Application of Lean Manufacturing Tools for Cycle Time Reduction and Productivity Improvement in Cleanroom Actuator Assembly: A Case Study Using ECRS and Kaizen Approaches

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ABSTRACT

This study investigates the application of lean manufacturing principles to optimise the actuator assembly process within a cleanroom semiconductor facility. A detailed time-study analysis was conducted on a four-station assembly line, revealing inefficiencies and identifying Workstation 2 as the main bottleneck. Using lean tools such as waste identification and the ECRS (Eliminate, Combine, Rearrange, Simplify) method, several short-term improvements were implemented. These modifications significantly reduced cycle times, rebalanced workload distribution, and improved ergonomics. Results demonstrate that even low-cost, incremental changes through Kaizen can yield measurable gains in productivity and quality. The study provides a practical framework for continuous improvement in cleanroom assembly lines and adds to the body of knowledge on lean implementation in high-precision manufacturing environments.

Keywords: Lean Manufacturing, Actuator Assembly, Productivity, Cycle Time, ECRS, Kaizen, Cleanroom Optimisation

INTRODUCTION

In today's global manufacturing environment, the need to enhance productivity while maintaining high quality is critical to remain competitive. This pressure is especially pronounced in sectors like the semiconductor industry, where product complexity, miniaturisation, and strict regulatory requirements present unique operational challenges. The actuator is a key component in semiconductor manufacturing equipment, responsible for regulating vacuum valves that manage atmospheric conditions in wafer processing chambers. These actuators require precise assembly processes carried out under cleanroom conditions to ensure contamination-free operation.

In the context of Industry 4.0, firms are increasingly turning to lean manufacturing strategies to improve efficiency, reduce waste, and streamline operations. Lean methods are widely applied across multiple manufacturing domains, including automotive, electronics, and aerospace. However, lean's application in cleanroom-based semiconductor assembly remains relatively underreported, especially in Southeast Asian contexts. This study focuses on a case within a multinational semiconductor firm operating in Malaysia, where productivity constraints in actuator assembly were affecting throughput and delivery schedules.

Preliminary observations and assembler feedback indicated imbalances across workstations, particularly at Workstation 2, which reportedly had longer cycle times and greater ergonomic strain. In response, the study was initiated to systematically evaluate the current assembly process, quantify inefficiencies, and implement short-term solutions through Kaizen activities. The study's broader aim is to demonstrate how lean tools, even when applied incrementally, can drive measurable improvements in performance with minimal resource investment.

The study employs a structured methodology involving time-study analysis, lean waste classification, and the application of ECRS principles to address identified inefficiencies. The resulting improvements are expected to not only reduce cycle time but also enhance assembler comfort, streamline material flow, and balance workload across workstations. The findings from this research contribute to the operational excellence literature by presenting a real-world case of lean manufacturing implementation in a controlled cleanroom setting within the Malaysian semiconductor industry.

Research Objectives

1. To identify process inefficiencies and bottlenecks in the cleanroom actuator assembly line using time-study analysis and lean waste classification.
2. To apply ECRS (Eliminate, Combine, Rearrange, Simplify) and Kaizen techniques to redesign and improve the existing workstation layout and task allocation for better productivity and ergonomics.
3. To evaluate the impact of lean-based improvements on cycle time reduction, workload balance, and assembler performance within a high-precision cleanroom manufacturing environment.

LITERATURE REVIEW

The integration of lean manufacturing tools in assembly operations has demonstrated consistent success in improving productivity, reducing cycle time, and enhancing operational flow across different industries. In cleanroom actuator assembly lines—where environmental controls, process precision, and space limitations are critical—such tools become even more essential. Afifi et al. (2020) showed that combining lean tools with simulation helped eliminate inefficiencies and improved overall productivity in door assembly lines, providing a practical reference for cleanroom environments. Al-Rifai (2024) expanded on this by redesigning electronic device assembly cells using Kaizen and lean tools, demonstrating the power of incremental improvements such as layout modification and waste reduction in high-mix low-volume production systems. This mirrors the challenges found in actuator assembly, where slight process changes can yield significant outcomes.

