OPERATIONS AND SUPPLY CHAIN MANAGEMENT
Vol. 19, No. 3, 2026, pp. 381- 389
ISSN 1979-3561 | EISSN 2579-9363

Enhancing Productivity in PCB Assembly through Low-Cost Automation: A Kaizen-Driven Case Study

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ABSTRACT

In the highly competitive global electronics sector, manufacturing productivity is paramount. Manual processes within otherwise automated assembly lines frequently become critical bottlenecks, constraining throughput and hindering growth. This research presents a case study of a Printed Circuit Board (PCB) assembly facility in Thailand that faced a significant capacity shortfall. The primary objective is to analyze the implementation and impact of a Kaizen-driven, low-cost automation (LCA) solution designed to resolve a specific manual bottleneck in an adhesive application process. The methodology combines a detailed analysis of the industrial case study with established theoretical frameworks of lean manufacturing, including the Toyota Production System (TPS), time study, and the ECRS (Eliminate, Combine, Rearrange, Simplify) principles. The intervention, executed through three iterative Kaizen cycles, involved developing a custom automated dispensing machine using repurposed, on-site assets. The results demonstrate a profound improvement in operational performance: the bottleneck process cycle time was reduced by 73.6%, from 11 minutes 53 seconds to 3 minutes 8 seconds per unit. This directly enabled an increase in total production capacity to 245 units per week, exceeding the demand target and yielding an estimated annual cost saving of 98,700 THB. This study's principal contribution is its empirical demonstration of how a culture of continuous improvement, coupled with creative problem-solving, can leverage existing resources to achieve significant productivity gains without substantial capital investment, offering a viable and practical model for small and medium-sized enterprises (SMEs) and other resource-constrained manufacturers.

Keywords: *PCB Assembly, Kaizen, Jidoka, Low-Cost Automation, Lean Manufacturing*

1. INTRODUCTION

The global Electrical and Electronics (E&E) industry operates within a landscape of intense competition, where the ability to enhance effectiveness and efficiency is not merely an advantage but a requisite for survival (Al-Rifai, 2024; Thongbunchum *et al.*, 2022). For manufacturers, continuous productivity improvement serves as a critical success factor and the fundamental basis of profitability (Bhasin, 2008; Susilawati *et al.*, 2013; Thongbunchum *et al.*, 2022). These imperative drives organizations to perpetually seek measures to reduce operational costs, shorten lead times, and increase output without compromising quality (Bhasin, 2008; Susilawati *et al.*, 2013; Thongbunchum *et al.*, 2022). Central to this industry is the process of Printed Circuit Board (PCB) assembly, a technologically complex procedure that forms the functional backbone of virtually all modern electronic products (Bhasin, 2008; Esfandyari *et al.*, 2015; Susilawati *et al.*, 2013; Thongbunchum *et al.*, 2022). As products become more intricate and diversified, the challenges associated with PCB assembly escalate, demanding sophisticated and adaptable production systems (Chams-Anturi *et al.*, 2022).

While automated technologies such as Surface Mount Technology (SMT), wave soldering, and robotic soldering have revolutionized high-volume PCB assembly, many production environments, particularly those characterized by high-mix, low-volume (HMLV) manufacturing, continue to rely on manual, skill-dependent tasks (Normand & Bradley, 2024; Raghavan & Yoon, 2014; Thongbunchum *et al.*, 2022). Processes like selective hand soldering, intricate component placement, or specialized adhesive applications are often performed by human operators due to their complexity or the impracticality of automating them for small batch sizes (Normand & Bradley, 2024; Raghavan & Yoon, 2014; Thongbunchum *et al.*, 2022).

These manual workstations frequently evolve into production bottlenecks the resources or processes that have the largest impact on overall system performance and ultimately constrain throughput (Chams-Anturi *et al.*, 2022; Skoogh *et al.*, 2023). Such bottlenecks lead to a cascade of negative consequences, including extended manufacturing lead times, increased work-in-process (WIP) inventory, wasted time at downstream stations, and delayed deliveries, which can collectively result in substantial financial losses and diminished customer satisfaction (Alzameli *et al.*, 2016). The challenge is amplified in HMLV settings, where the high variability in products and processes makes the identification and management of these shifting bottlenecks significantly more difficult than in stable, mass-production environments (Gan *et al.*, 2023; Normand & Bradley, 2024).

