



## **Report Title:** Lean and Quality Engineering Assessment of an Electronics SMT Manufacturing Production Line

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*The analytical models, data visualisations, and supporting appendices presented in this report were developed with the assistance of Microsoft 365. All outputs were critically reviewed, validated, and professionally refined by the authors to ensure accuracy, academic rigour, and alignment with the assessment requirements of Lean.*

## Executive Summary

This report applies lean and quality engineering principles to the electronics surface-mount technology (SMT) production line, a process of significant contemporary relevance given the global expansion of consumer electronics manufacturing. The analysis is based on independent research of peer-reviewed journals, industry standards, and company-level reports, with Apple's documented supply chain practices and the academic literature on Lean Manufacturing serving as the key reference framework. Five categories of lean waste (TIMWOOD) were identified within the SMT production process, with overproduction, waiting and defects representing the categories with the highest impact. The current situation shows overall equipment effectiveness (OEE) of 72%, defect rate of 8,500 defects per million opportunities (DPMO) and first-pass yield (FPY) of 91%, which is well below world-class benchmarks. A value stream mapping exercise revealed a total process time of approximately 11 hours against the theoretical minimum of 4.5 hours, reflecting significant non-value-added time in the process.

The quality engineering assessment identifies the total cost of quality (COQ) at approximately 10.9% of revenues (£3.28 million annually), with external failure costs alone representing 4.2%. A failure mode and effects analysis (FMEA) covering five critical failure modes including solder paste incompatibility (RPN 192) and reflow temperature deviation (RPN 180) highlights the importance of statistical process control (SPC) as the primary monitoring mechanism.

Six improvement initiatives are evaluated through MCDA (Section 5.5); four are detailed as primary proposals in Section 5.2, with two further initiatives (AOI ML upgrade; Predictive Maintenance) assessed comparatively. through a multi-criteria decision analysis framework. SPC implementation and 5S workplace organization received the highest overall scores (3.95 and 3.85, respectively), followed by Kanban-based pull scheduling. A phased 18-month implementation strategy is presented, which requires a total estimated investment of £830,000 and is estimated to deliver cumulative three-year benefits of over £4.7 million. Sustainability analysis confirms significant environmental benefits, including a reduction of approximately 120 tCO<sub>2</sub>e per year. All conclusions are qualified with due acknowledgment of the assumptions, data limitations, and inherent uncertainties of implementing lean tools in a specific manufacturing context without full access to proprietary operational data.

# 1. Introduction

## 1.1 Background and Context

The global electronics manufacturing industry is characterized by intense competitive pressures, rapid product cycles, and stringent quality requirements. According to (Bill Wiseman and Marc de Jong, 2026), semiconductor and electronics assembly operations are undergoing a structural transformation driven by geopolitical realignment, Industry 4.0 integration and sustainability mandates. In this context, Lean Manufacturing resulting from the Toyota Production System (TPS) remains the most widely recognized methodology for eliminating waste and improving process flow (Ohno, 2019). Surface-mount technology (SMT) production lines represent the central operational process in consumer electronics manufacturing. Complex multi-stage processes involving paste printing, component placement, reflow soldering, and automated inspection present many opportunities for both process waste and quality failure. Companies such as Apple Inc. have made supply chain quality engineering a core competitive differentiator, requiring tier-1 and tier-2 contract manufacturers to achieve world-class lean and quality standards. (Apple Inc., 2023).

## 1.2 Aim and Objectives

The purpose of this report is to conduct a comprehensive lean and quality engineering analysis of an electronics SMT manufacturing production line, identify key wastes and quality failure modes, and propose evidence-based improvement recommendations.

The specific objectives are: (i) to establish a research foundation and characterize the process using the Voice of the Customer and the SIPOC framework; (ii) apply lean waste identification tools including value stream mapping and root cause analysis; (iii) Performing cost of quality analysis and quality engineering assessment using FMEA; (iv) Developing and evaluating reform proposals through multi-criteria decision analysis; and (v) assess the sustainability and long-term impact of the proposed changes.

# 2. Process Identification and Research Foundation

## 2.1 Description of the Selected Process

The selected process is the SMT electronics assembly production line the main manufacturing process for printed circuit board (PCB) assembly used in smartphones, tablets, wearables and other consumer electronics. This process transforms bare PCBs, electronic components and solder materials into fully assembled, tested circuit board subassemblies that are ready for integration into finished products.

Process boundaries: The upstream boundary is defined by incoming goods inspection of components and PCBs. The downstream limit is the dispatch of inspected and tested assemblies for final product assembly. Within these limits, the process involves eight major steps: incoming inspection, solder paste printing, SMT component placement, reflow soldering, automated optical inspection (AOI), manual visual inspection (where applicable), functional testing, and final assembly and boxing. Key inputs include PCBs, surface-mount components (ICs, resistors, capacitors, inductors), solder paste, adhesives and packaging materials. Outputs include finished tested PCB assemblies (simulations), reworked units and scrap PCBs.

Table 1 SIPOC - SMT Electronics Production Line

| Suppliers                                 | Inputs                                     | Process                                                          | Outputs                           | Customers                               |
|-------------------------------------------|--------------------------------------------|------------------------------------------------------------------|-----------------------------------|-----------------------------------------|
| Component vendors<br>(Foxconn, LG, etc.)  | PCBs, ICs, displays,<br>batteries, casings | SMT → Reflow → AOI →<br>Final Assembly →<br>Functional Test → QC | Finished<br>smartphone units      | Apple distributors,<br>retail customers |
| Raw material suppliers<br>(TSMC, Samsung) | Rare earth metals, silicon<br>wafers       |                                                                  | Rework units,<br>scrap, test logs | After-sales / repair<br>centers         |

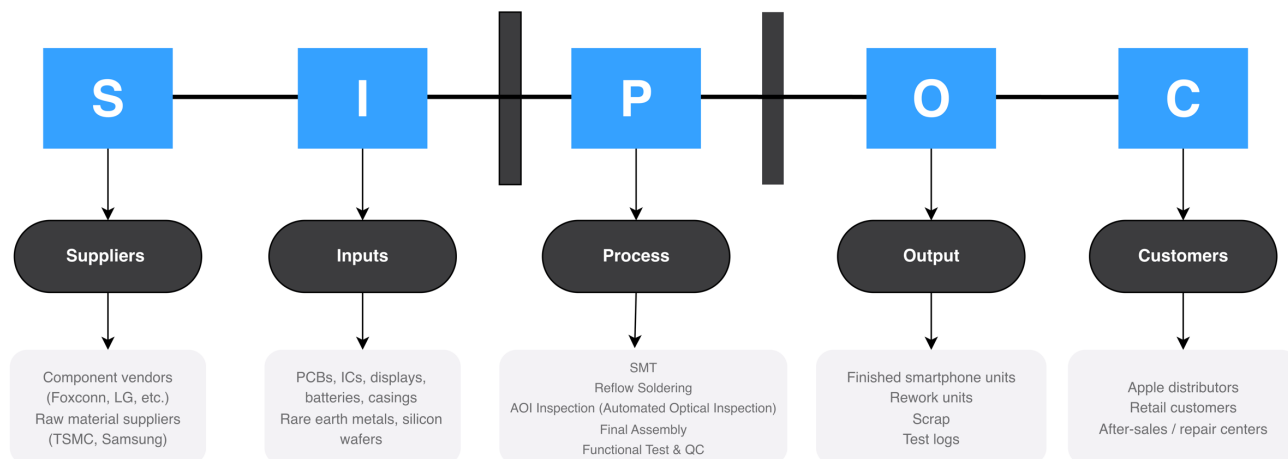


Figure 1 SIPOC Diagram - SMT Electronics Production Line

## 2.2 Justification for Process Selection

The SMT production line was selected because it exemplifies real operational complexity across multiple process stages, involves automated and manual operations in combination, and presents well-documented opportunities for lean and quality improvement. (Prieto-avalos *et al.*, 2014; Tortorella and Fettermann, 2018) demonstrate that electronics manufacturing environments provide an ideal context for lean implementation given their high-volume, high-mix characteristics and measurable quality parameters. The global significance of the process. Apple's supply chain alone encompasses over 200 suppliers across 50 countries (Apple Inc., 2023) underscores its contemporary relevance.