Bastos et al. (2021) explored the reconfiguration of assembly lines using lean thinking, reinforcing the importance of line flexibility and workstation arrangement to optimise flow and reduce lead times. Similarly, Borgave and Sapkal (2020) applied ECRS, 5S, and work standardisation to improve compressor assembly line efficiency, achieving faster cycle times and better ergonomics—benefits highly applicable to cleanroom actuator setups. Dhamija (2021) highlighted that training in lean principles improved operator engagement and adaptability, which is vital in cleanroom assembly where manual precision plays a key role. Fortuny-Santos et al. (2020) contributed insights on balancing workload and workforce capacity using lean management strategies in multi-model assembly lines, showing measurable improvements in operator performance and reduced bottlenecks.

Line balancing was also studied by Hillali et al. (2024), who employed lean tools to restructure assembly processes and reduce idle time, while Jeyaraman et al. (2021) demonstrated that optimising internal logistics using lean approaches like kanban and point-of-use storage reduced handling time and improved process reliability. These are especially relevant in cleanroom scenarios, where efficient material handling contributes directly to contamination control and production stability. González and Rios (2023) reinforced the role of Kaizen in continuous improvement by applying lean tools to automotive part assembly, reporting improved quality and reduced takt time through worker-driven adjustments.

In applications more specific to actuator systems, Kubacki et al. (2024) examined lean implementation in subsea electric actuator assembly, which parallels many aspects of cleanroom actuator manufacturing in terms of precision and contamination control. Their results highlighted gains in productivity, defect reduction, and cycle time. Lin and Helmi (2020) provided supporting evidence by showing how lean initiatives in an electronics assembly firm reduced process variation and improved workstation efficiency using visual controls and standardised workflows. Liu and Lu (2023) optimised the production of automotive wire harnesses using lean principles like value stream mapping and layout adjustments, reporting tangible cycle time improvements and better operator coordination.

Simulation-based approaches were discussed by Harish et al. (2023), who applied lean and simulation tools to a multi-model assembly line, enabling decision-makers to predict the impact of process changes before implementation. Mortada and Soulhi (2023) combined line balancing techniques with lean tools to improve assembly flow, reduce downtime, and increase space utilisation. Pattanaik and Kant (2022) introduced lean

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assembly problem-solving with reconfigurable machine cells, proving their effectiveness in improving system responsiveness and efficiency—key considerations in cleanroom settings where flexibility and contamination control must coexist.

Markov and Vitliemov (2022) contributed to this perspective by exploring semi-automated lean assembly lines using Lean 4.0 frameworks, offering insights into combining automation and lean for optimal performance. Rodas et al. (2021) showcased the application of lean optimisation in bicycle assembly through ECRS and standard work methods, which resulted in more balanced operations and increased throughput. Minh et al. (2024) reinforced the combination of Lean Six Sigma tools to drive continuous improvement in productivity and quality—an approach that is also viable in actuator assembly lines for long-term performance tracking.

Wending et al. (2020) examined hydraulic actuator assembly automation and found that integrating lean thinking into equipment design and workstation flow improved consistency and production output. Qin et al. (2022) applied Petri net optimisation to enhance intelligent assembly timing, useful for identifying and synchronising critical path operations in cleanroom environments. Mistry (2020) and Singh and Gandhi (2020) also confirmed the effectiveness of standard lean methods—5S, VSM, root cause analysis, and Kaizen—for productivity gains across manufacturing lines.

Further validation comes from Sivaraman et al. (2020), who enhanced engine assembly performance using lean tools like takt time calculation and process alignment. Selvaraj et al. (2023) explored lean implementation in aircraft sheet metal production, achieving substantial efficiency by focusing on waste elimination and operator workflow improvement. Zaman and Hosseinabad (2021) detailed improvements in production flow and visual mapping, supporting the use of value stream mapping in identifying delays and non-value activities in actuator assembly.

Zhang et al. (2024) integrated lean production with low-carbon optimisation in remanufacturing, a relevant consideration in actuator assembly for sustainability goals. Zhou et al. (2024) presented a stepwise optimisation of actuator placement for space structures, applying structured lean principles to high-precision tasks in constrained environments.

Collectively, these studies confirm the value of lean manufacturing tools, particularly ECRS and Kaizen, in enhancing productivity, balancing workloads, reducing cycle times, and improving ergonomic factors. Applied within cleanroom actuator assembly, such tools offer a validated path toward continuous process improvement without major capital investment or disruption. The literature supports the conclusion that structured, incremental lean interventions can sustain long-term performance and quality gains in high-precision manufacturing environments.