This study investigates an electronics manufacturing company in Thailand facing a classic problem from a production bottleneck. The company, a producer and assembler of electrical circuit boards for a global clientele, was confronted with a critical disparity between its production capacity and escalating customer demand. For a key product line, market demand was projected to increase to 240 units per week. However, the existing assembly line, operating at maximum capacity under standard labor laws, could only produce 189 units per week. This shortfall represented not just lost revenue but a strategic risk to the company's market position and relationship with its customers.

An initial analysis identified the primary constraint as a manual sub-process known as "TX2 Adhesive," which involves the precise dispensing of a viscous glue around an aluminum tray following the arrangement of fiber optic cables. This task was the most time-consuming step in the entire assembly sequence, relying entirely on the skill and stamina of a single operator. The failure to address this bottleneck was the single point of failure preventing the company from capitalizing on a significant growth opportunity, transforming an operational inefficiency into a critical business impediment.

This manuscript has two primary objectives: (1) to analyze the application of a Kaizen-driven, low-cost automation (LCA) intervention designed to resolve the identified production bottleneck; and (2) to situate the case study's methodology and outcomes within the established theoretical frameworks of lean manufacturing, particularly the Toyota Production System (TPS) principles of Jidoka (automation with a human touch) (Wee *et al.*, 2019) and ECRS (Eliminate, Combine, Rearrange, Simplify).

The contribution of this paper is to provide a detailed, empirical account of how foundational lean principles can be pragmatically and successfully applied to achieve substantial, cost-effective improvements in a modern, resource-constrained HMLV manufacturing environment. By documenting a solution built from repurposed assets rather than large capital investment, this study addresses a recognized gap in the literature concerning accessible, cost-effective Industry 4.0 solutions for SMEs and offers a replicable model for practitioners seeking to enhance productivity through ingenuity and continuous improvement (Gan *et al.*, 2023).

2. LITERATURE REVIEW

A critical examination of the literature reveals several intersecting themes pertinent to enhancing productivity in modern electronics manufacturing: the foundational role of Lean principles, the specific operational complexities of High-Mix, Low-Volume (HMLV) environments, and the strategic deployment of Low-Cost Automation (LCA). However, a synthesis of these domains exposes a distinct gap in how resource-constrained enterprises can effectively align LCA with the extreme flexibility required in HMLV production.

2.1 The Dichotomy of PCB Assembly Optimization: Advanced Technologies vs. Lean Methodologies

The optimization of Printed Circuit Board (PCB) assembly lines remains a focal point of academic inquiry (Alzameli *et al.*, 2016). While a significant body of recent work advocates for the integration of advanced technologies such as artificial intelligence (AI), predictive data analytics, and discrete event simulation to optimize critical sub-processes and validate "what-if" scenarios (Alzameli *et al.*, 2016; Kgobe & Ozor, 2021), these capital intensive solutions often exceed the financial and infrastructural capacities of Small and Medium-sized Enterprises (SMEs).

Consequently, for resource-constrained facilities, the foundational principles of Lean manufacturing and Kaizen (continuous improvement) remain the most viable mechanisms for operational enhancement. Fostering a Kaizen culture has been empirically proven to positively influence operational performance in the Electrical and Electronics (E&E) sector (Mui *et al.*, 2022). Rather than relying on heavy capital investment, Lean practitioners utilize localized, short-term Kaizen events to empower employees in bottleneck resolution (Kumar *et al.*, 2018). Within this framework, tools such as ECRS (Eliminate, Combine, Rearrange, Simplify) provide a structured methodology to systematically eradicate non-value-added activities, effectively reducing cycle times in complex assembly workflows (Kasemset *et al.*, 2014).

