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Optimization of High-Volume PCB Assembly: A Lean Six Sigma Approach Through Pin-in-Paste Technology Integration

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Abstract

The dual reliance on surface-mount technology (SMT) and pin-through-hole (PTH) assembly lines in high-volume printed circuit board (PCB) manufacturing induces logistical bottlenecks, excessive operational costs, and elevated thermal stress on components. This study presents the optimization of a wireless detector terminal production line by integrating Pin-in-Paste (PiP) technology within a Six Sigma DMAIC (Define, Measure, Analyze, Improve, Control) framework. By accurately calculating the required solder volume (V_{req}) and stencil aperture dimensions based on pin and pad geometries, the wave soldering process was eliminated without altering existing thermal profiles. The integration consolidated the assembly into a single heat cycle, ensuring IPC-A-610 Class 2 compliance for barrel fill ratios. The results demonstrate a 97% reduction in average assembly costs, yielding annual savings of USD 92,513 while eliminating USD 44,025 in work-in-progress (WIP) inventory. Furthermore, the single-reflow approach mitigated component thermal degradation and reduced the facility's carbon footprint by an estimated 13.32–17.76 metric tons of CO₂ equivalent annually. This research validates a comprehensive methodology for transitioning to PiP technology, offering a sustainable, cost-effective framework for operational excellence in the electronics' manufacturing industry.

Keywords: Six Sigma; DMAIC; Pin-in-Paste technology; printed circuit board; cost reduction; pin-through-hole; surface-mount technology



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1. Introduction

The manufacturing of modern electronic systems is governed by a rigorous paradigm where market competitiveness relies on achieving high-volume production rates and minimizing operational expenditures without compromising the structural or functional integrity of the final product [1]. These systems, ranging from telecommunication hardware to industrial safety sensors, rely on Printed Circuit Boards (PCBs) as the fundamental structural and electrical backbone [2]. Although the industry has largely transitioned toward surface-mount technology (SMT) to leverage high-speed automated assembly, through-hole technology (THT) remains indispensable for components requiring superior mechanical robustness, such as connectors and power modules [3,4].

Traditionally, this technological duality necessitates a hybrid assembly approach utilizing disparate soldering processes, typically reflow soldering for surface-mount devices

(SMDs) and wave or selective soldering for THT components. However, such dual-line configurations induce logistical bottlenecks, extended lead times, and excessive work-in-progress (WIP) inventories [3,5]. The emergence of Pin-in-Paste (PiP) technology, alternatively referred to as through-hole reflow (THR) or intrusive reflow, represents a critical evolution in mitigating these inefficiencies, aligning with recent industry imperatives to optimize printed circuit board production toward sustainable manufacturing [6–8] by integrating THT soldering into the standard SMT reflow cycle.

While current research has successfully validated the technical viability of the PiP process [5,6]—specifically evaluating the metallurgical performance of lead-free Sn-Ag-Cu (SAC) solder alloys, predominantly SAC305 (96.5% Sn, 3.0% Ag, 0.5% Cu) [9], and deploying Artificial Neural Networks (ANNs) for defect prediction [10]—the literature predominantly isolates these technical parameters from holistic operational efficiency [2,3]. This fragmentation leaves a critical gap regarding how PiP technology translates into systemic manufacturing improvements. This study addresses this void by presenting a comprehensive framework that synchronizes metallurgical quality with Lean Six Sigma methodologies [11,12]. Specifically, this study utilizes the DMAIC framework to optimize operational efficiency and synchronize production flow, utilizing the precise metallurgical volumetric requirements of the PiP process as strict quality inputs. The core novelty of this research lies in demonstrating that the transition to PiP is not merely a logistical adjustment to eliminate throughput mismatch, but a strategic enabler for the ‘Lean-to-Green’ manufacturing paradigm—a methodological integration strongly supported by recent applications of Green Lean Six Sigma [13,14]—concurrently driving drastic cost reductions, eliminating non-value-adding transport, and significantly lowering the facility’s carbon footprint.