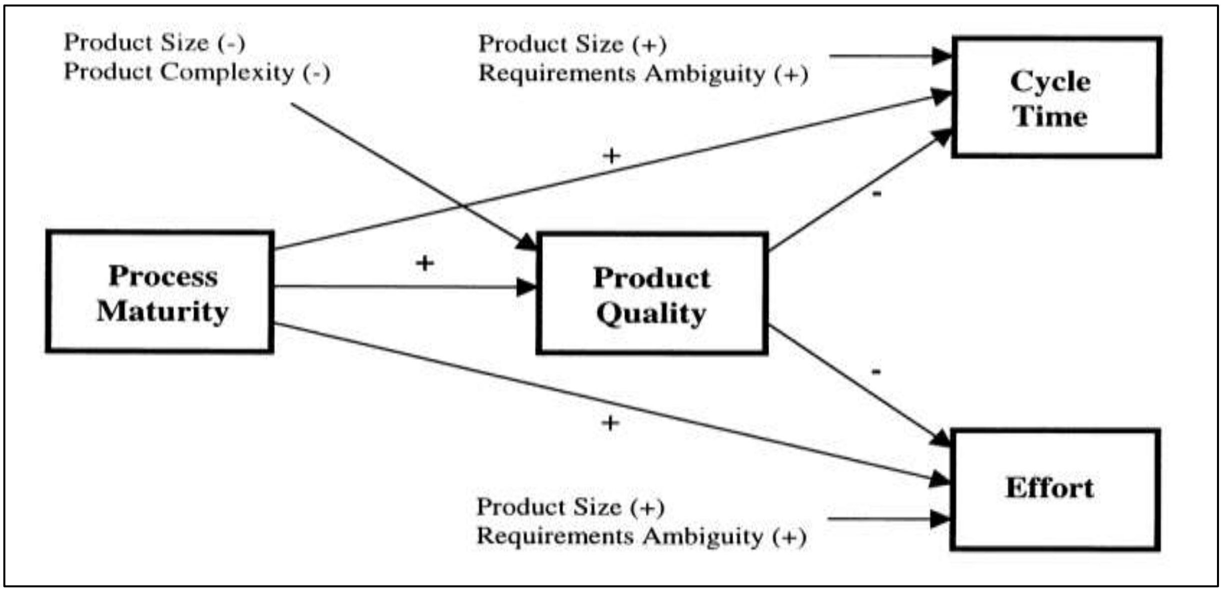

Figure 1: Conceptual Model of Process Maturity Study

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Figure 2: Framework Model of Study

METHODOLOGY

This study was conducted at a semiconductor manufacturing facility located in Penang, Malaysia, focusing on the actuator assembly process required for vacuum valve production. The assembly takes place in a controlled cleanroom environment to maintain ultra-clean standards suitable for semiconductor equipment. Actuators, which operate the valve's gate mechanism, are assembled across four sequential workstations. These workstations are designated based on the component sub-assemblies involved in the actuator's full build-up.

To strengthen the connection between the narrative and visual elements, each figure is now referenced directly in the discussion to guide the reader through the process changes. For example, Figure 3 illustrates the baseline workstation layout, showing the positioning of tools, material flow, and operator zones before improvements. Figure 4 complements this by mapping the actual positions of assemblers along the line, enabling a clearer understanding of workflow patterns and potential inefficiencies. Post-improvement flow diagrams, placed alongside the revised workstation layouts, highlight how ECRS-based changes—such as combining tasks or relocating tools—altered the sequence of operations. These visual integrations make it easier for readers to follow the progression from problem identification to solution implementation, while reinforcing the link between observed issues, applied methods, and measured outcomes.