2.2 The Complexity of Bottleneck Management in HMLV Environments

Applying Lean principles becomes markedly more complex in High-Mix, Low-Volume (HMLV) manufacturing environments. Defined by high product variety, small batch sizes, and non-repetitive process flows (Raghavan & Yoon, 2014), HMLV settings inherently lack the process stability found in traditional mass production. Because of this variability, production bottlenecks are rarely static; they shift frequently based on the product mix, making identification and management highly dynamic (Normand & Bradley, 2024).

Current literature offers robust methodologies for identifying these shifting bottlenecks such as analyzing machine utilization states and observing queue accumulations (Skoogh *et al.*, 2023) as well as diagnosing them through root-cause analysis tools like Ishikawa diagrams (Plomp, 2019). Furthermore, structural interventions like cellular manufacturing have shown success in reducing motion and waiting waste in these settings (Normand & Bradley, 2024). However, while these studies excel at diagnosing and organizing HMLV workflows, they provide limited mechanistic guidance on how to physically resolve machine or manual bottlenecks without defaulting to manual labor redundancies or expensive, flexible automation.

2.3 Low-Cost Automation (LCA) in Resource-Constrained SMEs

To bridge the gap between manual labor constraints and prohibitive full-scale automation, SMEs are increasingly adopting Low-Cost Automation (LCA) and cost-effective digital transformations (Yilmaz *et al.*, 2023). Frameworks such as the "Digital Shoestring" approach advocate for assembling digital and automated solutions using affordable, off-the-shelf hardware and open-source software (Yilmaz *et al.*, 2023). This paradigm successfully lowers the financial barrier to automation and fundamentally aligns with Kaizen philosophies by promoting incremental, resourceful enhancements.

2.4 Critical Synthesis and Research Gap

Despite the individual maturity of research in Lean methodologies, HMLV management, and LCA, critical synthesis reveals a significant intersectional gap. Existing studies on LCA heavily presume a baseline level of process standardization and continuous production to justify the automation effort (Yilmaz *et al.*, 2023). Conversely, the literature on HMLV environments emphasizes the need for rapid changeovers and extreme flexibility (Raghavan & Yoon, 2014; Normand & Bradley, 2024), conditions under which rigid, singular-purpose LCA solutions frequently fail.

At present, the literature falls short in detailing an empirical framework for how LCA can be successfully designed and sustained specifically within the volatile parameters of an HMLV environment. Furthermore, while the concept of resourcefulness is central to SMEs, there is a lack of structured case research demonstrating how Kaizen and ECRS principles can be directly applied to repurpose obsolete, on-site mechanical assets into flexible LCA solutions.

To address this shortcoming, this study aims to elucidate the mechanisms by which a Kaizen-driven approach can facilitate the successful integration of LCA in an HMLV PCB assembly facility. By mapping the iterative repurpose of existing equipment through ECRS principles, this paper bridges the gap between static automation models and the agile requirements of modern SME electronics manufacturing.

3. PRODUCTIVITY IMPROVEMENT IN A PCB ASSEMBLY LINE

3.1 Initial State Analysis and Bottleneck Identification

The subject of this study is a PCB assembly line within an electronics manufacturing facility in Chonburi, Thailand. The line produces a variety of modules for global customers, operating in an HMLV context. An analysis of the entire production flow revealed that the "TX2 Adhesive" sub-process was the primary bottleneck constraining the line's output of the product of the manufacturer, as shown in Figure 1.

Figure 1 An Example of the Major Product of the Manufacturer (Rocketlabstore, 2025)

