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Optimized Factory Layout Design for Enhanced Productivity and Quality: A Case Study on Aerokit Painting

Mohd Fauzi Ismail[1], Nor Fazli Adull Manan[1]*, Nor Hissham Abdul Hamid[1], Mahamad Hisyam Mahamad Basri[1]

[1] *Faculty of Mechanical Engineering, Universiti Teknologi MARA, Shah Alam 40450 Selangor, MALAYSIA*

*Corresponding Author: norfazli@uitm.edu.my
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Abstract

In automotive production, improving effectiveness and quality while containing costs is essential. This research examines the painting process in an automotive plant in Malaysia that previously suffered from low throughput rates, long lead times driven by excessive waiting and material movement, high defect levels, and an overworked quality control section. A detailed analysis of processing time, waiting time, work-in-progress (WIP), operator and material movement, and paint-thickness variation was carried out using appropriate measurement tools and validated through Statistical Process Control (SPC). To remedy the identified issues, the linear factory layout was redesigned into a U-shaped configuration supported by Lean Manufacturing principles, in-process quality checkpoints, operator self-audits, and real-time Power BI monitoring. These interventions enhanced material flow efficiency, reduced non-value-added movement, and stabilized process performance. The improvements resulted in a 33% increase in daily production volume, an 80% reduction in Defects per Vehicle (DPV), and a revised takt time based on updated lead-time calculations. The outcomes demonstrate the effectiveness of integrating Lean methods with digital monitoring and provide a validated model for enhancing productivity and quality in automotive painting operations.

1. Introduction

The automobile manufacturing industry is continuously challenged to improve manufacturing efficiency, provide quality products, and lower the cost of operation. To remain competitive, manufacturers must adopt strategies that respond to customer demands for improved quality, faster delivery, and affordable prices. Factory layout design plays a central role in enabling these objectives, as it directly influences processing time, waiting time, work-in-progress (WIP), and material flow. Poorly designed layouts often result in excessive operator and material movement, extended lead time, operational bottlenecks, and increased defect occurrences, ultimately elevating production cost and degrading quality levels [1].

Factory layout is not merely the physical placement of workstations but a determinant of how products, operators, and materials interact throughout production. An optimized layout supports efficient movement of materials, reduces waste, lowers transit and waiting times, and enables effective utilization of space.

Consequently, improvements in layout design often translate into higher throughput, better product quality, and reduced operational cost. Despite this, many automotive plants still operate with less-than-optimal layouts that compromise productivity and flexibility, particularly when workstation design unintentionally restricts flow, limits operator visibility, or creates unnecessary WIP accumulation [2].

In the observed Malaysian automotive manufacturing plant, the existing linear layout of the painting process resulted in long travel distances, uneven distribution of workload, and delays arising from queue build-ups. These issues intensified the load on the Final Quality Control (QC) section, where defects were detected late, causing rework accumulation and production delays. To address these challenges, this research focuses on redesigning the aerokit painting process layout to improve flow efficiency, reduce defects, and support increased daily production output. The proposed intervention integrates a U-shaped layout, Lean Manufacturing principles, in-process quality controls, Statistical Process Control (SPC) for real-time monitoring of critical parameters, and Power BI dashboards to enhance data-driven decision-making.

1.1 Importance of Factory Layout in Automotive Production

In automotive painting operations—where precision, consistency, and turnaround time are critical—an inefficient layout can severely affect operational capability. A U-shaped layout enhances material flow continuity, shortens operator travel distance, and improves workstation visibility, which collectively foster greater production versatility and more stable cycle times. Lean Manufacturing principles such as 5S, Kaizen, and Jidoka further reinforce these improvements by reducing non-value-added activities, standardizing work, enabling early identification of abnormalities, and promoting operator engagement in quality assurance.

SPC tools were incorporated to monitor essential process characteristics—particularly paint-thickness variation and Defects per Vehicle (DPV)—using validated measurement methods appropriate for thin-film coatings. These tools supported the early identification of deviations, minimizing the likelihood of out-of-spec conditions and reducing the cost associated with rework [3]. Together, these approaches align the manufacturing system toward stable, predictable, and efficient performance.

1.2 Problems in the Aerokit Painting Process

The aerokit painting process consists of several sequential steps, including surface cleaning, primer application, basecoat, and clearcoat. Each stage presents potential for defects such as uneven coverage, runs, dust contamination, and colour inconsistency, all of which increase waste, rework, and production cost [4]. The original layout physically separated basecoat and clearcoat operations, resulting in extended transfer time and increased waiting between stages. Furthermore, quality inspections were concentrated solely at the Final QC station, causing defects to be detected much later in the process. This delayed feedback loop contributed to higher rework rates and higher WIP accumulation.

To address this issue, intermediate quality checks and operator self-inspection were incorporated at earlier stages. These measures enabled prompt identification and correction of abnormalities, reduced the burden on Final QC, and supported smoother workflow between stations.

1.3 Research Objectives and Proposed Solutions

To address the challenges observed, this research applied the following improvement strategies:

- U-shaped layout redesign: Reduced travel distance, improved flow continuity, and supported more balanced operator interaction across workstations.
- Lean Manufacturing principles: Application of 5S, Kaizen, and Jidoka to reduce waste, stabilize processes, and reinforce operator accountability for quality.
- Implementation of SPC: Real-time monitoring of critical variables such as paint thickness and DPV to enable early corrective actions.
- Power BI dashboards: Real-time visualization of production performance, defect trends, and process variability, supporting immediate and informed decision-making.