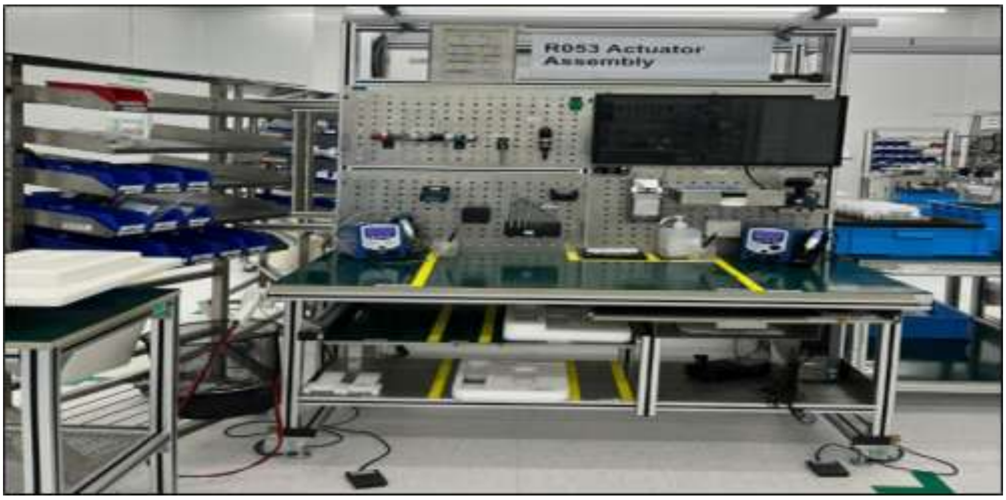

Figure 3: Assembly Workstation

To ensure the reliability and validity of the data collected, the research adopted a time-study approach that combined direct observation with video documentation. A sample of 20 actuator units was selected for detailed study. Three operators with varying years of experience were involved, enabling the analysis to reflect differences in manual dexterity, familiarity, and speed. All observations were conducted during the day shift to ensure consistency in production rhythm, support team availability, and environmental control.

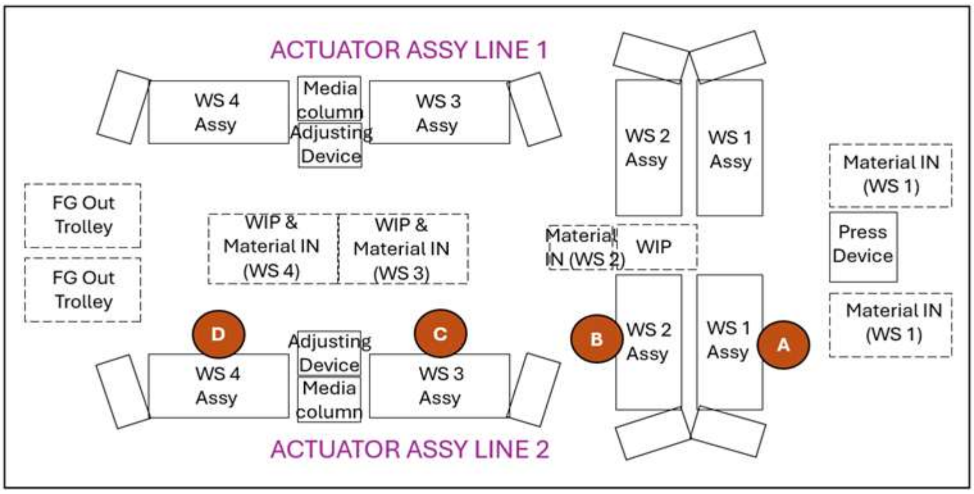

Figure 4: Position of assemblers in assembly line

The study began with a mapping of the existing assembly process. Each workstation was documented for its tools, material flow, component handling steps, and operator ergonomics. Video footage was recorded throughout the process using mounted cameras to minimise disruption. The footage was later reviewed frame-by-frame to confirm the accuracy of observed times. Each action - from tool pick-up to component placement - was broken down into measurable segments. Time was recorded using a standard time-study template, which included normal time, rating factor, and allowance percentages to calculate standard time for each step.

Once cycle time data was captured, the analysis proceeded with the identification of lean wastes. The seven traditional categories of waste (overproduction, inventory, waiting, motion, transportation, overprocessing, and defects) served as the basis. Additional notes were made on unnecessary hand movements, operator fatigue, repeated travel between stations, and misaligned material setups. The lean waste identification phase relied on both recorded data and first-hand feedback collected from assemblers during debrief sessions.

To design improvement strategies, the study adopted the ECRS technique - Eliminate, Combine, Rearrange, simplify which is widely used for low-cost, high-impact Kaizen activities. These strategies focused on immediate, implementable changes requiring minimal investment or retraining. The improvement proposals were reviewed collaboratively with the Process Engineer, Production Supervisor, and Line Leaders before being trialled. Post-improvement data was collected using the same time-study protocol. Comparisons were made between baseline and improved states, focusing on cycle time reduction, reduction in motion, task reallocation, and operator fatigue.

RESULTS & OUTCOMES

The chapter presents an in-depth analysis of cycle time data collected from four assemblers in a cleanroom actuator assembly process, highlighting areas of inefficiency and improvement using lean manufacturing tools, especially the ECRS (Eliminate, Combine, Rearrange, Simplify) method. The assemblers involved had varying levels of experience, with Assembler B being the most experienced and Assembler D the least. This diversity helped provide a comprehensive view of the assembly process and its variability. The workstations were structured to represent a typical assembly line, and each assembler was assigned a specific station for consistency during data collection. Workstation 1 had the shortest cycle time, averaging around 12 minutes, and was dedicated mainly to minor subassembly tasks like pressing ball bearings using a press-fit tool. The tool's location near the station supported process efficiency and reduced unnecessary movement.