Figure 2 Example of Dispensing Adhesives around the Aluminum Tray

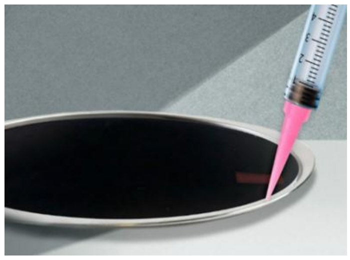

Figure 3 Example of a Syringe with a Fine-Tipped Glue Nozzle

This process required an operator to manually dispense a highly viscous adhesive from a syringe onto an aluminum tray to secure pre-arranged fiber optic cables (Figures 2 and 3). This meticulous and physically demanding task was evaluated through the theoretical lens of the seven wastes (muda) (Liker, 2004), revealing four critical systemic inefficiencies. First, the slow, manual nature of the adhesive application generated substantial waiting waste; it acted as a severe production bottleneck that starved downstream processes of components, thereby increasing system-wide idle time and disrupting overall manufacturing flow. Furthermore, the task inherently demanded excessive, non-value-added motion. The operator was forced to execute complex, two-handed coordination manually rotating the tray 360 degrees with one hand while simultaneously maintaining consistent pressure on the syringe with the other resulting in a process that was both procedurally slow and ergonomically deleterious.

This reliance on subjective manual pressure and rotational speed directly contributed to the waste of defects. Inconsistencies in adhesive volume and placement created a high probability for quality failures, such as insufficient bonding or excess glue spillage, which subsequently necessitated costly rework or generated scrap. Finally, the standard operating procedure itself mandated significant over-processing. Operators were required to perform superfluous preparatory steps, including shaking the adhesivecontainer fifty times and manually filling the

Table 1 Baseline Performance Metrics of the TX2 Adhesive Process

Metric	Value
Process Name	TX2 Adhesive (Manual)
Average Observed Cycle Time (per unit)	11 minutes 53 seconds
Total Process Time (including rework allowance)	37 minutes 48 seconds
Maximum Weekly Production Capacity	189 units
Calculated Required Workstations (to meet demand)	1.3

syringe, neither of which added direct value to the final product. To empirically quantify the cumulative impact of these systemic wastes on production capacity, a formal time study was conducted on 30 consecutive units over a full operational shift. The resulting empirical data, summarized in Table 1, confirmed the severity of the bottleneck and established the baseline for subsequent Kaizen interventions. The time study revealed an average cycle time of 11 minutes and 53 seconds per unit. This slow pace limited the line's capacity to 189 units per week, far short of the 240-unit demand. The data clearly indicated that without a significant improvement in this single process, the company could not meet its strategic objectives.

The Total Process Time (Hours per Unit: HPU) represents the total standard labor time required to complete one unit of the TX2 Adhesive process. The HPU includes not only the adhesive dispensing cycle time but also additional operational elements such as preparation activities, handling time, inspection, and a historical rework allowance recorded by the company. In the baseline condition, the standard processing time was 29 minutes and 43 seconds, while the average rework allowance was 8 minutes and 5 seconds, resulting in a total process time of 37 minutes and 48 seconds (0.63 hours per unit). Because several supporting activities remained unchanged during the Kaizen interventions, the proportional reduction in total HPU was smaller than the reduction observed in the adhesive dispensing cycle time.

3.2 The Kaizen-Driven Intervention: An Iterative Approach to Automation

Guided by the Plan-Do-Check-Act (PDCA) cycle, the company's cross-functional improvement team initiated a series of Kaizen events to address the bottleneck. The approach was explicitly iterative, focusing on rapid, low cost experiments using existing, unused equipment from the production floor a direct application of lean principles to turn idle assets (waste) into value-creating solutions. The ECRS framework provided a clear mental model for structuring the improvements.

3.2.1 Kaizen Cycle 1: Simplifying Motion (Rearrange/ Simplify)

The initial Kaizen intervention targeted the highly inefficient manual rotation of the assembly tray. Guided by the 'Rearrange' and 'Simplify' principles of the ECRS framework, the improvement team engineered a rudimentary, manually operated rotating platform to stabilize the workpiece. Emphasizing resourcefulness, this fixture was fabricated entirely from dormant, on-site materials: a perforated circuit board served as the base, an empty fiber optic cable reel functioned as the bearing mechanism, and a vertical optical post provided structural stability (Figures 4 and 5). While this physical rearrangement successfully smoothed the rotational motion, the process still necessitated simultaneous manual control for both rotation and adhesive dispensing. A subsequent