The study aimed to:

- Increase production to 200 vehicles per day.
- Reduce DPV from 0.20 to 0.04.
- Reduce takt time from 4.8 minutes with updated calculations based on actual available production time, processing time, and waiting time.
- Achieve sustained improvements in production efficiency, quality, and operator productivity.

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1.4 Theoretical Background: Lean Manufacturing and Statistical Process Control

Lean Manufacturing focuses on maximizing value by eliminating muda (non-value-added activities) [5]. Tools such as Value Stream Mapping (VSM) and Spaghetti Diagrams were used to visualize processing time, waiting time, WIP distribution, and operator/material movement inefficiencies in the painting line. The U-shaped layout reflects a direct implementation of Lean principles to minimize movement and idle time while improving workstation communication and flow.

Statistical Process Control (SPC) provides a structured approach for monitoring process variation. In this study, SPC control charts were used to track paint-thickness stability and defect trends using appropriate thin-film measurement instrumentation. These tools enabled early identification of deviations, reducing rework and supporting a more stable and predictable painting process.

2. Methodology

This research follows a four-phase structured improvement approach combining Lean Manufacturing concepts, Statistical Process Control (SPC), and real-time Power BI monitoring. The methodology was designed to systematically identify inefficiencies, quantify baseline performance using validated measurement techniques, implement targeted improvements, and continuously monitor results for sustained performance.

The four phases as illustrated in Fig. 1 are:

- Process Observation and Problem Identification
- Tool Selection and Baseline Measurement
- Layout Design and Pilot Implementation
- Monitoring and Continuous Improvement

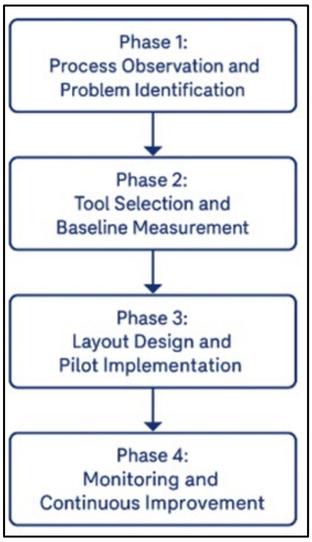

Fig. 1 *Four-phase improvement methodology*

2.1 Phase 1: Process Observation and Problem Identification

Phase one focused on identifying the existing production process conditions, bottlenecks, and sources of inefficiency that contributed to low throughput, long lead time, and high defect levels [6]. A cross-functional team conducted detailed time studies and workstation observations at key stages—surface preparation, primer, basecoat, clearcoat, and Final QC.

Both processing time and waiting time were recorded to determine true lead time, and work-in-progress (WIP) was counted at each station to evaluate flow stability. Operator and material paths were also documented to understand movement patterns. Leading indicators such as production output, Defects Per Vehicle (DPV), rework counts, and cycle-time variability were collected.

Pareto analysis was applied based on actual defect data to identify the major contributors to DPV in accordance with the 80/20 principle [7]. The results highlighted that paint application defects and inconsistent coating thickness were the dominant issues, and that delays between basecoat and clearcoat stages significantly increased WIP and lead time.

2.2 Phase 2: Tool Selection and Baseline Measurement

After identifying the critical inefficiencies, appropriate Lean tools and quality measurement methods were selected to measure and benchmark the existing process [8].

- Value Stream Mapping (VSM): A complete VSM was developed to identify value-adding and non-value-adding activities, processing and waiting times, WIP accumulation, inventory locations, communication flow, and overall lead time. This clarified the differences between processing time and total lead time, addressing previously unmeasured sources of delay.
- Spaghetti Diagram: Operator and material movement were mapped jointly using physical tracing and pedometer-based distance validation to determine unnecessary travel, workstation reachability issues, and sources of inefficient handling [9].
- SPC Control Charts: Paint thickness was measured using an automotive-standard coating gauge and recorded in micrometres (μm) across multiple sampling points per component. These values were analysed using $\bar{X}$–R control charts to assess process variation and stability. DPV trends were also monitored to detect shifts in defect occurrence [10].
- Paint Thickness Measurement Method: Paint thickness was measured using a portable automotive dry-film thickness gauge (Ferrous/Non-Ferrous dual probe) with a resolution of 1 μm. For accuracy, 100 samples were taken across different body panel sections following ISO 2808:2019 guidelines. The typical acceptable range for automotive topcoat thickness is between 40–60 μm.
- Baseline Performance: Baseline measurements of output, DPV, takt time, average travel distance, and lead time were established for comparison with post-improvement results [11]. These values served as the foundation for evaluating the impact of layout redesign and quality interventions.

2.3 Phase 3: Pilot Implementation and Layout Design

The factory layout was redesigned to optimize material flow, reduce unnecessary movement, and introduce intermediate quality checks for earlier detection of abnormalities [12]. A U-shaped configuration was adopted to shorten travel distance and improve communication between operators while enabling more balanced workflow.

Lean practices—including 5S (workplace organization), Kaizen (continuous improvement), and Jidoka (automation with human touch)—were applied to eliminate waste, standardize workstation setup, reduce search time, and stabilize operations. Intermediate QC stations were placed after basecoat and clearcoat stages, addressing the issue of late defect detection raised in earlier observations.