2. Materials and Methods

To systematically execute the transition to PiP technology and ensure rigorous process optimization, the Lean Six Sigma DMAIC (Define, Measure, Analyze, Improve, and Control) methodology was adopted as the structural framework [11,12]. This five-phase sequence, illustrated in Figure 1, provides a data-driven roadmap to minimize process variation, synchronize production flow, and eliminate non-value-adding activities [15–17].

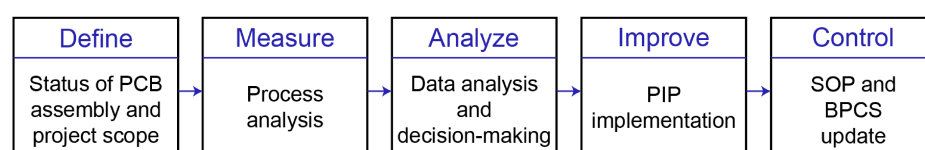


Figure 1. DMAIC steps for the implementation of Pin-in-Paste (PiP) technology.

2.1. Definition Phase

Motion sensor PCBs represent a high-volume product line for the facility, with an annual output of approximately 1,000,000 units distributed across two distinct production lines (baseline layout mapped in Figure 2). The primary objective of this project was to implement PiP technology to eliminate the wave soldering stage, which was previously dedicated solely to assembling the positive and negative battery terminals. To preserve established product integrity, two strict operational constraints were defined: both the solder paste printing parameters for existing SMDs and the pre-established reflow oven thermal profile had to remain unaltered. Consequently, the Critical to Quality (CTQ) metrics were defined around the reduction in operational expenses (lead-free solder alloy, flux, electrical consumption, and stencil fabrication) and the synchronization of production throughput.

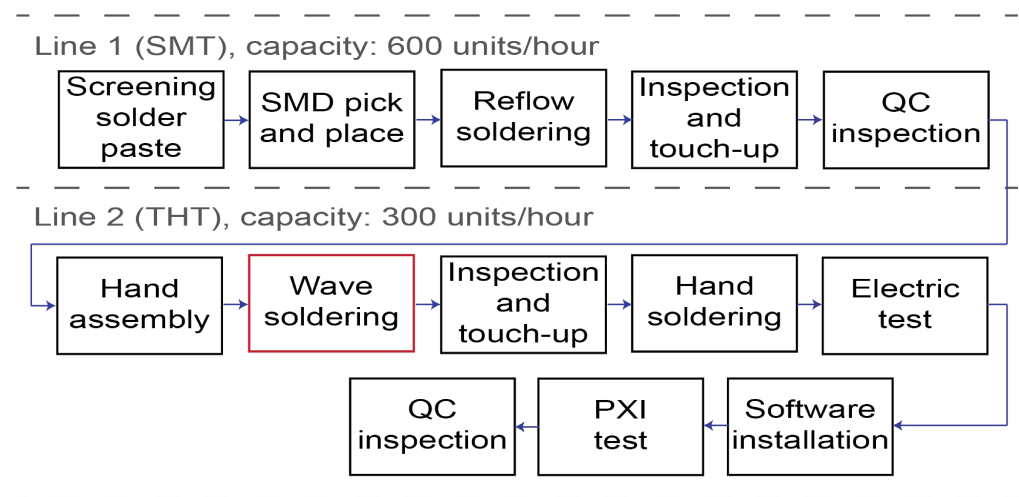


Figure 2. Baseline process map for PCB assembly prior to wave soldering elimination, detailing throughput capacities for surface-mount technology (SMT) and through-hole technology (THT) lines.

2.2. Measurement Phase

During this phase, baseline consumption, manual assembly cycle times, and component thermal resistance were quantified. Consumable expenditures for wave soldering were monitored over a 12-month period, establishing a baseline cost of USD 71,180 (comprising lead-free solder bars, flux, and energy), detailed in Table 1, plus an additional USD 3688 for wave solder pallet fabrication. Furthermore, the critical quality characteristic for the PTH assembly was defined as the barrel fill ratio of the battery terminals. In accordance with IPC-A-610 Class 2 acceptance criteria [18], the lower specification limit (LSL) was firmly set at 75%. Finally, the thermal durability of the terminals was verified via the manufacturer's Material Safety Data Sheet (MSDS), confirming a fusion temperature of 870 °C, which provides a robust safety margin against the 270 °C peak reflow temperature.