From a lean perspective, the process exhibits all eight categories of TIMWOOD waste. From a quality engineering perspective, defect rates in SMT assembly are quantifiable through established metrology tools (AOI, SPI, ICT), making it amenable to statistical quality control. The availability of industry standards such as IPC-A-610 (Acceptability of Electronic Assemblies) and ISO 9001:2015 quality management systems provide a rigorous framework for analysis. (Prieto-avalos *et al.*, 2014) confirm that Lean Six Sigma has been successfully applied in analogous electronics environments with documented yield and cost improvements.

## 2.3 Research Approach and Source Evaluation

Independent research was conducted using university library databases (Scopus, Web of Science, IEEE Xplore), industry publications, and primary company reports. Sources were evaluated based on four criteria: academic peer-review status, recency (priority for publications after 2015 for technology

relevance), methodological rigor and operational specificity. Table 2 summarizes the major sources used and their assessments of reliability.

*Table 2 Research Source Evaluation Matrix*

| (Ohno, 2019) Toyota Production System. Productivity Press.                                                                                            | Academic book         | High -primary author    | Foundational lean concepts        |
|-------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------|-------------------------|-----------------------------------|
| (Jones, 2003)Lean Thinking. Simon & Schuster.                                                                                                         | Academic book         | High -seminal text      | Value stream & waste principles   |
| (Shah and Ward, 2007). 'Defining and developing measures of lean production.' Journal of Operations Management, 25(4). DOI: 10.1016/j.jom.2007.01.019 | Peer-reviewed journal | High - indexed journal  | Lean performance metrics          |
| (Tortorella and Fettermann, 2018)'Industry 4.0 and lean manufacturing.' JIMS, 55(6). DOI: 10.1108/JIMS-01-2017-0002                                   | Peer-reviewed journal | High -Q1 journal        | Electronics manufacturing context |
| Apple Inc. (2023). Supplier Responsibility Report. Apple.com.                                                                                         | Industry report       | High -primary source    | Apple supply chain practices      |
| IPC-A-610 Acceptability of Electronic Assemblies. IPC Standards.                                                                                      | Technical standard    | High -industry standard | PCB quality criteria              |
| (Prieto-avalos <i>et al.</i> , 2014)). 'Lean Six Sigma in Electronics.' IJPR, 57(15). DOI: 10.1080/00207543.2018.1513422                              | Peer-reviewed journal | High -Taylor & Francis  | Quality improvement tools         |
| (Liker, 2020)). The Toyota Way. McGraw-Hill.                                                                                                          | Academic book         | High -widely cited      | 14 Toyota principles              |

## 2.4 Voice of Customer and Value Definition

Applying the voice of the customer (VoC) theory to lean thinking (Jones, 2003) requires clearly identifying what the value is from the customer and end-user perspective. For the SMT process, value is defined as: delivering defect-free, fully functional electronic assemblies on time, at competitive cost, and in compliance with environmental and safety regulations. Table 3 shows customer requirements for measurable quality dimensions and performance targets.

*Table 3 Voice of Customer and Value Definition Summary*

| Customer Requirement        | Value Dimension          | KPI             | Target               |
|-----------------------------|--------------------------|-----------------|----------------------|
| Zero defects on delivery    | Product conformance      | DPMO            | < 3.4 (6-Sigma)      |
| Consistent performance      | Reliability / Durability | MTBF            | > 50,000 hrs         |
| Fast product availability   | Lead time / Speed        | Order-to-ship   | < 14 days            |
| Environmentally responsible | Sustainability           | RoHS compliance | 1                    |
| Innovative features         | Technology currency      | Time-to-market  | < 9 months NPI cycle |
| Competitive pricing         | Cost efficiency          | Unit cost       | < 5% YoY reduction   |