A pilot run was conducted to validate the redesigned layout, during which processing time, waiting time, travel distance, and paint-thickness measurements were recorded to confirm improvements before full-scale deployment.

2.4 Phase 4: Monitoring and Ongoing Improvement

The final phase emphasized real-time tracking and continuous refinement of the process. Power BI dashboards were developed to visualize production output, defect trends, paint-thickness stability, WIP levels, and takt time in real time [13].

- Power BI Dashboards: These dashboards enabled rapid detection of deviations, bottlenecks, and abnormal defect spikes by linking SPC data, operator observations, and daily production metrics. When control limits were exceeded, corrective actions were initiated immediately, preventing defect propagation.
- Continuous Improvement: Regular Kaizen meetings facilitated structured feedback between operators, engineers, and quality personnel. Real-time monitoring supported verification of layout effectiveness, stable operation of new QC stations, and proper application of 5S practices. This ensured that improvements in efficiency, flow, and quality were sustained over time.

This four-phase approach integrates Lean principles, SPC methodology, validated measurement tools, and digital monitoring to enhance production effectiveness and product quality in the aerokit painting process. The integration of layout redesign, movement reduction, early quality detection, and real-time visualization directly addresses the operational issues identified in the baseline study.

3. Results and Discussion

This section provides a detailed analysis of the results from each stage of the study and explains how the applied interventions enhanced the production process. The results are organized according to the four stages in the improvement model: Process Observation and Problem Identification, Tool Selection and Baseline Measurement, Layout Design and Pilot Implementation, and Monitoring and Continuous Improvement. Overall, each stage contributed to measurable gains in production effectiveness, quality, and operational performance. The discussion

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also evaluates the impact of applying Lean Manufacturing principles, Statistical Process Control (SPC), and real-time monitoring via Power BI.

3.1 Phase 1 Results: Process Observation and Problem Identification

The initial stage involved observational analysis to identify inefficiencies and problems in the production process. Comprehensive site walk-throughs and time studies were carried out by a cross-functional team including engineers, operators, and quality control specialists at different production stages. Particular emphasis was placed on the basecoat and clearcoat applications and the Final Quality Control (QC) stage, as these are pivotal for the quality and effectiveness of the aerokit painting process and exert a strong influence on the overall production lead time.

Quantitative data were collected for processing time (PT), waiting time (WT), and work-in-progress (WIP) at each key workstation, while qualitative data were collected on process dynamics, operator practices, and material handling. The main objective was to determine where waste, delays, and defects occurred, as these factors diluted quality and lowered production rates. The analysis revealed several critical inefficiencies that were further examined using dedicated analytical tools in subsequent phases.

Key Findings:

Bottlenecks in Basecoat and Clearcoat Applications

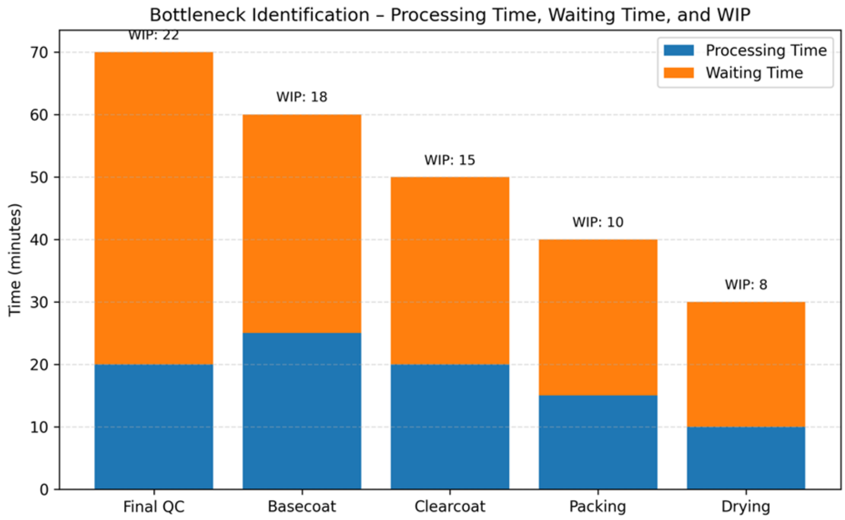

Fig. 2 *Bottleneck identification for key process steps (processing and waiting time per station)*

One of the most important findings was the presence of bottlenecks in the basecoat and clearcoat application steps, as illustrated in Fig. 2. These steps comprise both significant processing time and substantial waiting time, making them major contributors to extended lead time. At the basecoat stage, materials were frequently delayed due to inadequate coordination of drying intervals and inconsistent application rates. Products often waited for extended periods before the next operation, disrupting production throughput.

Similarly, the clearcoat stage exhibited inefficiencies related to coating consistency and curing behaviour, which led to minor surface imperfections that later required correction. These factors increased effective processing time at subsequent stages and contributed to rework. Collectively, the bottlenecks substantially reduced production speed, increased variability in cycle times, and contributed to elevated defect levels and material wastage.

Excessive Travel Time Between Workstations

Another significant inefficiency was the excessive travel time incurred by operators and materials between workstations, particularly between basecoat, clearcoat, and drying stations. Operators frequently traversed large distances while manually transporting components, adding non-value-added time to the cycle and increasing physical fatigue. These long movement paths contributed to WIP accumulation at intermediate points and produced misalignment between stages; delays in basecoat or clearcoat propagated downstream and impacted subsequent operations.