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ECRS Work Analysis Sheet										Eliminate	Combine	Rearrange	Simplify
#	Work Elements	Safety | Distance | Dimension | Quality | Ease	Why	What	Where	When	Who	How	Improvement Ideas	E	C	R	S
1	Step 110 - Assemble piston shaft	Walk to press device which is 30 steps away			X				Assemble the part at workstation 1			X	
2	Step 355 - Tightening horizontal piston	Repeat picking material on wing, connecting automatic torque tool & confirming step						X	Tighten left & right side of horizontal piston in same step		X		X
3	Step 365 - Tightening locking screw on horizontal piston	Repeat picking material on wing, connecting automatic torque tool & confirming step						X	Tighten left & right side of locking screws in same step		X		X

Figure 5: ECRS Work Analysis Sheet

Workstation 2 showed the longest average cycle time of 55 minutes and emerged as the production bottleneck. Assembler B handled this station and was required to assemble major components like piston shafts and perform greasing operations. Several tasks at this station involved motion waste—such as repeated travel to Workstation 1 to use the press-fit tool and multiple repetitive steps like tightening left and right piston screws in separate actions.

These inefficiencies contributed significantly to high cycle times. At Workstation 3, pressure regulators were installed, and pressure-drop tests were performed to ensure that the actuators met functional requirements. An additional step at this station involved cleaning the test fixtures, which was necessary only for the first unit in each batch. Although this activity was not repeated for subsequent units, it slightly extended the initial cycle time and created minor delays for downstream operations. Assembler C, responsible for this station, recorded an average cycle time of approximately 2,210 seconds, reflecting both the precision required and the time consumed by the testing and cleaning processes.

Workstation 4 was the final stage of the assembly line and involved multiple steps: installing the actuator covers, fitting the tubes, placing completed units into designated packaging, and transferring them to the warehouse for storage or dispatch. These activities, though straightforward, required careful handling to prevent damage and ensure correct assembly. Assembler D managed this station with cycle times ranging between 1,048 and 1,286 seconds, depending on unit complexity and part availability. Across all units processed during the observation period, the throughput times remained steady and within a narrow band, averaging between 1 hour 58 minutes and 2 hours 7 minutes. This consistency indicates that while certain stations operated efficiently, bottlenecks and idle times, particularly in earlier stages, added up and influenced the total cycle duration. Improvements in task distribution, part staging, and minor automation could potentially reduce these cycle times and improve overall productivity.

