while maintaining a 'clean' process flow as defined in Lean Manufacturing concepts. Additionally, the new layout demonstrates a significant improvement in space utilization; the total square footage was reduced from 650 sq. ft. to 368 sq. ft. (43% reduction). The compact design was accomplished through proper angular placement of machines and elimination of unnecessary operator pathways. The increased efficiency of layout design enhances facility costs and improves the organization, visibility, and safety of the workplace, which are all very important features in an SME environment. The use of robotic handling as part of the optimized layout promotes synchronized machining and handling, which reduces variability in cycle time - cycle times dropped from 120 seconds to 105 seconds - representing approximately a 30% improvement in productivity. This is principally due to the elimination of manual labour and the introduction of continuous flow between production processes. Additionally, the layout supports the use of built-in quality (Poka-Yoke and Jidoka) mechanisms that improve reliability of manufacturing processes. The arrangement of processes in a structured manner provides the opportunity to implement usable sensor, interlock and indexing devices to accurately position parts and prevent defects. This results in consistent quality of finished output and lower levels of rework compared to the original manual method.

Additionally, a significant outcome of the proposed design is the reduction in operator dependency. The number of operators required per shift in the manual process was three and only one operator would be required per shift in the automated process. This results not only in reduced costs associated with labour, but can also alleviate all of the fatigue; variability, and error issues typically associated with human labour. In addition, operators will be required to act as supervisors for their own automated systems, thereby signalling a move toward more skilled-based manufacturing. An important outcome from this research is that the layout redesign, combined with automation and lean principles, provides the basis for significantly improving manufacturing performance. The data collected supports the conclusion that the use of a flow-oriented, human-independent, and space-efficient design can enhance sustainable productivity improvements in SMEs.

#### **4. Conclusion**

This study provides a structured, practical framework that integrates lean manufacturing principles into robotic automated manufacturing systems to address significant inefficiencies present in machining operations within SMEs. Through the application of this methodology, a traditional, labour-intensive production process was successfully transformed into a dynamic, flow-oriented, and efficient manufacturing system.

The findings from the present state analysis indicate that the operator-dependent manual machining system presents an operationally fragmented workflow process with excessive amounts of non-value-added time (~30 seconds), excessive cycle times (120 seconds), and minimal production outputs (27,846 units/month). In addition, significant evidence of Kaizen hotspots were documented, demonstrating that manual loading/unloading, operator fatigue, extended waiting times, and variability in product quality due to the burr formation significantly impact the system's ability to adequately address the needed production output of 40,000 units.

Through the application of the optimized robotic cell layout, along with systematic identification and elimination of waste, a significant improvement in overall production was achieved. The overall system produced a 12.5% reduction in production cycle time, a 30% increase in productivity, and a 43% reduction in floor space utilization, providing data to clearly indicate the effectiveness of layout re-design and continuous flow design. The further integration of first-side and second-side machining operations and the elimination of non-value-added activities allowed for a near-continuous production flow process with improved production synchronization. The automation of the loading/unloading operations significantly reduced reliance on operator involvement, reducing the number of operators required per shift from three to one. In addition to significantly reduced operational costs, this change has reduced fatigue and variability of the physical work place associated with manual operations. The use of Poka-yoke and Jidoka mechanisms to provide error-proofing and automation has improved process reliability, provided a more consistent product and improved overall product quality.

From an operational standpoint, the optimized Robotic Cell manufacturing system produced increased operational flow efficiency, reduced operational variability and stable production output. As a result, the transition from an unintegrated manual process to an integrated robotic cell has improved material flow, workspace organization, and overall workplace safety. Therefore, the overall manufacturing system is now more resilient to potential disruptions in production and is significantly more scalable. In conclusion, this research supports the concept that a “lean-first, automation-next” methodology is necessary to achieve long-term, sustainable productivity improvements in all areas of the manufacturing process, i.e., productivity, quality and cost. By identifying and addressing workspace inefficiencies present in the current state map and systematically eliminating waste prior to introducing additional automation, this framework maximizes the potential effectiveness of technology-based interventions and therefore increases the potential return on investment.

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