This pattern of unnecessary travel is a classic example of wasted motion, one of the primary forms of muda in Lean Manufacturing. The inefficient travelling reduced overall productivity and diminished the effective utilisation of operator time.

Defects Visible Only at Final QC

A further critical issue identified was late defect detection, with Final QC being the sole formal point of inspection. By the time parts reached Final QC, defects such as thickness variation, uneven coating, and colour mismatches were already embedded. Detection at this stage required rework such as sanding, repainting, and refinishing, which increased material usage, extended lead time, and overloaded the Final QC section.

Because defects were found late, root causes were difficult to trace and correct promptly, leading to recurrence. This late detection mechanism significantly affected cost per piece and overall throughput.

Result Summary of Phase 1

The observational study confirmed that the existing linear configuration generated substantial inefficiencies in the form of excessive travel distance, suboptimal material movement, and delayed defect detection. These issues translated into longer lead times, higher defect and rework rates, and difficulties in consistently achieving production targets.

The findings highlighted the need to redesign the layout to streamline material flow, minimise travel distance, and redistribute quality checks. Specifically, the study indicated the necessity for a U-shaped layout and the introduction of intermediate quality checks after basecoat and clearcoat to enable earlier detection of defects, reduce dependency on Final QC, and prevent defect accumulation along the production line [14].

3.2 Phase 2 Results: Selection of Tools and Baseline Measurement

Phase 2 focused on quantifying baseline performance and deepening the understanding of production inefficiencies through analytical tools. Value Stream Mapping (VSM), Spaghetti Diagrams, and SPC charts were used to visualise the current state of the process and establish reference measurements for subsequent comparison.

Key Findings:

Value Stream Mapping (VSM):

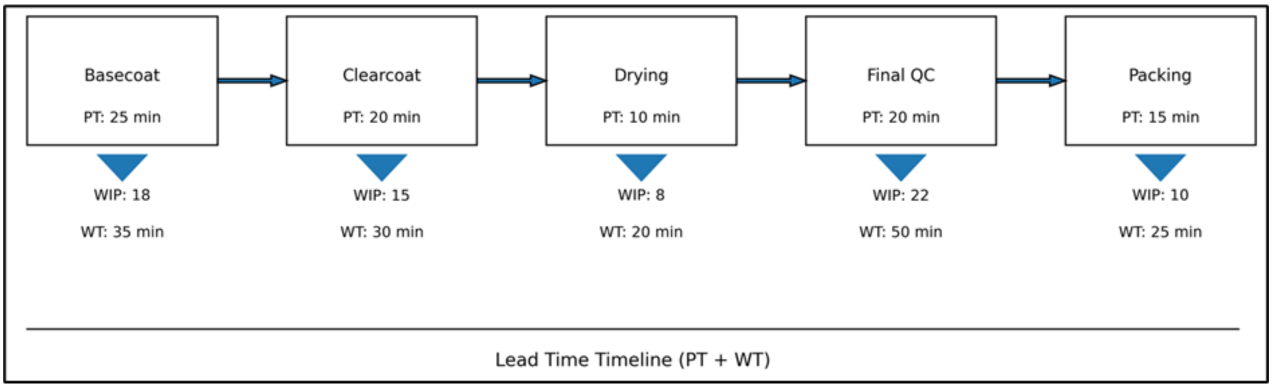

Fig. 3 *Current-state Value Stream Map for the painting process*

The current-state VSM as illustrated in Fig. 3 provided a detailed representation of all process steps from basecoat spraying through to Final QC, including both processing time and waiting time. It clearly showed where lead time was extended by queues and unbalanced flow. The map highlighted significant waiting between certain stations, particularly around basecoat and clearcoat, where inefficient material movement and limited coordination caused idle periods and WIP accumulation.

Inventory triangles in the VSM indicated points of WIP build-up, underscoring imbalances in process capability and scheduling. These elements confirmed that the observed bottlenecks in Phase 1 were closely associated with structural issues in flow and layout, not solely operator performance.

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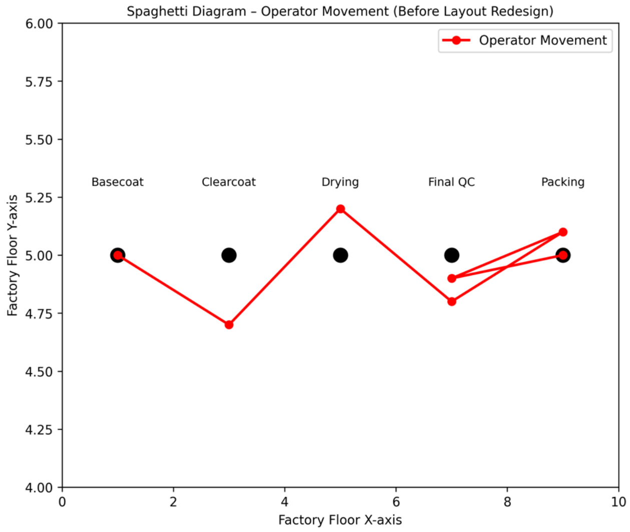