Figure 4 The Three Parts that were Assembled into a Device to Assist with Glue Dispensing for the First Kaizen Improvement

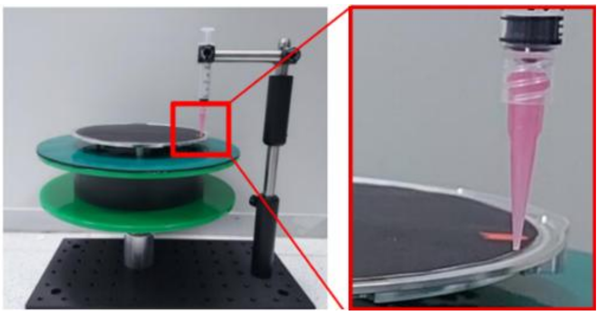

Figure 5 The Device for the First Kaizen Improvement of the Glue Dispensing Process

study of this modified procedure indicated only a marginal reduction in average cycle time to 10 minutes and 48 seconds, an improvement deemed insufficient to satisfy the required capacity target.

3.2.2 Kaizen Cycle 2: Aiding Dispensing Action (Combine)

Building upon the foundational stabilization achieved in the first cycle, the second iteration aimed to optimize the adhesive dispensing mechanism by applying the 'Combine' principle. The team integrated a previously unused pneumatic, foot-pedal-operated dispenser into the workstation architecture (Figure 6). This integration functionally decoupled the dispensing action from the operator's hands, transferring control to the foot pedal and allowing the operator to dedicate their upper-body mechanics entirely to guiding the platform's rotation. Although this combinatorial approach yielded a more substantial cycle time reduction down to 9 minutes and 36 seconds it inadvertently introduced a new category of waste: operator overburden (muri). Ergonomic assessments and operator feedback revealed significant lower-extremity fatigue due to the high frequency of foot-pedal actuations required (approximately 31 presses per unit). Consequently, despite the time reduction, the projected production capacity remained below the 240 unit goal, and the ergonomic strain rendered the solution unsustainable.

3.2.3 Kaizen Cycle 3: Full Automation (Jidoka) (Eliminate)

To resolve the persistent ergonomic constraints and capacity deficits, the final Kaizen cycle sought to fully automate the process, embodying the Toyota Production System (TPS) principle of Jidoka (autonomation) alongside the ECRS principle of 'Eliminate'. The team synthesized the mechanical insights from prior cycles into a bespoke, fully

Figure 6 Example of a Pneumatic Adhesive Dispenser Operated by a Foot Pedal (Shopklub, 2025)

Figure 7 Example of the Automatic Glue Dispensing Tool for the Third Kaizen Improvement

automated dispensing apparatus. The structural and mechanical core of this solution was derived from a dormant, automatic wire-winding machine. The equipment's dual motors were strategically repurposed: one was reconfigured to drive a software-controlled rotating base for the aluminum tray, while the second actuated a piston-based mechanism for precise adhesive extrusion. This critical intervention effectively eliminated all manual process controls.

To ensure zero supplementary capital expenditure, the proprietary control software was developed internally by the facility's IT department. Following rigorous calibration of the platform's rotational velocity (RPM) and the corresponding volumetric adhesive flow, the finalized machine architecture was established (Figure 7). This definitive automation cycle yielded profound operational enhancements, compressing the average cycle time to precisely 3 minutes and 8 seconds per unit. Given its validated empirical efficacy, this automated solution was subsequently standardized and permanently integrated into the production line, completely superseding the legacy manual operation.

This iterative journey highlights a critical aspect of successful lean implementation. The success was not due to a single, brilliant idea but to a systematic process of trial, measurement, and refinement. The final solution was not a purchased, off-the-shelf robot but a creative and resourceful application of existing assets, demonstrating that the most valuable resource for improvement is often the ingenuity of the workforce, a central tenet of both Kaizen and TPS.