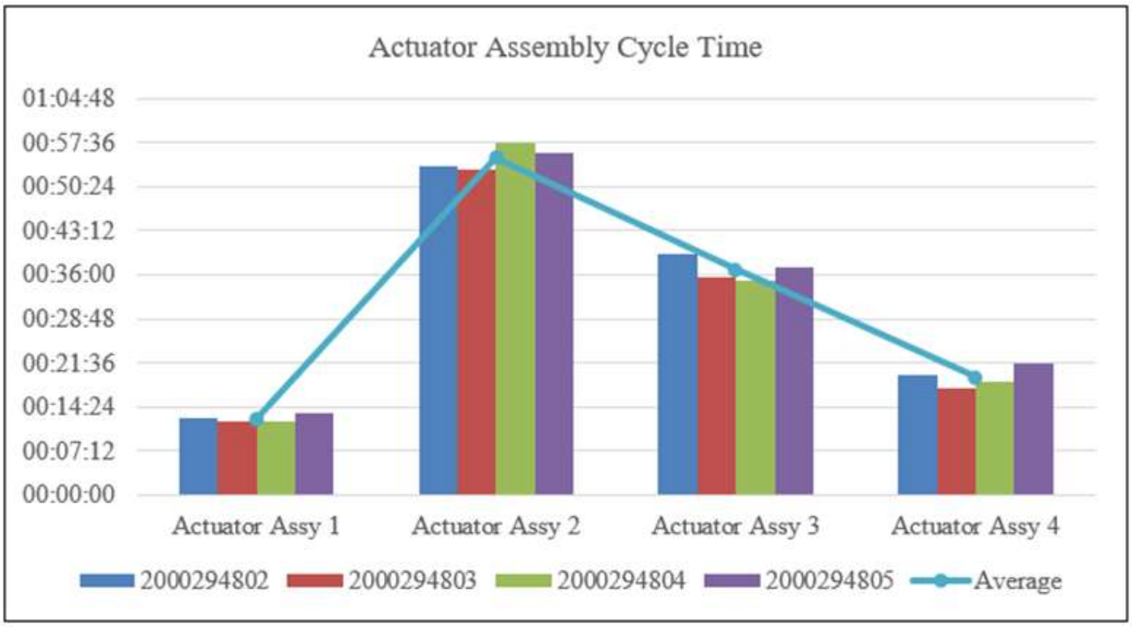

Figure 6: Actuator Assembly Cycle Time Combination Graph

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The cycle time graph revealed Workstation 2 as the clear outlier with significantly longer processing time. This imbalance caused waiting at subsequent stations, particularly Workstation 3, leading to inefficiencies in the flow. A Gemba walk was conducted to assess these issues directly on the shop floor. Observations confirmed motion waste at several points in Workstation 2, particularly when assemblers moved to other stations for tool access. The team documented these wastes and brainstormed improvements. The ECRS approach was then applied to restructure the tasks. The pressing and gauging steps that required movement to Workstation 1 were reassigned fully to Assembler A, eliminating the need for cross-station travel. This change alone reduced Workstation 2's cycle time by about 4 minutes and 48 seconds.