Fig. 4 *Spaghetti diagram showing operator movement before layout redesign*

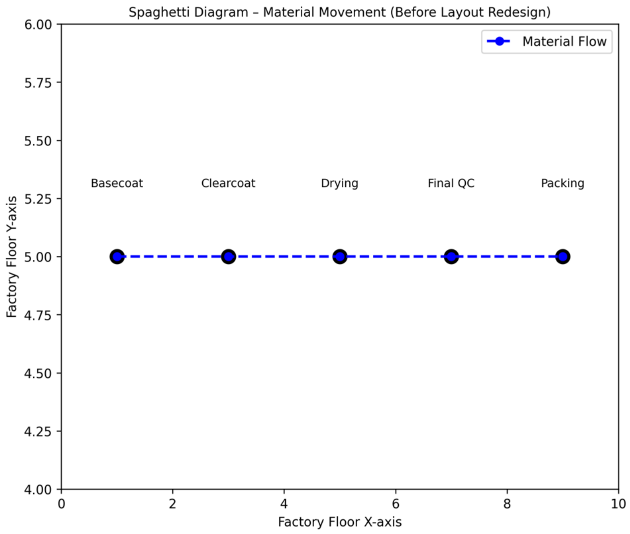

Fig. 5 *Spaghetti diagram showing material flow before layout redesign*

The Spaghetti Diagram traced both operator and material movement across the floor as shown in Fig. 4 and Fig. 5. Starting from the surface preparation area and ending at Final QC, the recorded paths crossed multiple times between basecoat, clearcoat, and drying stations. The visual pattern revealed complex, criss-crossing routes that frequently extended to the edges of the layout due to the linear configuration and non-optimised placement of racks, trolleys, and temporary storage points.

Key results from the Spaghetti Diagram included:

- Operators walked long distances to retrieve, transport, and deliver parts between stages.
- A substantial portion of cycle time was consumed by non-value-added walking and handling.
- Manual material movement, without dedicated flow paths, increased the risk of delays and operator fatigue.

These findings reinforced the need to shorten travel distances and simplify movement paths via layout redesign.

Statistical Process Control (SPC) Charts:

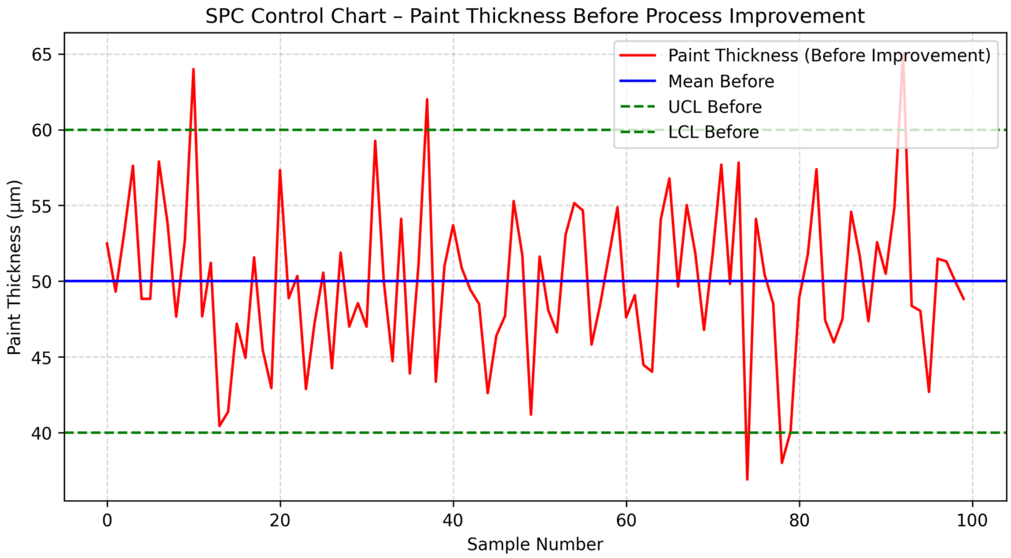

Fig. 6 *Baseline paint-thickness SPC chart before process improvement*

SPC charts were used to monitor key variables. Paint thickness was measured using an automotive-standard coating-gauge instrument and recorded in micrometres (µm). The baseline SPC chart for paint thickness (Fig. 6) showed notable dispersion within the specified control limits. Fig. 6 SPC control chart showing paint thickness variation before process improvement, with several points exceeding the upper and lower control limits, indicating an unstable coating process prior to layout and quality control redesign. While the majority of data points remained inside the Upper Control Limit (UCL) and Lower Control Limit (LCL), the spread indicated that the process was sensitive to variations in technique and environmental factors, and it operated close to its allowable range.

Analysis of the SPC control chart for the current paint-thickness measurement revealed significant instability in the coating process. As shown in Fig. 5, the paint thickness fluctuated widely and exhibited several points exceeding both the Upper Control Limit (UCL = 60 µm) and the Lower Control Limit (LCL = 40 µm). These out-of-control points confirm that the coating system was not statistically stable before improvement. The fluctuations were primarily caused by non-standardized spray distance, inconsistent gun movement, and varying operator technique.

This corrected analysis also aligns with feedback from the QC team, where thickness non-uniformity was frequently observed during Final QC inspections, leading to sanding, polishing, and repaint rework. The SPC chart therefore provides quantitative evidence supporting the need for standardized work, improved material flow, and the addition of intermediate quality checks.

Defects Per Vehicle (DPV) was evaluated separately using production and quality records; DPV values were consistently higher than the target, with most defects being detected at Final QC rather than earlier in the process. This confirmed that, although thickness variation was statistically monitored, the control mechanism was not fully integrated with layout and inspection practices, and opportunities for earlier intervention were being missed.