4. RESULTS AND DISCUSSION

4.1. Quantitative Analysis

The implementation of the final automated solution yielded substantial and measurable improvements across multiple performance dimensions. The data, comparing the initial state to the state after the third Kaizen cycle, demonstrates the profound impact of resolving a single bottleneck through a focused, lean-driven intervention.

The most direct impact was on the process cycle time. The "TX2 Adhesive" process time was reduced from an average of 11 minutes and 53 seconds to 3 minutes and 8 seconds per unit, representing a 73.6% reduction. This dramatic decrease in the bottleneck's cycle time had a direct and immediate effect on the entire line's throughput. Weekly production capacity increased from 189 units to 245 units, a 29.6% rise that comfortably surpassed the customer demand target of 240 units.

Statistical analysis confirms that the cycle time decreased progressively across the Kaizen improvement stages. Baseline measurements were obtained from a time study of 30 consecutive units, while five representative observations were recorded for each Kaizen stage. Because the automated process became highly stable after calibration, five representative observations were considered sufficient to characterize the cycle time distribution. The results indicate that even the first Kaizen intervention resulted in a statistically significant reduction in cycle time compared with the baseline ($p = 0.020$). Although the magnitude of improvement at this stage was modest, it demonstrates that low-cost ergonomic enhancements can already deliver measurable performance gains. The second Kaizen stage further improved performance and showed a highly significant reduction in cycle time ($p < 0.001$). The implementation of the automated dispensing system produced a dramatic reduction in cycle time (mean = 3.12 min), accompanied by extremely low variability (SD = 0.06), indicating a highly stable and consistent process. This stage exhibited a highly significant difference compared with the baseline process ($p < 0.001$), as summarized in Table 2.

This increase in output was achieved with remarkable efficiency. The calculated number of workstations required for the process dropped from 1.3 (indicating a constant bottleneck) to a stable 1.0, all while utilizing the same number of daily workers. This signifies a major gain in labor productivity and asset utilization. The iterative improvements are summarized in Table 3.

The operational improvements also translated into direct financial benefits. By eliminating the bottleneck and increasing capacity with existing resources, the company avoided the significant costs associated with hiring and training additional staff or running extensive overtime shifts. The calculated cost savings, based on the reduction in labor hours per unit, amounted to approximately 98,700 THB per year (Table 4).

It should be noted that the automation solution implemented in this study did not require additional capital investment in new equipment. The automated dispensing system was developed by repurposing a dormant automatic wire-winding machine that was already available within the

Table 2 Statistical Summary of Cycle Time Measurements Across Kaizen Improvement Stages

Process Stage	n	Mean (min)	SD	95% CI (min)	p-value vs Baseline
Baseline Process (Manual)	30	11.88	0.74	11.60–12.16	–
After Kaizen 1 (Turntable)	5	10.80	0.69	9.94–11.66	0.02
After Kaizen 2 (Pneumatic)	5	9.58	0.33	9.17–9.99	<0.001
After Kaizen 3 (Automation)	5	3.12	0.06	3.05–3.19	<0.001

Table 3 Summary of Iterative Kaizen Improvements and Performance Outcomes

Metric	Baseline (Manual)	After Kaizen 1 (Turntable)	After Kaizen 2 (Pneumatic)	After Kaizen 3 (Automated)	Target
Avg. Cycle Time	11 min 53 sec	10 min 48 sec	9 min 36 sec	3 min 8 sec	N/A
Total Process Time (HPU)	0.63 hr	0.61 hr	0.59 hr	0.49 hr	0.50 hr
Weekly Production Capacity	189 units	196 units	202 units	245 units	240 units
Required Workstations	1.3	1.2	1.2	1.0	1.0

Table 4 Financial Impact Analysis of the Final Automation Solution

Metric	Value
Labor Cost (per hour)	70.5 THB
Production Plan (units per quarter)	2,500
Cycle Time Reduction (HPU in hours)	0.14 hours
Calculated Savings per Quarter	24,675 THB
Calculated Savings per Year	98,700 THB

facility. The mechanical modification and system integration were carried out internally by the engineering team using existing components and tools. In addition, the control software for the automated system was developed by the company's in-house IT personnel as part of their regular operational support activities. Consequently, the intervention did not incur external engineering or software development expenses. While no direct capital investment or external expenditure was required, it should be acknowledged that internal labor resources, including engineering and IT personnel, carry an implicit opportunity cost. However, these activities were undertaken within the scope of routine operational support and continuous improvement efforts. This approach reflects the principles of low-cost automation (LCA) and Kaizen-driven resource utilization, where productivity improvements are achieved primarily through the creative reuse of existing assets rather than through new capital expenditures.