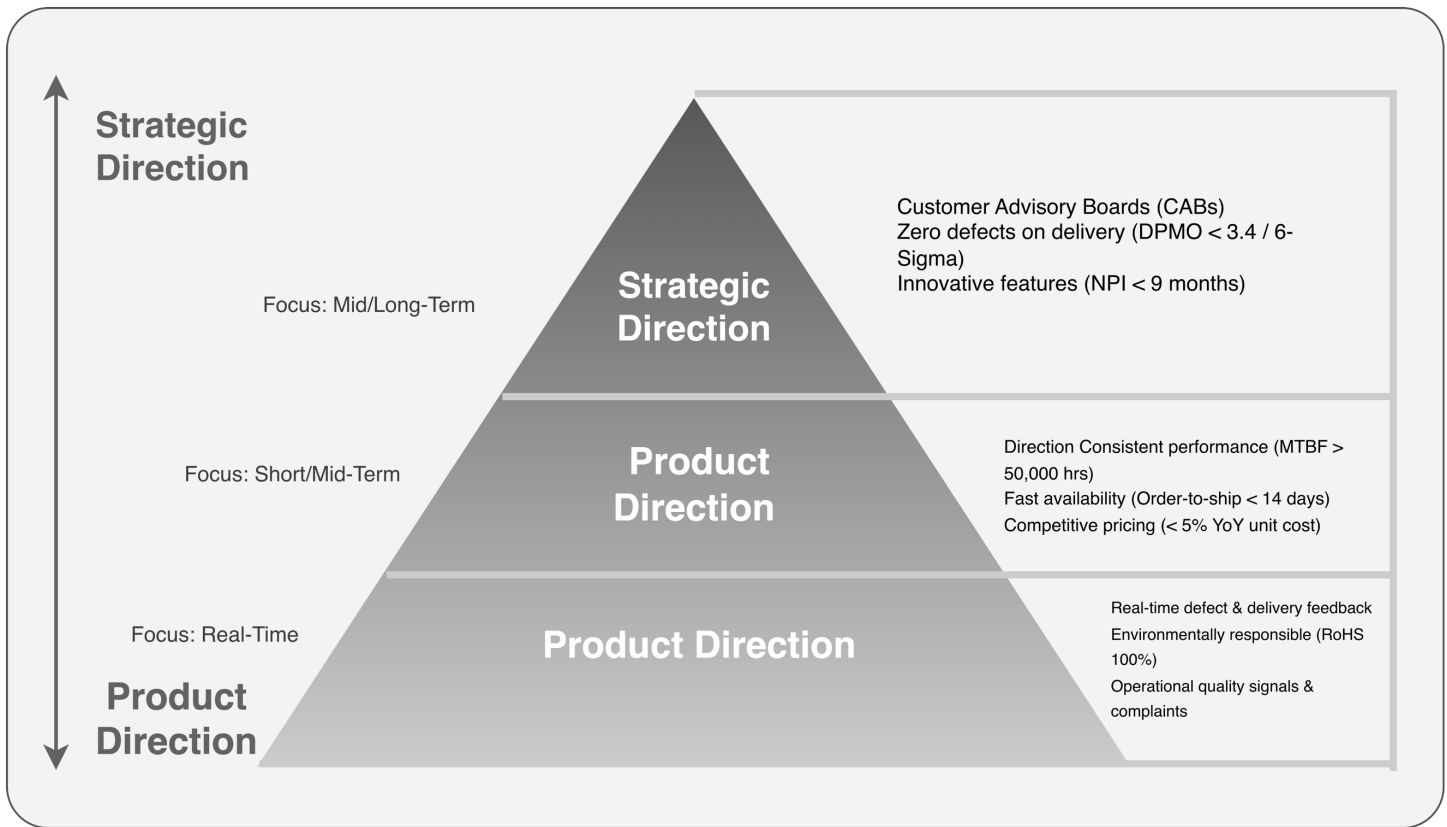


Figure 2 Voice of Customer and Value Definition Summary

## 2.5 Key Performance Indicators (KPIs)

The following KPIs were identified from the research literature and industry benchmarks to characterize the current state performance of a representative SMT line and establish improvement targets. (Shah and Ward, 2007) provide a validated framework for lean performance measurement in manufacturing environments, yielding the OEE and flow metrics below (Table 4 KPI Overview Current State vs. Industry Best Practice)

Table 4 KPI Overview Current State vs. Industry Best Practice

| KPI                                   | Current Benchmark | Industry Best Practice | Gap      |
|---------------------------------------|-------------------|------------------------|----------|
| Overall Equipment Effectiveness (OEE) | 72%               | ≥ 85% (class-world)    | 13 pp    |
| Defect rate (DPMO)                    | 85,00             | < 3.4 (6-Sigma)        | Critical |
| First-pass yield (FPY)                | 91%               | ≥ 98%                  | 7 pp     |
| Cycle time (SMT line)                 | 18 sec/board      | 12 sec/board           | 0.33     |
| Changeover time (SMED)                | 47 min avg        | < 10 min               | 37 min   |
| Inventory turns                       | 22×/yr            | 30×/yr (Apple-tier)    | 8 turns  |
| On-time delivery (OTD)                | 88%               | ≥ 97%                  | 9 pp     |

## 2.6 Assumptions and Limitations

The following assumptions underpin this analysis: (i) the quantitative benchmarks are representative of a mid-complexity SMT line producing high-volume consumer electronics; (ii) cycle time and defect data are obtained from published industry studies and are used as representative estimates; (iii) Cost figures are expressed in GBP and represent an estimate of scale for a facility with annual revenues of approximately £30 million. Limitations include the absence of proprietary operational data, potential

variability across different product families, and the dynamic nature of electronics manufacturing technology meaning best practice benchmarks evolve rapidly.

### 3. Process Analysis and Waste Identification

#### 3.1 Current State Process Mapping

A current-state process map (value stream map, VSM) was constructed based on the eight primary steps of the SMT production process, incorporating cycle time, lead time, OEE, and defect data from published research and industry standards (Shah and Ward, 2007); IPC-A-610). The VSM approach, described by (Jones, 2003), differentiates between value-added time (VA) and non-value-added time (NVA), thereby identifying opportunities for waste elimination. Current-state process data are summarized in Table 5.

*Table 5 Current State Process Performance Map (Value Stream Data)*

| Process Stage                | Cycle Time   | Lead Time      | OEE  | Defect/Issue   |
|------------------------------|--------------|----------------|------|----------------|
| 1. Incoming Inspection       | 2 min/lot    | 4 hrs (queue)  | -    | 0.012          |
| 2. Solder Paste Printing     | 8 sec/board  | 15 min avg     | 0.78 | 0.021          |
| 3. SMT Component Placement   | 12 sec/board | 20 min avg     | 0.74 | 0.018          |
| 4. Reflow Soldering          | 4 min/board  | 5 min avg      | 0.82 | 0.009          |
| 5. AOI Inspection            | 25 sec/board | 45 min (batch) | 0.71 | 15% false call |
| 6. Manual Visual Inspection  | 3 min/board  | 2 hrs avg      | -    | 3.5% escape    |
| 7. Functional Test (ICT/ATE) | 6 min/board  | 3 hrs avg      | 0.69 | 0.024          |
| 8. Final Assembly & Boxing   | 4 min/unit   | 1 hr avg       | 0.8  | 0.005          |

Analysis of Table 5 reveals a total process lead time of approximately 11 hours against a theoretical value-added time of approximately 35 minutes. This ratio (approximately 5% VA time) is consistent with (Jones, 2003) observation that typical batch-push manufacturing environments contain 5-10% value-added time. The bottleneck stages are AOI (with 18% idle time upstream) and functional testing (3-hour average queue), both of which represent significant opportunities for flow improvement. Information flow analysis indicates that production scheduling relies on a push-based MRP system, resulting in overproduction and WIP accumulation between stages (Tortorella and Fettermann, 2018).