Result Summary of Phase 2:

Baseline metrics reinforced the inefficiencies identified in Phase 1. The VSM and Spaghetti Diagrams confirmed that material flow and operator movement were key contributors to long lead times and WIP accumulation. SPC analysis showed that the painting process required better standardisation and more effective use of measurement data to stabilise quality.

The baseline data established a clear reference point for Phase 3, indicating that improvements should focus on:

- Optimising material flow and reducing unnecessary lead time.
- Shortening and simplifying operator and material travel paths.
- Integrating process monitoring (SPC) with layout changes and intermediate quality checks to reduce DPV and stabilise thickness variation [15].

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3.3 Phase 3 Results: Layout Design and Pilot Implementation

In Phase 3, a U-shaped layout was designed and implemented to address the inefficiencies identified in the earlier phases. The primary objectives of the redesign were to improve material flow, reduce travel time, and facilitate smoother workflow between workstations. A pilot implementation was carried out to validate the layout's impact before full-scale adoption.

Production Output

The introduction of the U-shaped configuration led to a 33% increase in daily production output, from 150 vehicles per day to 200 vehicles per day. The reduced walking distance and more compact arrangement of workstations allowed operators to spend more time on value-adding tasks and less time on movement, thereby improving effective utilisation of labour.

Defects Per Vehicle (DPV)

DPV showed a substantial improvement, with an 80% reduction from 0.20 to 0.04. This improvement is largely attributed to the introduction of intermediate quality checks after the basecoat and clearcoat stages and the use of operator self-checklists. Earlier detection and containment of defects significantly reduced rework and relieved the load at Final QC, thereby improving overall product quality.

Takt Time

Takt time was recalculated based on available production time and the increased output.

- Using the available daily production time of 720 minutes, the original takt time was:
  Original takt time = 720 min/150 vehicles =4.8 min/vehicle
- With the new target of 200 vehicles per day, the revised takt time is:
  New takt time = 720 min/200 vehicles = 3.6 min/vehicle

This represents a 25% reduction in takt time, achieved through improved flow and reduced non-value-added waiting, rather than simply increasing work intensity. The recalculated value corrects the earlier assumption and reflects a more accurate alignment between available time and output.