While the direct financial savings are notable, they understate the true strategic value of the intervention. The most significant outcome was the unlocking of growth potential. The company transformed from being production-constrained to being market-ready, capable of accepting larger orders, improving on-time delivery performance, and enhancing customer satisfaction factors critical for long-term competitiveness and market share (Alzameli *et al.*, 2016). This strategic value far outweighs the direct cost savings.

4.2. Aligning Practice with Theory: The Mechanics of Sequential Improvement

Beyond providing empirical validation for core Lean manufacturing principles, this case study elucidates the operational mechanisms by which these theories can be sequentially mobilized to resolve structural bottlenecks. The intervention was not an ad hoc technical fix, but the systematic application of a theory-driven methodology.

First, the case progression aligns with the Toyota Production System (TPS) principle of Jidoka (autonomation with a human touch) (Wee *et al.,* 2019). The improvement team avoided premature automation by following a rationalization trajectory: analyzing the manual state, stabilizing the process through incremental simplification (Cycles 1 and 2), and introducing intelligent automation after process optimization (Cycle 3). This phased approach mitigates the risk of "automating waste."

Second, this iterative progression operationalizes the ECRS (Eliminate, Combine, Rearrange, Simplify) framework not merely as a diagnostic checklist, but as a generative heuristic for process innovation (Ishiwata, 1991; Kasemset *et al.*, 2014; Suhardi *et al.*, 2019). The deliberate evolution from motion rearrangement (Cycle 1) to the functional combination of dispensing and foot control (Cycle 2), and finally to the complete elimination of manual control (Cycle 3), demonstrates the structured logic required to transition from manual assembly to Low-Cost Automation (LCA).

Finally, the intervention demonstrates a highly pragmatic approach to bottleneck management (Skoogh *et al.*, 2023). By concentrating all analytical and creative efforts strictly on the primary constraining process, the team achieved a disproportionate enhancement in overall throughput, reinforcing the theory that targeted constraint resolution is the most efficient vector for systemic performance improvement.

4.3. Theoretical Contributions: A Framework for Kaizen-Driven Asset Repurposing

While contemporary literature increasingly prioritizes high-end data analytics, artificial intelligence, and capital-intensive simulations for process optimization (Alzameli *et al.*, 2016; Gan *et al.*, 2023), this study advances an alternative, theoretically grounded paradigm for Small and Medium-sized Enterprises (SMEs). Moving beyond descriptive case analysis, this research proposes a novel conceptual framework that links foundational TPS principles to the tactical repurposing of physical assets.

By mapping how obsolete equipment can be transformed into customized LCA solutions within a High-Mix, Low-Volume (HMLV) environment, we advance the following theoretical propositions for empirical testing:

1) **Proposition 1** (The Generative Mechanism of ECRS): In resource-constrained manufacturing environments, the iterative, bottom-up application of ECRS principles acts as the primary transformative mechanism, converting dormant or obsolete physical assets into viable, customized Low-Cost Automation (LCA) solutions.
2) **Proposition 2** (Boundary Conditions for LCA Success): The sustained success of Kaizen-driven LCA in HMLV environments depends on high modularity and rapid changeover capabilities. LCA interventions that hard code product parameters (high rigidity) will likely fail or become secondary bottlenecks, whereas solutions designed for flexibility will sustain throughput improvements despite product mix variability.
3) **Proposition 3** (Socio-Technical Alignment): Grassroots Kaizen events that empower shop floor operators to co-design automation solutions result in higher operational acceptance and lower implementation failure rates compared to top-down Industry 4.0 implementations in SMEs.