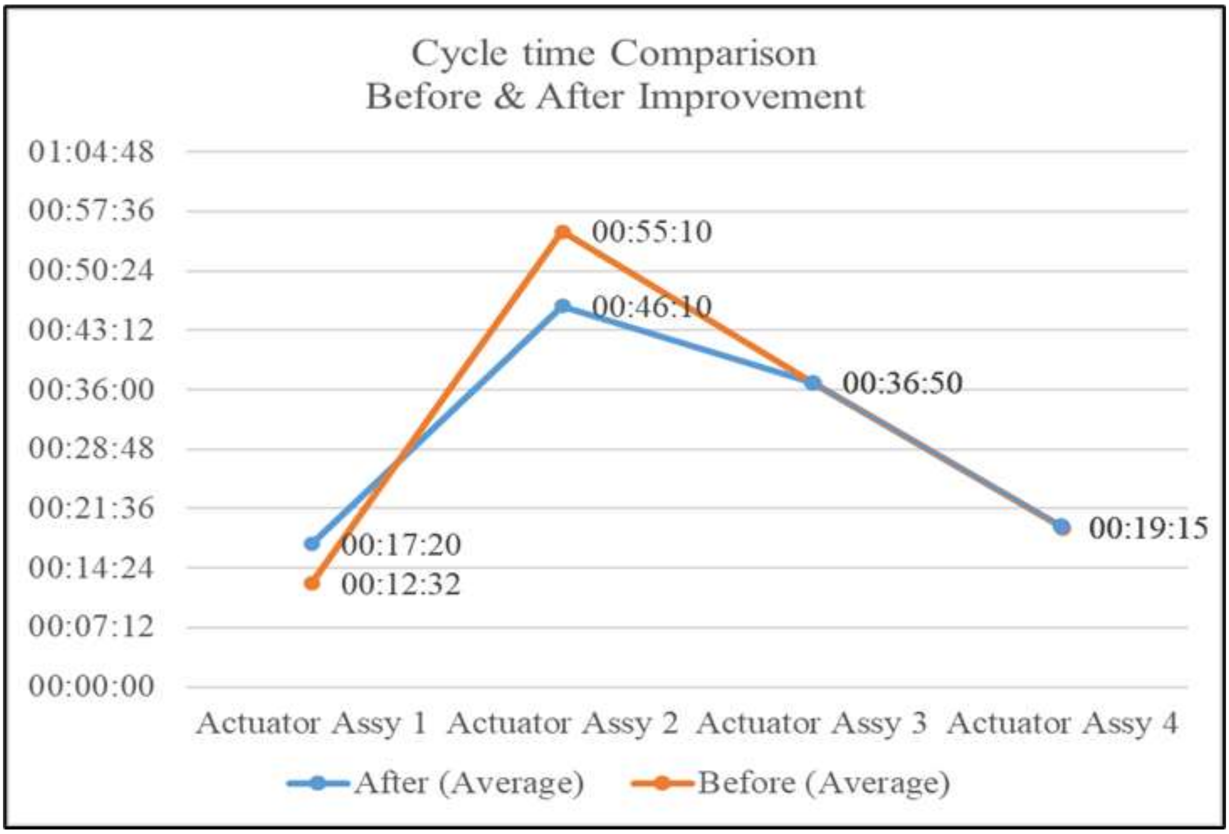

Figure 7: Cycle time comparison before and after improvement

In another improvement, separate steps for left and right piston screw tightening were combined into one integrated action, using the same set of materials and torque tools within a unified setup. This modification eliminated redundant handling and repositioning, which had previously required extra time and effort. By consolidating the process, operators were able to complete the tightening sequence more smoothly, resulting in a time saving of 4 minutes and 12 seconds per cycle. The evaluation of this improvement also accounted for typical process inefficiencies such as system lag, torque tool connectivity delays, and minor alignment checks that typically go unrecorded but affect actual work duration.

After implementing the ECRS (Eliminate, Combine, Rearrange, Simplify) methodology, the optimised process brought the cycle time at Workstation 2 down to 46 minutes and 10 seconds. This reduction had a direct effect on downstream flow, particularly at Workstation 3, by minimising the accumulation of work-in-progress and easing operator workload. With better coordination between stations, the likelihood of queuing and idle time decreased, enabling a more consistent rhythm across the line. These improvements helped reduce the overall assembly time from 2 hours and 3 minutes to about 1 hour and 59 minutes, marking a significant operational gain without the need for new tools, machines, or additional personnel. The results clearly demonstrate that targeted lean actions, especially those addressing motion, overprocessing, and waiting, are effective in improving performance without requiring high capital investment. The success of these changes highlights the importance of task sequencing, operator familiarity, and proactive problem-solving when applying lean tools to real manufacturing challenges. This case reinforces the value of practical lean implementation in cleanroom environments, where precision, timing, and consistency play a critical role in maintaining quality and throughput.

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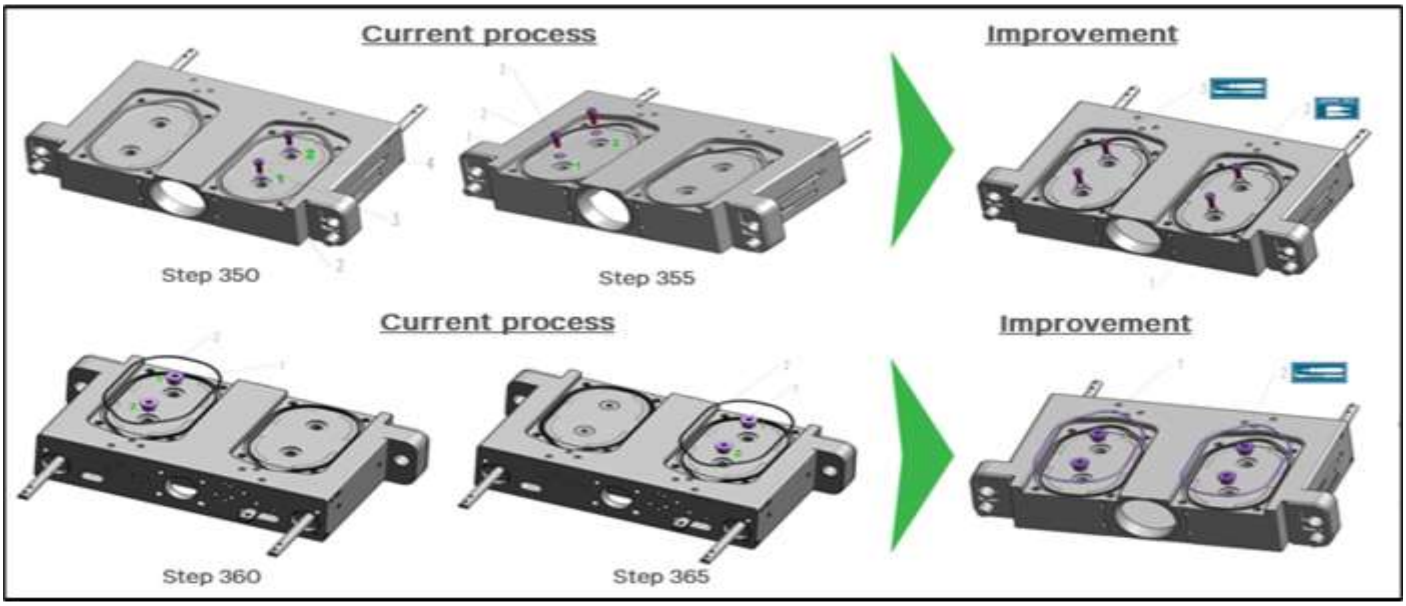