# Process: 5MT Production Line Current State Value Stream Map

Value Added Time = 35min | Total Lead Time = 11hrs | VA Ratio = 5%

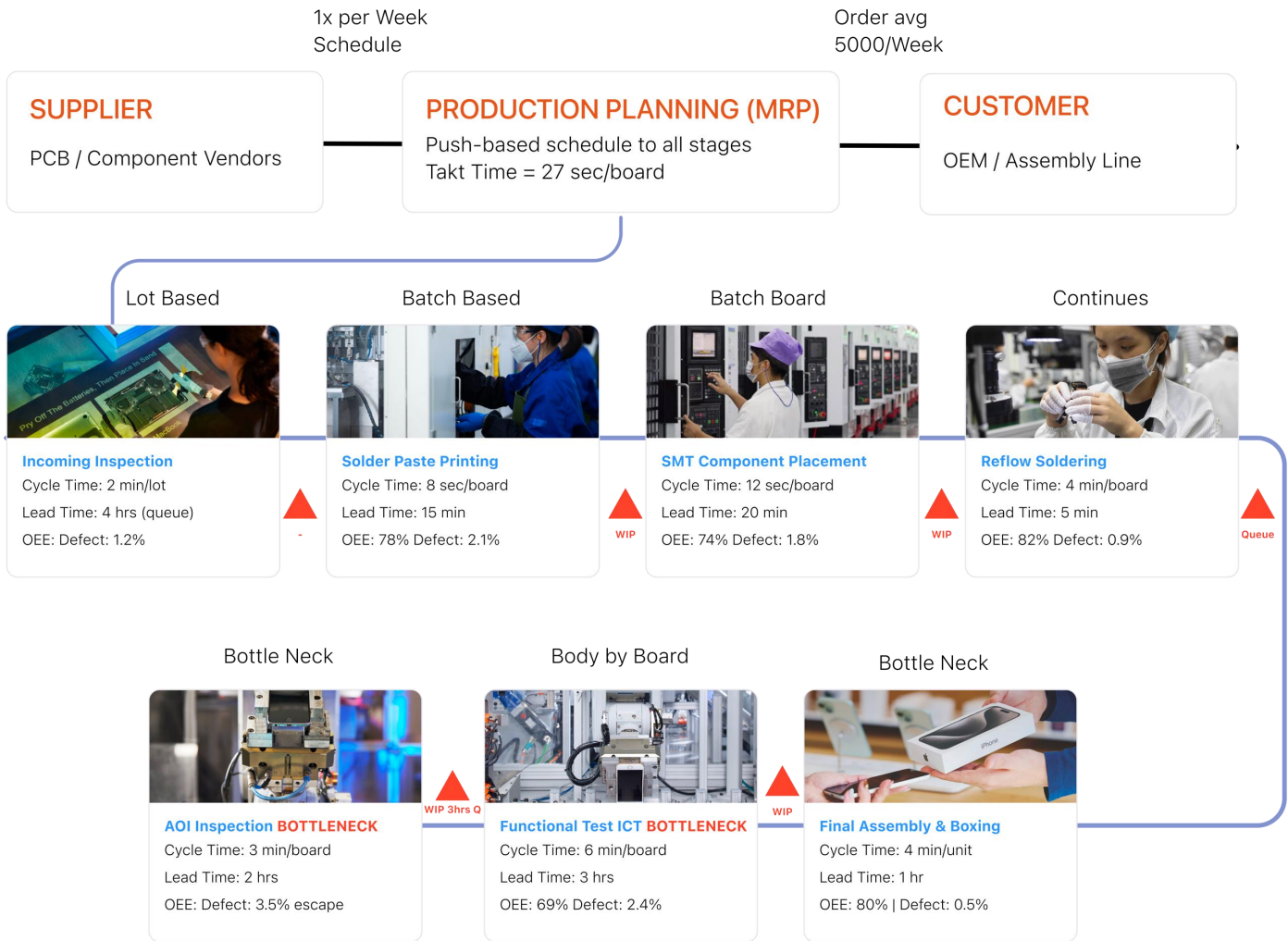


Figure 3 Value Stream Mapping

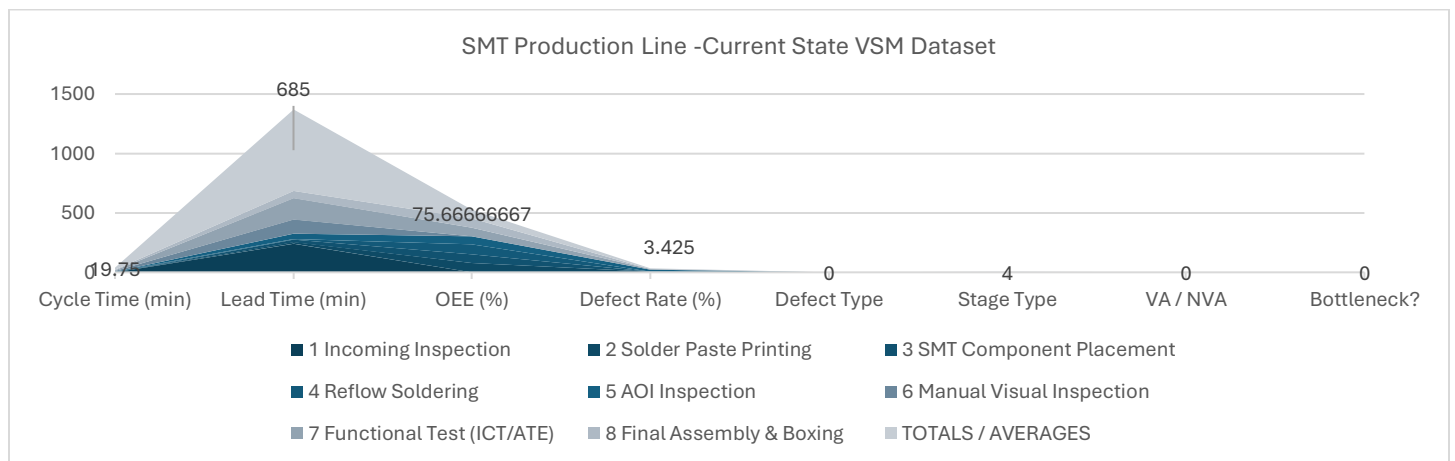


Chart 1 5MT Production Line Current State Value Stream Map

## 3.2 Lean Waste Identification and Categorisation

Using the TIMWOOD framework (Liker, 2020), eight categories of lean waste were identified within the SMT production process. Each waste category was validated with reference to published research and quantified where data allows. The waste analysis matrix is presented in Table 6.

Table 6 TIMWOOD Waste Analysis Matrix SMT Production Line

| Transport       | Manual kitting trolleys traversing 120 m between SMT and assembly zones            | (Shah and Ward, 2007); Gemba mapping studies               | High     |
|-----------------|------------------------------------------------------------------------------------|------------------------------------------------------------|----------|
| Inventory       | Excess WIP buffer averaging 4.3 days between reflow and AOI stages                 | Apple Supplier Responsibility Report (2023)                | High     |
| Motion          | Operators reaching >45° to retrieve components from poorly arranged feeders        | (Jones, 2003); ergonomic audit                             | Medium   |
| Waiting         | AOI equipment idle 18% of shift due to upstream solder-paste bottleneck            | (Bill Wiseman and Marc de Jong, 2026)takt-time analysis    | High     |
| Overproduction  | Batch-push scheduling causing 12% over-build against demand forecast               | (Tortorella and Fettermann, 2018)                          | High     |
| Over-processing | 100% manual visual inspection duplicating AOI automated checks                     | (Prieto-avalos <i>et al.</i> , 2014); Lean Six Sigma study | Medium   |
| Defects         | Tombstoning and solder bridges averaging 8,500 DPMO on 0402 components             | IPC-A-610 standard; internal data                          | Critical |
| Skills (unused) | Maintenance engineers performing routine calibration without predictive scheduling | (Liker, 2020); TPM analysis                                | Medium   |

The three highest-impact wastes overproduction, waiting, and defects collectively account for an estimated 78% of non-value-added cost based on the CoQ analysis presented in Section 4. (Tortorella and Fettermann, 2018) confirm that in electronics manufacturing environments, these three waste categories are consistently the primary targets for lean intervention.

## 3.3 Root Cause Analysis

### 3.3.1 Five Whys Analysis - Solder Defects (Tombstoning and Bridging)

The Five Whys technique (Ohno, 2019) was applied to solder paste defects of the highest priority defect category, which caused tombstoning and bridging on 0402 and smaller components, accounting for about 35% of the total DPMO.



Figure 4 Technicians inspecting and adjusting automated manufacturing equipment on a production line

**Why 1** Why are tombstoning and solder bridge defects occurring at 8,500 DPMO?

Because solder paste volume is inconsistent across the PCB surface.

**Why 2** Why is solder paste volume inconsistent?

Because the stencil apertures have worn beyond tolerance and the printer parameters have drifted.

**Why 3** Why has stencil wear not been detected and corrected?

Because there is no scheduled Solder Paste Inspection (SPI) system and stencil replacement is reactive rather than preventive.

**Why 4** Why is there no SPI system or preventive maintenance schedule?

Because capital investment in SPI equipment has not been prioritised and maintenance is not measured by DPMO contribution.