Table 1. Baseline monthly expenditure for wave soldering consumables (solder, flux, and electrical power) over a 12-month period prior to PiP integration.

Month	Solder		Flux		Power		PCBs Produced	Cost/PCB USD
	Pounds	USD	Gallons	USD	Watts	USD		
February	100	2344	15	195	3464.24	407	62,435	0.052095
March	225	5274	64	831	3846.48	450	104,644	0.065576
April	150	3516	15	195	3722.40	436	56,818	0.078383
May	175	4102	40	519	3846.48	450	56,003	0.096041
June	300	7032	30	389	3722.40	436	75,685	0.107872
July	150	3516	21	273	3846.48	450	110,253	0.041232
August	275	6446	25	325	3846.48	450	80,275	0.093776
September	100	2344	27	350	3722.40	436	76,562	0.044896
October	250	5860	28	363	3846.48	450	99,231	0.070349
November	300	7032	15	195	3722.40	436	86,126	0.092534
December	350	8204	15	195	3846.48	450	67,294	0.136061
January	250	5860	40	519	3846.48	450	107,130	0.066616
Total	2625	61,530	335	4349	45,279.20	5301	982,456	

2.3. Analysis Phase

Data analysis revealed a severe throughput mismatch between the two production layouts: Line 1 (SMT) operated at a capacity of 600 units/h, while Line 2 (THT and wave soldering) was restricted to 300 units/h, creating a significant logistical bottleneck. By eliminating the wave soldering process, the baseline expenditure of USD 74,868 (consum-

ables and stencils) for 982,456 PCBs translates directly into potential operational savings. Regarding human resource allocation, relocating the two operators responsible for terminal insertion from Line 2 directly to Line 1 (pre-reflow) ensures complete line synchronization. This integration allowed for the total elimination of Line 2 without introducing new bottlenecks in Line 1. Thermally, the substantial delta between the terminal fusion temperature (870 °C) and the peak reflow temperature (270 °C) confirmed the thermodynamic viability of consolidating the assembly into a single heat cycle.

2.4. Improvement Phase

At Line 1, SMT technology and reflow soldering are utilized for component mounting. To solder the positive and negative terminals on this line, it is necessary to achieve the ideal joint features of pin-through-hole (PTH) technology, i.e., a 100% filled barrel and a proper fillet formed on the terminals. To achieve this, it is essential to determine the required solder volume (V_{req}), which is proportional to the stencil hole dimensions.

The stencil hole dimensions are calculated based on the hole, pin, and pad dimensions. To accurately determine the required solder volume, a detailed spatial analysis of the components was conducted. Figure 3 presents the CAD layout of the PCB (designed using SolidWorks 2025, Dassault Systèmes, Vélizy-Villacoublay, France), specifically detailing the geometrical configuration and assigned numbering system for the positive and negative terminals (H1 to H7, P1 to P7, and PD1 to PD7). The specific physical dimensions extracted from this technical drawing are compiled in Table 2.