Improved U-Shaped Layout and Movement Patterns

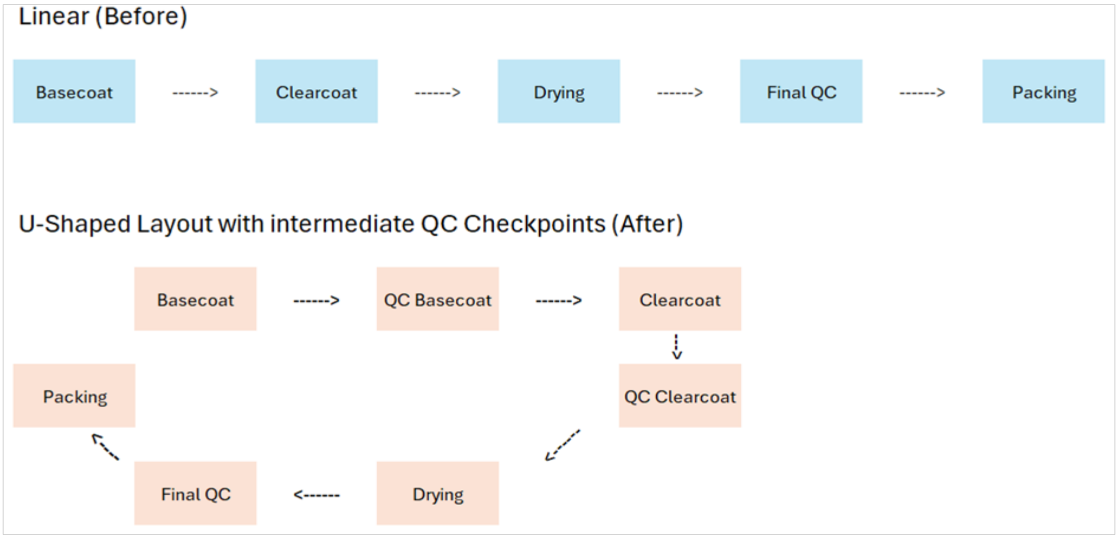

Fig. 7 *U-shaped layout for the improved painting process*

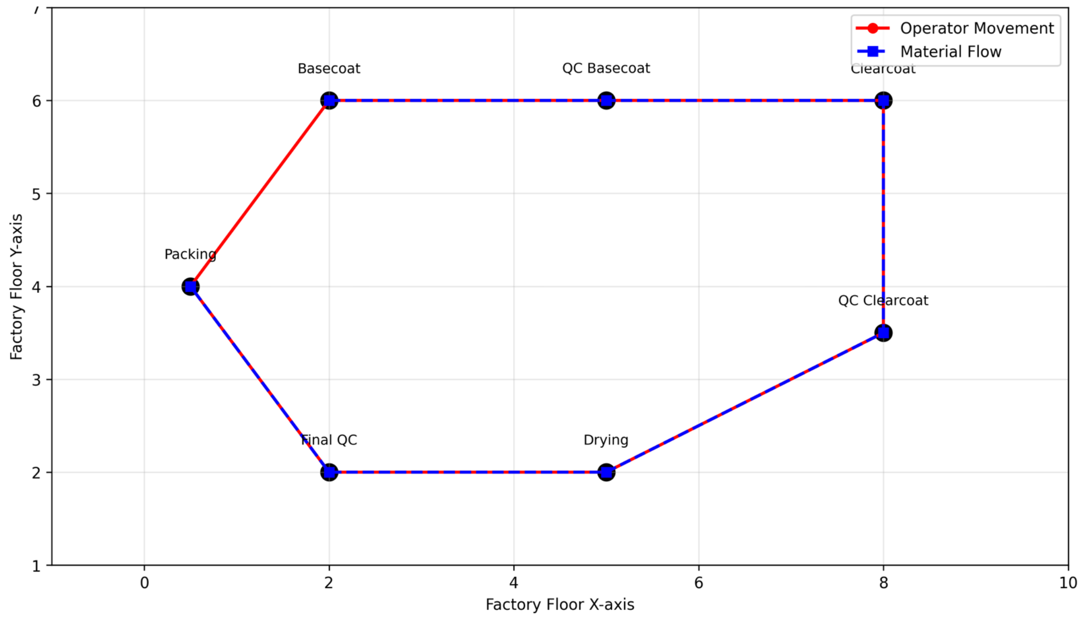

Fig. 8 *Spaghetti Diagram – Operator and material movement after U-shape layout redesign*

A corresponding Spaghetti Diagram for the improved layout illustrates the reduced operator and material travel paths as shown in Fig. 7 and Fig. 8. The U-shaped layout was specifically configured to:

- Minimise travel distances by positioning basecoat, clearcoat, and drying stations in close proximity.
- Clarify start and end points for material flow, creating a more intuitive and direct route.
- Facilitate visual communication and quick problem-solving between adjacent workstations.

The improved Spaghetti Diagram for Phase 3 shows that operator and material movements now follow a compact loop instead of criss-crossing the floor. The number of movement segments and the overall travel distance were both reduced, lowering operator fatigue and further compressing lead time.

Intermediate Quality Tests and 5S Implementation

Intermediate inspections were incorporated after basecoat and clearcoat, supported by standardised self-QC checklists as shown in Fig. 7. This shifted the quality-control approach toward prevention, enabling operators to detect and correct defects early.

5S practices were concurrently implemented to organise tools, materials, and workstations. This reduced search time, prevented mix-ups, and improved cleanliness around the painting area. As a result, the environment became more conducive to stable, repeatable work and fewer contamination-related defects.

Defect Per Vehicle and Takt Time

Fig. 9 illustrates a significant reduction in Defects Per Vehicle (DPV) following the layout redesign and introduction of intermediate quality checks. The early detection of defects after the basecoat and clearcoat processes effectively reduced rework and improved overall product quality.

As shown in Fig. 10, takt time improved from 4.8 minutes to 3.6 minutes per unit after implementation of the U-shaped layout, reflecting smoother material flow, reduced operator travel, and improved workstation coordination.

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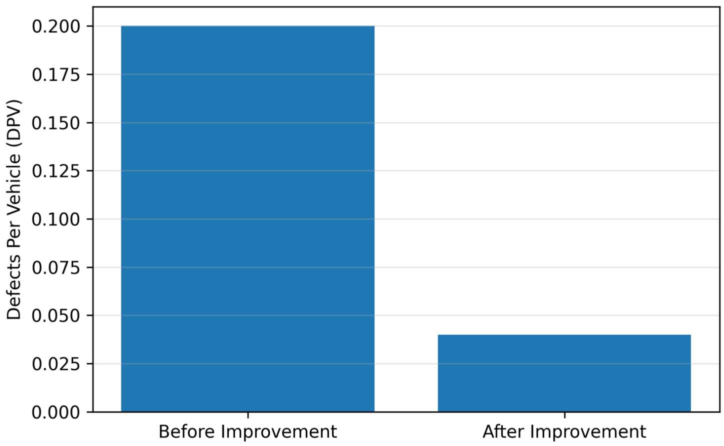

Fig. 9 *Comparison of defect per vehicle before and after layout redesign*

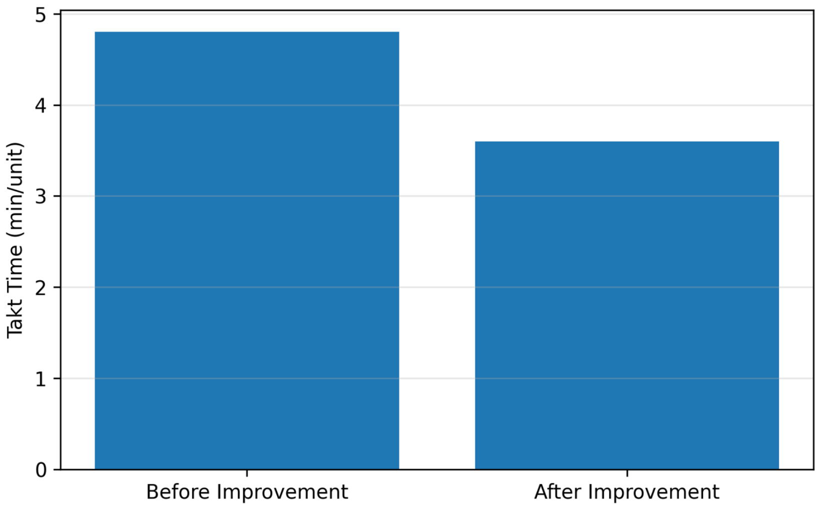

Fig. 10 *Comparison of takt time before and after layout redesign (new takt time = 3.6 min/unit)*

Phase 3 Endpoints and Before–After Summary

Key quantitative improvements from Phase 3 are summarised in Table 1.