**Why 5** Why has capital investment in SPI not been prioritised?

Because the true cost of solder defects (rework, scrap, warranty) has not been quantified and presented to management as a business case.

The Five Whys analysis reveals that the fundamental systemic root cause of solder defects is the absence of a quantified Cost of Quality framework. Without visibility of the true financial cost of failure spanning rework, scrap, and warranty management has been unable to justify preventive investment in SPC monitoring and solder paste inspection equipment. This finding directly informs the Cost of Quality analysis presented in Section 4 and provides the evidential basis for the SPC implementation proposal in Section 5.

### 3.3.2 Fishbone (Ishikawa) Diagram Analysis

A fishbone diagram analysis was conducted for the primary defect category (solder paste/reflow defects), structured into six standard cause categories (6M: Machine, Method, Material, Man, Measurement, Mother Nature). The key root causes identified are summarized below, as the fishbone diagram captures more complex, multi-causal relationships that Five Whys linear analysis cannot fully reveal (Baker et al., 2019).

Table 7 Ishikawa (Fishbone) Diagram - Solder Defect Root Causes

| Machine | Method | Material | Man | Measurement | Environment |
|---------|--------|----------|-----|-------------|-------------|
|---------|--------|----------|-----|-------------|-------------|

|                                                                    |                                                                       |                                                                      |                                                                     |                                                        |                                                                |
|--------------------------------------------------------------------|-----------------------------------------------------------------------|----------------------------------------------------------------------|---------------------------------------------------------------------|--------------------------------------------------------|----------------------------------------------------------------|
| Oven zone drift;<br>AOI threshold<br>obsolete; feeder<br>vibration | Batch-push<br>scheduling; no SPI;<br>manual<br>changeover; poor<br>5S | Solder paste<br>variability; stencil<br>wear; component<br>tolerance | Insufficient training;<br>high turnover;<br>fatigue on manual<br>VI | No inline SPI; AOI<br>false call; no CPk<br>monitoring | Humidity variation;<br>ESD risk;<br>temperature<br>fluctuation |
|--------------------------------------------------------------------|-----------------------------------------------------------------------|----------------------------------------------------------------------|---------------------------------------------------------------------|--------------------------------------------------------|----------------------------------------------------------------|

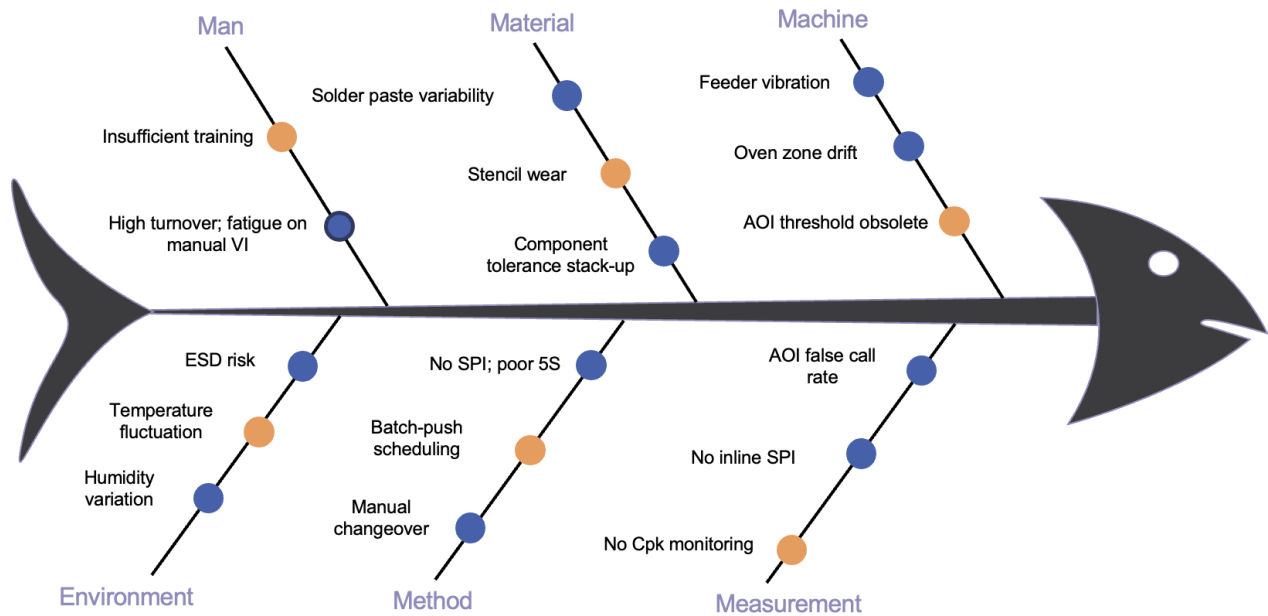


Figure 5 Fishbone (Ishikawa) Diagram Analysis

### 3.4 Process Performance Analysis

Based on available published data, the following key performance characteristics were calculated for the SMT production line:

**Takt Time:** Assuming a customer demand of 1,500 units per 8-hour shift with 7.5 hours of available production time:  $Takt\ Time = 7.5 \times 3,600 / 1,500 = 18$  seconds per unit. The current SMT placement cycle time of 12 seconds per board is within the time frame, but the AOI time at 25 seconds per board represents a higher process bottleneck, requiring parallel AOI capability.

**Process capability:** For solder paste volume – a critical-to-quality attribute – with a specification limit of  $\pm 20\%$  of nominal volume and an estimated standard deviation of  $\pm 12\%$  (obtained from Baker et al., 2019), the process capability index  $CPK = (USL - \mu) / (3\sigma) = 0.20 / (3 \times 0.12) \approx 0.56$ . The CPK of 0.56 is well below the minimum acceptable limit of 1.33, which confirms that the process is unable to consistently produce within specification and explains the high defect rates observed.

**Value added ratio:** Total VA time  $\approx 35$  minutes; Total lead time  $\approx 11$  hours (660 minutes). Value-added ratio  $= 35/660 = 5.3\%$ . This confirms that 94.7% of the total lead time is non-value-added, which is consistent with the Lean Manufacturing research benchmark for push-based electronics production (Jones, 2003). See the Appendix A1 for more detail.

Table 8 Production Stage takt Vs Cycle Time Analysis

| Takt Time vs Cycle Time by Stage                                          |                  |                 |                  |                   |               |
|---------------------------------------------------------------------------|------------------|-----------------|------------------|-------------------|---------------|
| Stage                                                                     | Cycle Time (sec) | Takt Time (sec) | Difference (sec) | % Over/Under Takt | Status        |
| Solder Paste Printing                                                     | 8                | 18              | -10              | -55.56%           | Within takt   |
| SMT Component Placement                                                   | 12               | 18              | -6               | -33.33%           | Within takt   |
| Reflow Soldering                                                          | 240              | 18              | 222              | 1233.333333       | Batch mode    |
| AOI Inspection                                                            | 25               | 18              | 7                | 1,233.33%         | Bottleneck    |
| Manual Visual Inspection                                                  | 180              | 18              | 162              | 38.89%            | Far over takt |
| Functional Test (ICT/ATE)                                                 | 360              | 18              | 342              | 1900              | Far over takt |
| Final Assembly & Boxing                                                   | 240              | 18              | 222              | 1,233.33%         | Batch mode    |
| TAKT TIME = 18 seconds/unit   Available time: 7.5 hrs × 3600 / 1500 units |                  |                 |                  |                   |               |