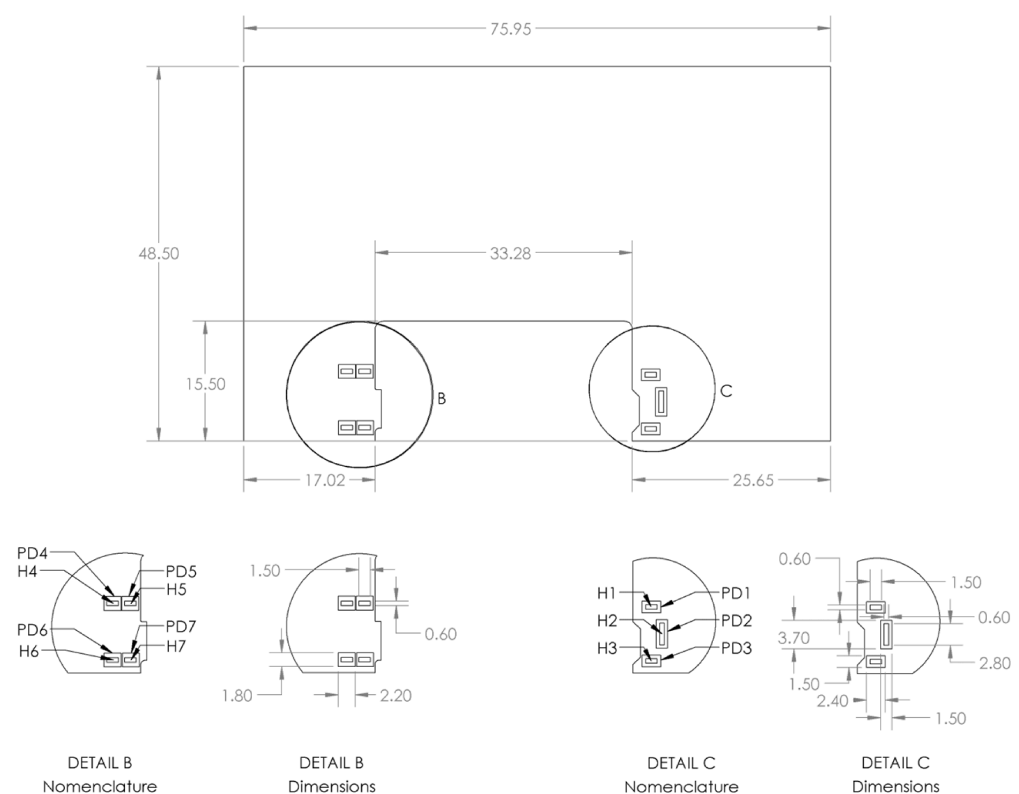


Figure 3. CAD layout of the PCB detailing the geometrical configuration, dimensions, and nomenclature of the positive and negative terminal footprints. Dimensions are in millimeters and correspond to the volumetric parameters detailed in Table 2.

Table 2. Geometrical dimensions (length, width, and depth in millimeters) and calculated volumes for the through-holes (H1–H7), pin terminals (P1–P7), and surface pads (PD1–PD7).

	H1 H3–H7	H2	P1 P3–P7	P2	PD1, PD3	PD2	PD4–PD7
Length	1.5	2.8	1.3	2.5	2.4	3.7	2.2
Width	0.6	0.6	0.4	0.4	1.5	1.5	1.8
Depth	1.5	1.5	1.5	1.5	-	-	-
Volume	1.35	2.52	0.78	1.5	-	-	-

Following the methodology established by Phil Zarrow and validated by Krammer et al. [19,20], the required printing solder volume (V_{req}) to ensure complete joint saturation is calculated using the following equation:

$$V_{req} = 2(V_{hole} - V_{pin}), \quad (1)$$

where V_{hole} represents the total solder volume required to fill the through-hole, and V_{pin} is the physical volume occupied by the pin terminal. These terms are multiplied by an expansion factor of two to compensate for the volumetric shrinkage (approximately 50%) that solder paste undergoes during the reflow process.

Subsequently, to calculate the precise stencil aperture dimensions, the required printed area ($A_{printed}$) is defined as follows:

$$A_{printed} = \frac{(0.80 \times V_{req})}{t_{stencil}} \quad (2)$$

where $t_{stencil}$ represents the standard stencil thickness (selected as 0.127 mm), and 0.80 serves as an empirical adjustment factor optimized for single fillet formation. Finally, the length and width of each stencil aperture were derived by applying the length-to-width ratio of each corresponding pad (RLA_{pad}).

The resulting target values for length and width for each stencil aperture, along with the foundational metrics used for the calculation, are presented in Table 3.