Figure 8: Illustration of improvement steps

A detailed cost–benefit analysis and ROI evaluation of the Kaizen improvements applied in this cleanroom actuator assembly confirmed their strong practical value and strategic relevance. Calculations showed that the combined reduction of nearly nine minutes at Workstation 2 translated into substantial labour time savings when multiplied across the plant's average monthly production volume, delivering significant cumulative productivity gains. These financial benefits far exceeded the minimal implementation costs, which were limited to time spent on Gemba walks, process analysis, operator retraining, and minor workstation adjustments, with no new equipment purchases required. Additional measurable gains included shorter work-in-progress inventory holding times, smoother production flow, improved throughput consistency, and enhanced on-time delivery performance. Quality improvements were also observed, with reduced operator fatigue and fewer handling steps lowering the likelihood of assembly errors. Expressed in monetary terms, the results demonstrated that the lean interventions not only improved operational efficiency but also delivered a positive and rapid return on investment. This analysis now serves as a benchmark for prioritising future Kaizen projects, enabling the company to focus on initiatives with proven high payback and sustained impact on both productivity and profitability.

CONCLUSION

This study has demonstrated that meaningful productivity improvements can be achieved in cleanroom actuator assembly by applying lean manufacturing principles. By systematically observing the current process through time-study analysis, the research identified Workstation 2 as the primary constraint within the assembly line. Lean waste identification confirmed inefficiencies in motion, waiting, and overprocessing. Using the ECRS approach within a Kaizen framework, targeted process changes were implemented that resulted in a significant reduction in cycle time and a more balanced workload across stations.

One of the key outcomes was the reallocation of the press-fit process, which not only saved time but also redistributed the physical workload more evenly. Consolidation of redundant tasks further shortened the time to complete critical sub-assemblies. These improvements, while relatively simple in execution, exemplify the power of frontline involvement in lean projects. Operator feedback played a pivotal role in designing practical changes, and their engagement helped build a stronger culture of continuous improvement.

From a theoretical standpoint, this case supports previous literature advocating lean manufacturing's application beyond traditional automotive settings. The study contributes to the growing body of evidence that lean tools, when appropriately adapted, can thrive in precision-based, high-regulation industries like semiconductor manufacturing. It also reinforces the relevance of lean tools in Southeast Asia's manufacturing context, where resource constraints demand high-impact, low-cost solutions.

Several limitations must be acknowledged. The study focused on short-term improvements and did not explore the long-term sustainability of changes. The cleanroom's rigid layout and shared tools may restrict further cycle time reduction unless significant reengineering or investment occurs. Additionally, the sample size, while sufficient for initial analysis, could be expanded in future work to validate findings across different shifts and operator skill levels.

Future research could examine the integration of digital technologies with lean tools, such as using digital twins for real-time simulation of workflow changes or implementing sensor-based monitoring systems for automatic waste detection. Another promising area lies in examining the role of cross-training in cycle time variability and workload balance, especially in low-volume, high-mix production environments.

A follow-up study conducted over an extended period, such as 6 to 12 months, would provide valuable insights into the long-term sustainability of the lean interventions implemented in this cleanroom actuator assembly process. By continuously tracking key performance indicators—including cycle time, defect rates, equipment reliability, and operator workload distribution—researchers could assess whether the initial productivity gains are maintained once the novelty of the changes subsides. This longitudinal assessment would also allow for the detection of any unintended consequences that may arise, such as gradual increases in contamination risks due to altered material flows, shifts in equipment wear patterns, or the development of operator fatigue linked to the revised task structure. Incorporating periodic operator feedback sessions and analysing quality control data would add qualitative depth to the findings, helping to identify subtle process inefficiencies or ergonomic concerns that may not be apparent in short-term studies. Such an approach would not only validate the effectiveness of the lean interventions over time but also support continuous refinement of the workflow, ensuring that both productivity improvements and cleanroom compliance standards are sustained in the long run

Overall, this study has shown that practical application of lean tools—particularly ECRS and Kaizen—in a cleanroom environment leads to measurable productivity gains. Organisations aiming to improve output without large capital investment can adopt a similar approach to refine workflow, empower their operators, and strengthen operational excellence across the shop floor.

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