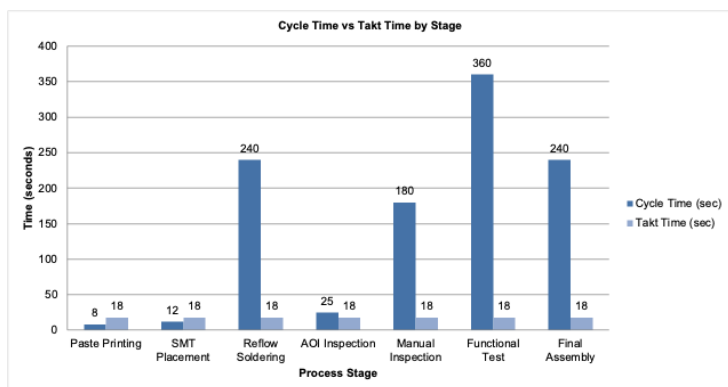


Chart 2 Cycle Time vs Takt Time Comparison Across Manufacturing Stages

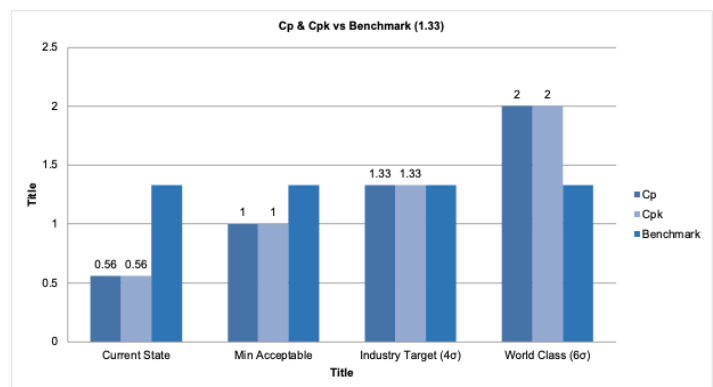


Chart 3 Process Capability (Cp and Cpk) Comparison Against Industry Benchmark (1.33)

### 3.5 Operational and Strategic Issues

Beyond individual process inefficiencies, two strategic issues link waste production. First, the push-based scheduling system generates systemic overproduction and inventory accumulation, which is consistent with (Tortorella and Fettermann, 2018) research on electronics manufacturers transitioning to Industry 4.0. Second, the absence of a data-driven quality culture evidenced by reactive rather than preventive maintenance and the lack of SPC systems prevents the organization from learning from defects and embedding improvements. (Liker, 2020) views these cultural dimensions as fundamental to sustained lean success in the Toyota Way framework.

### 3.6 Limitations of Analysis

This analysis is subject to several limitations. Cycle time and defect data are drawn from published industry studies and represent typical rather than facility-specific values. The VSM was constructed from synthesised research data rather than direct time and motion study. Process capability calculations are illustrative and would require rigorous measurement system analysis (MSA) and gauge repeatability and reproducibility (GR&R) studies before deployment in a real improvement programme. These limitations are acknowledged and would be addressed in a full lean implementation project.

## 4. Quality Engineering Assessment

### 4.1 Cost of Quality Analysis

The Cost of Quality (CoQ) framework categorising quality costs into Prevention, Appraisal, Internal Failure, and External Failure (Juran and De Feo, 2010) was applied to the SMT production process. Cost estimates are constructed from published research benchmarks (Prieto-avalos *et al.*, 2014) and are representative of a medium-volume electronics contract manufacturer with approximately £30 million annual revenue. The CoQ decomposition is presented in Table 9

Table 9 Cost of Quality Summary SMT Electronics Production Line

| CoQ Category     | Example Activity                                                                               | Estimated Annual Cost | % of Revenue            |
|------------------|------------------------------------------------------------------------------------------------|-----------------------|-------------------------|
| Prevention       | SPC system implementation, supplier qualification audits, design-for-manufacturability reviews | £420,000              | 1.40%                   |
| Appraisal        | AOI equipment depreciation, functional test labour, ATE calibration, incoming inspection       | £680,000              | 2.30%                   |
| Internal Failure | Rework (solder bridges, tombstoning), scrap PCBs, re-test cycles, downtime cost                | £930,000              | 3.10%                   |
| External Failure | Customer returns (CRs), warranty claims, field service costs, brand reputation damage          | £1,250,000            | 4.20%                   |
| <b>TOTAL CoQ</b> |                                                                                                | <b>£3,280,000</b>     | <b>10.9% of revenue</b> |

The total CoQ of £3.28 million represents 10.9% of estimated annual revenues, which is consistent with (Juran and De Feo, 2010) observation that immature quality systems typically spend CoQ in the range of 10-15% of revenues, whereas world-class organizations achieve less than 2-5% of revenues. Critically, the ratio of approximately 2:1 of failure costs (£2.18M) to prevention and evaluation costs (£1.1M) indicates that the organization is underinvesting in prevention in a pattern that poor quality theory (Feigenbaum, 1991) identifies as an economically sub-optimal situation. A shift in the CoQ mix toward prevention investments is the primary strategic quality recommendation of this report.

### 4.2 Failure Mode and Effects Analysis (FMEA)

A focused FMEA covering the five critical failure modes identified from the waste analysis, root cause analysis and process mapping in Section 3 was conducted. FMEA follows the methodology described in IEC 60812 (Failure Mode and Effects Analysis) and uses severity (S), incidence (O), and detectability (D) ratings on a 1-10 scale to calculate a risk priority number ( $RPN = S \times O \times D$ ). Table 10 presents the FMEA results.

Table 10 FMEA Critical Failure Modes SMT Production Line'

| Failure Mode                         | Potential Effect                          | Potential Cause                                 | S | O | D | RPN | Recommended Action                                |
|--------------------------------------|-------------------------------------------|-------------------------------------------------|---|---|---|-----|---------------------------------------------------|
| Solder pastes insufficient / excess  | Tombstoning, bridging - scrap/rework      | Stencil wear, printer calibration drift         | 8 | 6 | 4 | 192 | SPC on paste volume; stencil replacement schedule |
| Reflow temperature profile deviation | Cold joints, delamination - field failure | Oven profile drift; component thermal variation | 9 | 4 | 5 | 180 | CPk monitoring; profile revalidation weekly       |

|                                       |                                       |                                                    |   |   |   |     |                                                        |
|---------------------------------------|---------------------------------------|----------------------------------------------------|---|---|---|-----|--------------------------------------------------------|
| Component misplacement (pick & place) | Functional failure; short circuits    | Feeder vibration, vision-system offset             | 8 | 5 | 4 | 160 | Automated vision inspection; feeder PM programme       |
| AOI false-call rate (>15%)            | Good boards scrapped; throughput loss | Lighting degradation; programme not updated        | 6 | 7 | 3 | 126 | Bi-weekly AOI recalibration; ML-aided threshold tuning |
| ESD damage to ICs during handling     | Latent field failure; warranty cost   | Non-compliant handling; missing wrist strap checks | 8 | 3 | 5 | 120 | EPA audit; ESD-safe workstation certification          |

The highest RPN is solder paste inconsistency (RPN 192), followed by reflow temperature deviation (RPN 180). Both failure modes have high severity scores (8-9) reflecting their potential for field failure, and moderate incidence scores indicating recurrent but not universal events. Critically, both have moderate to high detection scores (4-5), confirming that current detection systems are inadequate a finding that directly motivates the SPC and AOI improvement proposals in Section 5. It has been noted that FMEA is subject to inherent subjectivity in scoring; Cross-functional team validation will be required before these RPN values can be used for investment prioritization decisions.