Table 3. Calculated volumetric requirements and stencil aperture dimensions for PiP implementation, including required solder volume (V_{req}), printing area ($A_{printed}$), and pad length-to-width ratio (RLA_{pad}).

Position	V_{req} (mm ³)	$A_{printed}$ (mm ²)	RLA_{pad}	Length _{stencil} (mm)	Width _{stencil} (mm)
1	1.14	7.18	1.60	3.39	2.12
2	2.04	12.85	2.47	5.63	2.28
3	1.14	7.18	1.60	3.39	2.12
4, 5, 6, 7	1.14	7.18	1.22	2.96	2.42

Based on these mathematical results, the total required solder volume for printing each PCB was established as 8.88 mm³.

2.5. Control Phase

To institutionalize the optimized continuous-flow process, the new sequence, methods, materials, labor allocations, and tools were standardized through updated Standard Operating Sheets (SOSs) [21]. Concurrently, the electronic routing registers controlled by the facility's Business Planning and Control System (BPCS)—mandatory for compliance in automotive and industrial PCB manufacturing—were systematically revised. These

administrative controls ensure stringent adherence to the new PiP protocol, preventing regression to the legacy wave soldering process and permanently securing the operational gains. The resulting optimized continuous-flow process map is illustrated in Figure 4.

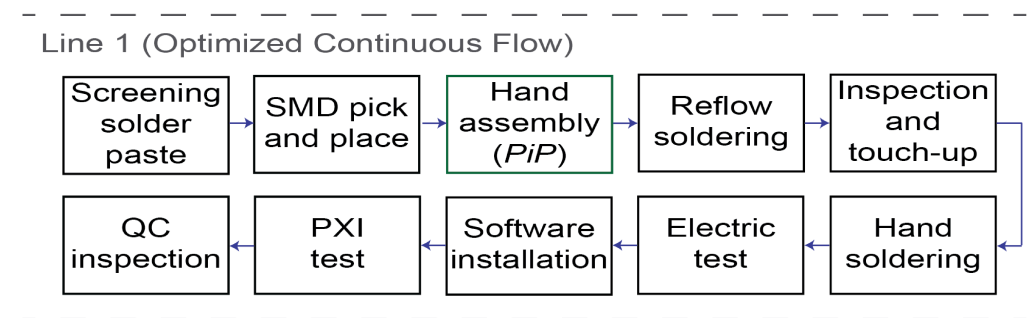


Figure 4. Optimized process map for PCB assembly after PiP implementation, demonstrating continuous flow integration.

3. Results

By implementing PiP technology, the wave soldering process was eliminated from the wireless sensor PCB assembly line. As a direct result, all expenses associated with soldering bars, flux, specialized wave stencils, and targeted electrical energy consumption were eradicated. Furthermore, the wave soldering equipment was physically removed from the production floor; this high-value capital equipment has since been repurposed to manufacture a new product line for the company, avoiding significant secondary investment.

The transition to PiP technology introduced a minor variable expenditure related to the increased paste solder usage for each PCB, quantified at USD 0.00225871 per unit. This was calculated by multiplying the added paste volume per PCB (8.88 mm³) by the volumetric paste solder cost (1 mm³ = USD 0.00025436). Table 4 presents a comprehensive comparison of the production costs before and after PiP technology implementation, detailing the monthly cost variations and the net financial savings achieved.

Table 4. Comparative analysis of monthly PCB assembly costs and total verified annual savings following the integration of PiP technology.

Month	PCBs (Units)	Cost (USD)		Savings (USD)
		Before	After	
February	112,403	5856	254	5602
March	111,630	7320	252	7068
April	93,379	7319	211	7108
May	105,100	10,094	237	9857
Jun	125,207	13,506	283	13,223
July	90,088	3714	203	3511
August	78,153	7329	177	7152
September	80,316	3606	181	3425
October	100,015	7036	226	6810
November	101,884	9428	230	9198
December	99,043	13,476	224	13,252
January	97,999	6528	221	6307
Total	1,195,217	95,212	2699	92,513

As demonstrated by the consolidated data in Table 4, the average PCB assembly cost decreased by 97%, culminating in total verified annual savings of USD 92,513. It is important to note that ‘Before’ costs represent empirical financial expenditures (actual material and energy billing), which exhibit natural month-to-month fluctuations due to

varying scrap rates, line stops, and process inefficiencies inherent to the legacy wave soldering process.