Through these propositions, this study addresses a gap in the literature on cost-effective Industry 4.0 adaptations (Gan *et al.,* 2023). It provides a testable, replicable model for researchers and practitioners seeking to leverage internal ingenuity and existing resources for scalable automation in volatile production environments.

5. CONCLUSION AND IMPLICATIONS

This research analyzed a successful productivity improvement initiative in a PCB assembly line. The study concludes that a Kaizen-driven, low-cost automation intervention, systematically guided by the principles of ECRS and the TPS philosophy of Jidoka, effectively resolved a critical manual production bottleneck. This intervention resulted in a 73.6% reduction in the bottleneck's cycle time, which in turn enabled a 29.6% increase in the total weekly production capacity of the line. These operational gains were achieved without capital investment in new machinery and resulted in significant annual cost savings by obviating the need for additional labor or overtime.

5.1. Practical Implications

The findings offer several actionable implications for production and engineering managers, particularly within the electrical and electronics (E&E) sector. First, the primary driver of this success was not capital, but the ingenuity of the cross-functional team. Managers should empower employees to identify problems and experiment with low-cost solutions. Second, the unused or outdated equipment should be viewed not as scrap to be disposed of, but as a valuable inventory of components (motors, controllers, frames) for future low-cost automation projects. Additionally, improvement efforts yield the greatest return when they are intensely focused on the system's primary constraint. A systematic approach to identifying and eliminating bottlenecks is crucial for enhancing overall throughput. Finally, significant improvements do not require a single, perfect solution. A series of small, rapid, and incremental changes, guided by the Plan-Do-Check-Act (PDCA) cycle, can lead to profound results.

5.2. Theoretical Implications

This case study provides robust empirical support for the enduring relevance of foundational lean principles in the contemporary Industry 4.0 landscape. It demonstrates that the TPS philosophy of Jidoka improving manually before automating intelligently is a powerful and effective strategy for implementing automation. Furthermore, it validates the ECRS framework as a practical and logical tool for structuring process redesign efforts in a real world industrial setting.

5.3. Limitations and Future Research

While this research provides rich, empirical insights into the mechanics of Kaizen-driven Low-Cost Automation (LCA), the authors acknowledge the inherent limitations of a single-case study design. To mitigate these constraints and strengthen external validity, this study relies on the methodological principle of analytical generalizability, generalizing the observed mechanisms of improvement to established Lean theories rather than attempting statistical extrapolation. Consequently, the findings and theoretical propositions advanced herein operate within specific boundary conditions. The efficacy of this ECRS-driven asset repurposing framework is primarily applicable to resource-constrained Small and Medium-sized Enterprises (SMEs) operating in High-Mix, Low-Volume (HMLV) environments, specifically where production bottlenecks are driven by discrete, repetitive manual tasks.

Because a single descriptive case inherently limits the scope of contribution to the broader literature, future research must build upon this foundational framework. Researchers are encouraged to employ multiple-case study designs or cross-sectional methodologies to empirically test the proposed boundary conditions across diverse manufacturing settings and varying levels of product mix variability. Furthermore, longitudinal studies are essential to monitor the sustained performance of custom-built LCA solutions. Evaluating long-term metrics such as mechanical reliability, maintenance cost degradation, and Overall

Equipment Effectiveness (OEE) will provide critical empirical insights into the lifecycle viability of repurposed automated assets.

Finally, future investigations should focus on the digital augmentation of these low-cost interventions. Integrating automated data collection, Internet of Things (IoT) sensors, and real-time performance monitoring into repurposed machines would effectively address the data reliability challenges prevalent in SME manufacturing environments (Correia *et al.*, 2018). Such an integration would successfully bridge the theoretical gap between bottom-up, grassroots Kaizen initiatives and the top-down, data-driven paradigms of Smart Manufacturing, ultimately creating a more holistic and resilient continuous improvement ecosystem.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENTS

The data from this study are available upon request from the corresponding author and are subject to privacy restrictions.

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