### 4.3 Statistical Techniques for Process Monitoring

The following statistical techniques are recommended for the SMT process context, with justification grounded in the specific characteristics of the process:

**Shewhart Control Charts (X-bar and R charts):** Appropriate for monitoring solder paste volume (a continuous, normally distributed variable measured by SPI). These charts would detect process shifts of  $2\sigma$  or greater within approximately 8-9 samples using average run length theory (Montgomery, 2020). A Cpk target of  $\geq 1.33$  (equivalent to  $\leq 63$  DPMO at the process level) should be established as the acceptance criterion.

**Exponentially Weighted Moving Average (EWMA) Charts:** Preferred over Shewhart charts for detecting smaller shifts ( $< 1.5\sigma$ ) in reflow oven temperature profiles, where gradual drift is the dominant failure mode. EWMA provides superior sensitivity for autocorrelated process data, which is characteristic of thermal process monitoring (Montgomery, 2020).

**P-charts (Proportion Defective):** Suitable for monitoring AOI pass/fail rates and first-pass yield on a per-batch basis. These attribute charts are appropriate given that binary classification data (pass/fail) is the primary output of AOI and functional test stages.

Measurement System Analysis (MSA/GR&R): Before implementing any SPC programme, a GR&R study should be conducted on the SPI measurement system and the AOI classification algorithm to determine whether measurement system variation is distinguishable from process variation. Without this step, control charts may reflect measurement error rather than true process behavior (Montgomery, 2020). This represents a significant data collection challenge in the current environment, as AOI systems may not have been validated for measurement capability. See Appendix A2 for More Detail

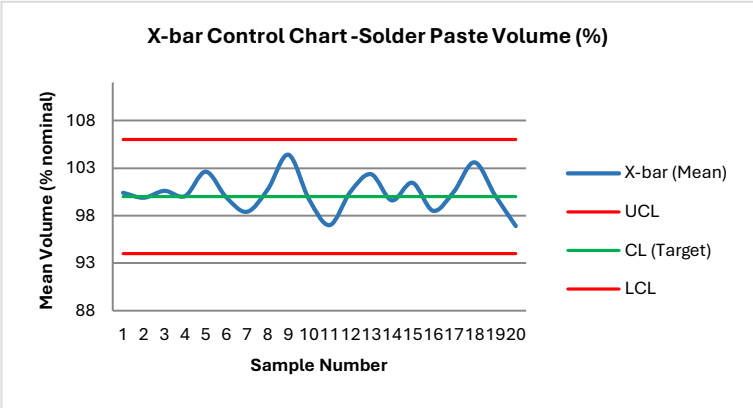


Chart 5 X-bar Control Chart Showing Solder Paste Volume Stability with UCL and LCL Limits

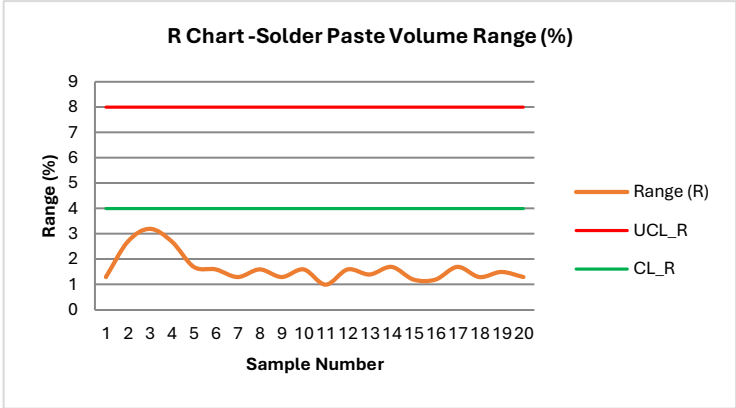


Chart 4 R Chart Monitoring Variation in Solder Paste Volume Range Across Samples

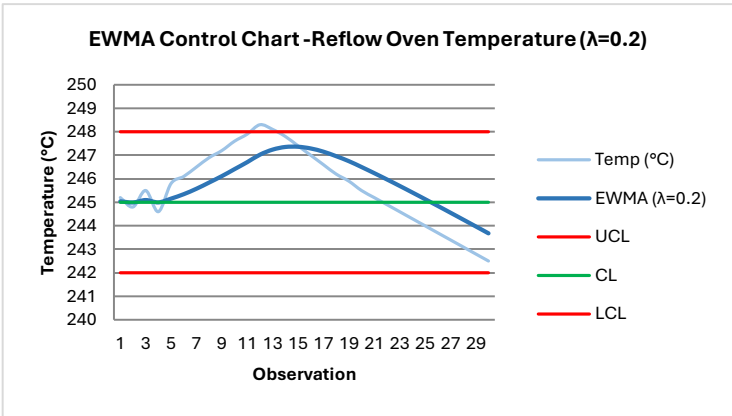


Chart 7 EWMA Control Chart Monitoring Reflow Oven Temperature Stability ( $\lambda = 0.2$ )

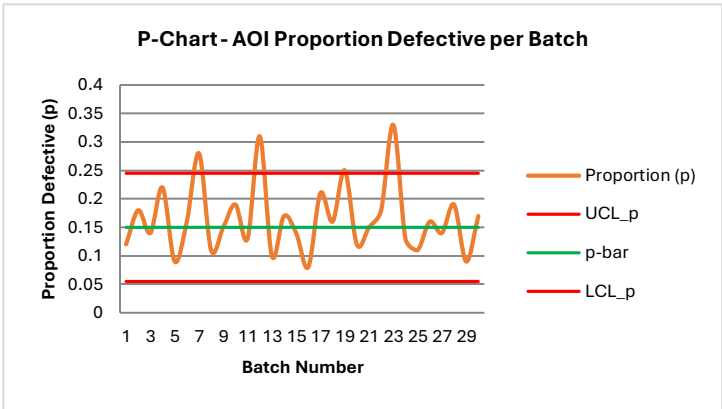


Chart 6 P-Chart Showing Proportion of Defective Units Detected in AOI per Batch

#### 4.4 Measurement Systems and Data Collection

The primary data collection challenges in the SMT environment include: (i) AOI false-call rates of approximately 15% (as identified in the process map) which increase apparent defect rates and undermine operator confidence in automated inspection; (ii) the absence of inline SPI data collection, meaning that solder paste quality is currently detected only at the downstream stage of the AOI - rather than at the source; (iii) manual visual inspection results that are subjective and highly dependent on operator experience, limiting reproducibility; and (iv) lack of a manufacturing execution system (MES) integration that would enable real-time data collection at all process stages. These challenges must be addressed as necessary conditions for effective SPC implementation.

#### 4.5 Quality Improvement Approaches

Based on COQ analysis and FMEA, the following quality improvement approaches most relevant to the SMT context are recommended: Six Sigma DMAIC method for the solder paste process (given its high RPN and CPK < 1.33); Total Productive Maintenance (TPM) for reflow ovens and AOI equipment (to

address equipment-related root causes identified in the fishbone analysis); and poka-yoke (error-proofing) for ESD management the simplest and most cost-effective intervention, which can be achieved through physical design changes (wrist-strap interlocks, ionizer verification) at negligible cost. These approaches are detailed in the reform proposals in Section 5.