An additional, yet critical, benefit realized from this technological transition was the structural optimization of the PTH assembly. The micro-photographic analysis of the negative and positive terminals validates the metallurgical success of the PiP process consolidation. Figure 5 presents a composite visual validation. Figure 5a shows the top-side insertion of the pins into the PTH. Figure 5b provides a magnified posterior view of the solder joints after reflow. As visually evidenced, robust external solder fillets were formed on the solder side, demonstrating optimal wetting and successful joint consolidation without visible surface voids or bridge defects, adhering to the surface acceptability criteria of IPC-A-610 Class 2 for wetting. The product engineering department corroborated these visual findings by subjecting the assemblies to rigorous soak testing and functional electrical analyses, confirming uncompromised mechanical robustness and electrical continuity.

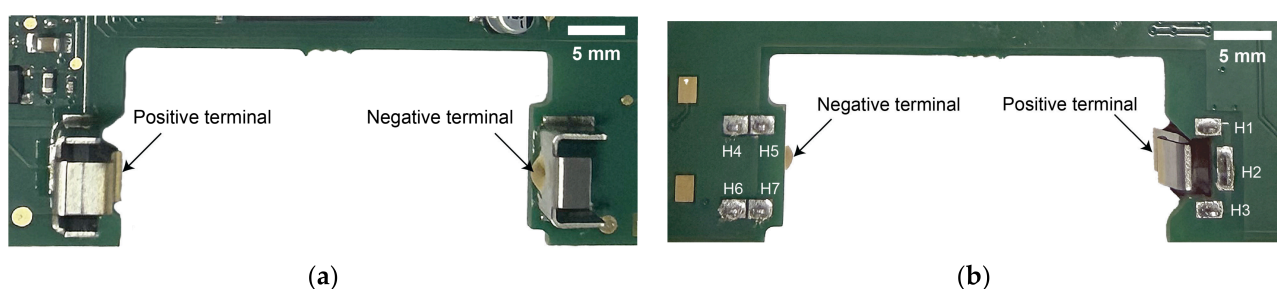


Figure 5. Visual validation of the PiP solder joints: (a) top-down view of the consolidated motion sensor PCB; (b) magnified posterior view showing robust solder fillet formation and wetting on the battery terminal pins after reflowing.

Operationally, the manufacturing line now runs in a continuous flow from the initial print to the final stage. This continuous-flow paradigm successfully eliminated work-in-progress (WIP) floor inventory valued at USD 44,025. Concurrently, it eliminated 4.2 km per day of internal material transportation (avoiding a logistics cycle of 105 m traversed 40 times per day). Total operational overhead was further minimized by the total elimination of a legacy touch-up workstation and two redundant quality inspections, as can be observed by comparing the original process map (Figure 2) with the optimized flow (Figure 4) [22].

4. Discussion

The transition to PiP technology facilitated a continuous-flow manufacturing model, successfully correcting the substantial throughput mismatch between SMT and THT assembly stages [5,6,21]. From a material science perspective, consolidating the process into a single heat cycle delivers significant metallurgical advantages: it minimizes the excessive growth of intermetallic compounds (IMCs) and mitigates the risk of thermal degradation in adjacent SMD components, which typically occurs during consecutive reflow and wave thermal cycles [6,7,9]. The environmental co-benefits of this implementation represent a substantive contribution to Green Manufacturing objectives. Wave soldering machines are historically among the most energy-intensive systems in electronics' assembly, consuming an average of 15–20 kWh [3,5]. Based on the facility's documented operational schedule of 8 h per day and 250 working days per year, eliminating the wave soldering process reduced electrical consumption by an estimated 30,000–40,000 kWh annually. Applying the carbon intensity factor for Mexico's national electrical grid (0.444 kg CO₂/kWh, as reported by SEMARNAT), this translates directly to a reduction of 13.32–17.76 metric tons of CO₂ equivalent per year [23]. Beyond energy savings, wave soldering processes in-