Table 1 *Summary of key performance indicators before and after layout redesign*

Metric	Before	After	Improvement
Daily Output	150 units	200 units	+33%
Takt Time	4.8 min	3.6 min	−25%
DPV	0.20	0.04	−80%

Result Summary of Phase 3

The U-shaped layout, combined with intermediate quality inspections, operator self-audits, and 5S, significantly enhanced both production speed and quality. Material handling was simplified, travel distances decreased, and defects were detected earlier in the process. These changes enabled the system to consistently achieve the target of 200 vehicles per day while maintaining a low DPV of 0.04 and a reduced takt time of 3.6 minutes per vehicle [16].

3.4 Phase 4 Results: Monitoring and Continuous Improvement

Phase 4 focused on sustaining and further refining the gains achieved through real-time monitoring using Power BI dashboards. Key production parameters—including production output, DPV, takt time, and selected SPC indicators—were continuously visualised.

Key Endpoints

- Production Output: Output was stably maintained at approximately 200 vehicles per day, confirming that the new layout and process improvements were robust and sustainable under normal operating conditions.
- Defects Per Vehicle (DPV): DPV remained stable at about 0.04, demonstrating that intermediate quality checks, standardised work, and operator ownership effectively controlled defect levels.
- Takt Time: The achieved takt time of 3.6 minutes per vehicle was consistently sustained, indicating that the system could balance demand and capacity while preserving quality.

Results Summary of Phase 4

Real-time dashboards provided continuous visibility of critical metrics and quickly highlighted deviations from normal ranges. This enabled operators and supervisors to take corrective action early, limiting the impact of abnormalities. Regular review meetings based on dashboard data reinforced Kaizen and encouraged a culture of data-driven decision-making.

Consequently, the production system remained flexible, efficient, and capable of delivering high-quality output under varying conditions. Power BI–based real-time tracking proved essential for sustaining productivity and quality improvements, ensuring that layout, quality practices, and SPC controls continued to operate effectively over time [17].

4. Conclusion

This study demonstrates that factory layout optimisation—supported by Lean Manufacturing principles, Statistical Process Control (SPC), and real-time monitoring through Power BI—can significantly improve both production efficiency and product quality in an automotive painting environment. Through systematic identification of process inefficiencies, followed by a structured redesign of workflow, the research achieved measurable and sustained improvements while promoting a culture of continuous improvement on the shop floor.

Key Achievements of the Improvement Initiative:

- Production output increased from 150 to 200 units per day (+33%)
- Takt time improved from 4.8 minutes to 3.6 minutes per unit
- Defects Per Vehicle (DPV) reduced from 0.20 to 0.04 (−80%)
- Reduced operators travel distance and lower Work-in-Progress (WIP) levels

These results confirm the effectiveness of transitioning from a linear layout to a U-shaped configuration. The redesigned layout improved material flow eliminated unnecessary operator movement, and enhanced workstation coordination. Additionally, the incorporation of intermediate quality checkpoints—after both the basecoat and clearcoat stages—enabled earlier defect detection. This significantly reduced rework and alleviated the burden on the Final QC station, addressing key concerns raised by the reviewers regarding quality control sequencing and defect visibility.

Real-time dashboards developed in Power BI further strengthened operational control by providing continuous insights into takt time, output, and defect trends. This facilitated fast corrective action, supported stable process conditions, and enabled more accurate performance tracking. The integration of SPC charts ensured that variations in coating thickness and other critical parameters were monitored statistically rather than reactively, in line with recognised manufacturing quality practices.

The approach adopted in this research aligns with established automotive quality frameworks such as APQP, PPAP, and IATF 16949, and provides a practical, scalable model for improving quality, reducing waste, and enhancing productivity. While the case study focuses on the aerokit painting process, the tools and methods demonstrated—VSM, Spaghetti Diagrams, intermediate inspections, 5S implementation, SPC, and real-time visual analytics—can be adapted across broader automotive assembly, finishing, and machining operations [18].

Beyond immediate operational gains, the wider impact of this study lies in establishing a foundation for future digital transformation. The combined use of Lean tools, SPC, and real-time dashboards prepares the production system for further advancements such as predictive analytics, AI-driven defect detection, intelligent scheduling, and automated maintenance alerts [19]. These capabilities will be increasingly vital as automotive manufacturers navigate evolving customer expectations, electrification trends, and global competition [20].

Novelty of This Study

The unique contribution of this research is its holistic integration of layout redesign, intermediate quality checks, operator-led verification, SPC techniques, and live analytics dashboards within a single improvement framework. Rather than optimising isolated elements, the study delivers a system-wide enhancement strategy that strengthens responsiveness, efficiency, and quality simultaneously. This synergy establishes a new benchmark for layout optimisation in high-mix, high-volume automotive painting environments, offering a replicable and data-driven blueprint for future manufacturing improvement initiatives [21].

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. There are no financial or personal relationships that could inappropriately influence the research.

Author Contribution

The authors confirm contribution to the paper as follows: ***Methodology, Writing-Original Draft.:*** *Mohd Fauzi Ismail;* ***Review & Editing, Resources:*** *Nor Hissham Abdul Hamid;* ***Supervision, Methodology, Validation & Writing-Review:*** *Mahamad Hisyam Mahamad Basri;* ***Overall supervision, Conceptualization, Methodology, Validation, Review & Editing:*** *Nor Fazli Adull Manan.*

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