herently generate hazardous alloy dross due to the oxidation of the molten solder bath, typically at a rate of 3–5% of the total mass consumed. Eliminating this process prevents the generation of approximately 35–60 kg of SAC305 dross per year (calculated based on a 3–5% oxidation rate of the 1190 kg of solder consumed annually), which would otherwise require specialized hazardous material disposal procedures under Mexican environmental regulation NOM-052-SEMARNAT-2005 [24]. Additionally, the liquid flux required for wave operations is a major source of volatile organic compound (VOC) emissions; eliminating the flux stream further reduces the facility's atmospheric impact. These comprehensive outcomes align tightly with the Lean-to-Green framework, which advocates for the integration of quantifiable environmental sustainability indicators alongside financial performance metrics within the DMAIC framework, ensuring that ecological accountability is fully institutionalized.

5. Conclusions

The implementation of Pin-in-Paste (PiP) technology via a structured Six Sigma DMAIC framework successfully optimized a high-volume PCB assembly line by eliminating the wave soldering process. This transition was executed without altering the established solder paste printing parameters for SMD components or the pre-set reflow oven thermal profile, thereby ensuring strict compliance with IPC-A-610 Class 2 standards. By subjecting the assemblies to a single heat cycle, the added thermal stress on sensitive surface-mount devices was eliminated. In the highly competitive global electronics' manufacturing market, the operational and financial benefits realized in this study are highly substantial: an annual operational soldering cost reduction of 97%, yielding USD 92,513 in direct savings, a floor inventory (WIP) reduction of USD 44,025, and the elimination of 4.2 km per day of non-value-adding material transport. Furthermore, the project minimized personnel safety risks associated with batch transfer and provided clear Green Manufacturing advantages, reducing greenhouse gas emissions by up to 17.76 metric tons of CO₂ equivalent annually while eliminating hazardous dross and VOC emissions. This study provides a validated and scalable framework for facilities seeking to achieve concurrent economic and environmental operational excellence.

Although the PiP methodology successfully consolidated the thermal cycle and eliminated wave soldering inefficiencies in this specific case study, certain limitations must be acknowledged. Future research should focus on long-term thermo-mechanical reliability testing—such as subjecting the PiP joints to accelerated thermal cycling and vibration tests—to fully understand the microstructural evolution of the intermetallic compound (IMC) layer over extended operational lifespans. From an operational automation perspective, future improvements will evaluate transitioning positive and negative terminal packaging to tape-and-reel feeding. This would enable automated SMT pick-and-place insertion, completely eliminating residual manual assembly from the optimized line and advancing toward fully automated continuous flow. Furthermore, while validated in a high-volume sensor manufacturing context, this Lean-to-Green framework offers a scalable blueprint that can be generalized and adapted for higher-complexity assemblies in the automotive and telecommunications sectors, where stringent joint reliability and environmental sustainability are equally critical imperatives.

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Abbreviations

The following abbreviations are used in this manuscript:

PCB	Printed Circuit Board
SMT	Surface-Mount Technology
PIP	Pin-in-Paste (Intrusive Reflow) Technology
DMAIC	Define, Measure, Analyze, Improve, and Control
PTH	Pin-Through-Hole Technology
THT	Through-Hole Technology
WIP	Work-In-Process Inventory
SMD	Surface-Mount Device
SOS	Standard Operating Sheet
BPCS	Business Planning and Control System
COPQ	Cost of Poor Quality
AXI	Automated X-ray Inspection
CTE	Coefficient of Thermal Expansion
IMC	Intermetallic Compound
VOC	Volatile Organic Compound
SAC	Sn–Ag–Cu (Lead-free solder alloy)
SAC305	96.5% Sn, 3.0% Ag, 0.5% Cu alloy composition

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