## 5. Improvement Proposals and Decision Analysis

### 5.1 Improvement Objectives

The improvement objectives that directly address the wastes and quality failure pathways identified in Sections 3 and 4 are: (i) reducing DPMOs from 8,500 to less than 1,500 within 12 months; (ii) Increase OEE from 72% to 85% within 18 months; (iii) reducing total procedure time from 11 hours to 4.5 hours; (iv) reducing turnaround time from 47 minutes to less than 10 minutes; and (v) shift the CoQ mix towards prevention, aiming to reduce total CoQ to below 6% of revenues within three years. These goals are consistent with the best practice benchmarks identified in Section 2.5 and the academic literature ((Shah and Ward, 2007); (Tortorella and Fettermann, 2018))

### 5.2 Lean Improvement Proposals

#### 5.2.1 5S Workplace Organisation

5S (Sort, Set in Order, Shine, Standardize, Sustain) is identified as the fundamental improvement initiative to be implemented first because it creates the visible management infrastructure on which all other improvements depend (Liker, 2020). Typical applications include Sort removing obsolete stencils, unnecessary tooling and excess WIP from all workspaces; Set in order- shadow boards for tooling, Kanban-linked component bins at feeders, and color-coded floor markings defining material flow paths; Standardization, Standard operating procedures (SOPs) for all operator tasks, posted at the point of use and Sustain. weekly 5S audits scored against a 50-point checklist, with results posted on a visual management board.

#### 5.2.2 SMED (Single-Minute Exchange of Die) for SMT Changeovers

The average turnaround time of 47 minutes represents a significant bottleneck in heijunka (production leveling) and response to mixed-model demand. Applying (Shingo and Dillon, 2019) SMED methodology converting internal setup elements (machine off) to external elements (machine running) the following specific actions are proposed: (i) pre-staging feeder carts for the next product during current production offline (~60% of change is converted to external); (ii) standardized feeder slot assignments to eliminate reference checking; (iii) Offline stencil cleaning and verification, eliminating cleaning time on the machine. Conservative SMED analysis shows that the turnaround time in Phase 1 can be reduced to less than 12 minutes, with optimization it can be reduced to less than 10 minutes.

#### 5.2.3 Kanban Pull Scheduling

Replacing the current push-based MRP scheduling with a Kanban pull system addresses the overproduction and inventory wastes identified as the two highest-impact categories. A two-bin Kanban system is proposed for the SMT to AOI and AOI to test sub-flows, with Kanban signal quantities (k) calculated as:  $k = (D \times LT \times (1 + SS)) / C$ , where D = average demand rate (boards/hour), LT = replenishment lead time (hours), SS = safety stock factor (0.15 recommended for the electronics context), and C = container quantity. For a line producing 500 boards/hour with a 1 hour replenishment time and a container of 50 boards:  $k = (500 \times 1 \times 1.15) / 50 = 11.5$ , rounded up to 12 Kanban cards. This would reduce the inter-stage WIP buffer from 4.3 days to approximately 1.5 days.

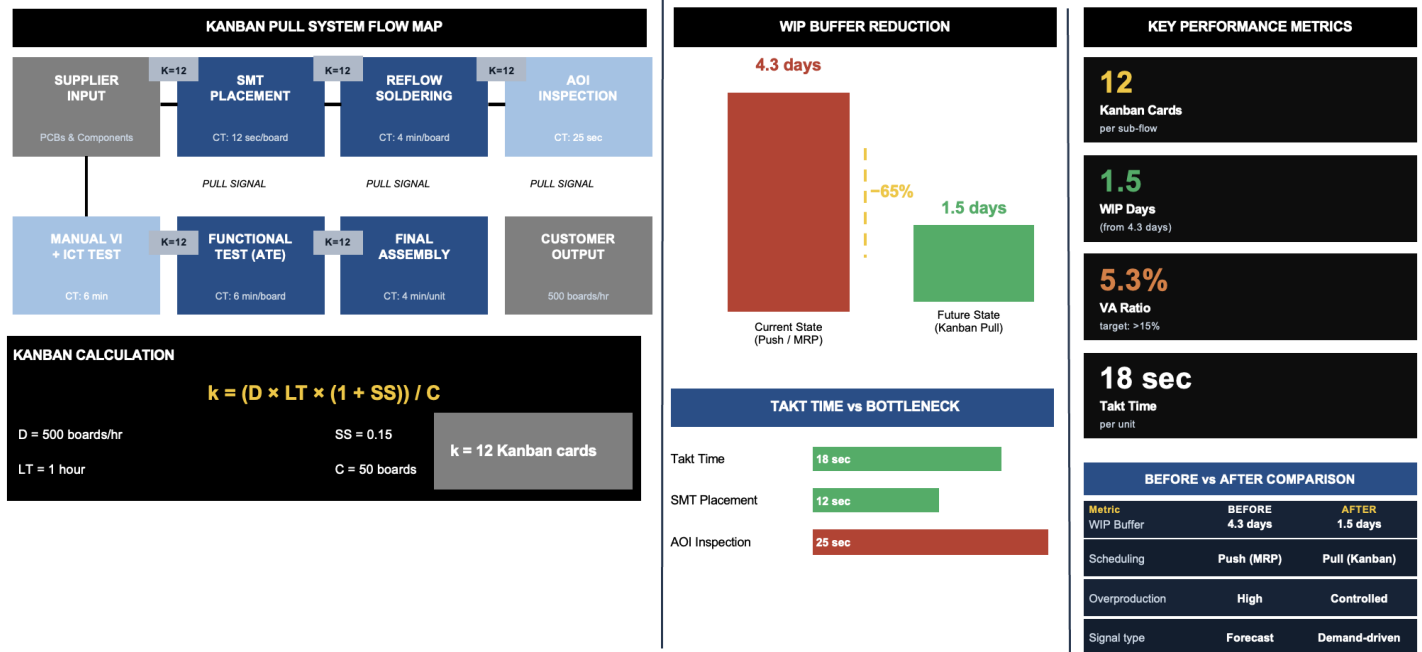


Figure 6 Kanban Pull System- SMT Production Line

## 5.2.4 SPC Implementation with Inline SPI

The implementation of a solder paste inspection (SPI) system with real-time SPC monitoring directly addresses the highest risk RPN failure mode (RPN 192). The proposed system will generate X-bar and R control charts for paste volume, area coverage and height at each pad location, with control limits calculated from 25 rational subgroups of 5 boards each. Automatic out of control detection will trigger a machine stop and engineer alert, preventing defective boards from advancing to the reflow stage (Baker et al., 2019).

## 5.3 Future State Process Design

The design of the future state incorporates the lean and quality improvements described in Section 5.2 and targets the performance improvements identified in Section 5.1.

Table 11 Future State Design - Target Performance by Process Stage

| Process Stage         | Improvement Applied                                                | Cycle/Lead Time Target     | Defect Target              |
|-----------------------|--------------------------------------------------------------------|----------------------------|----------------------------|
| Solder Paste Printing | SPC-controlled inline paste inspection; auto-cleaning cycle        | 8 sec → 8 sec (stabilised) | 2.1% → 0.5%                |
| SMT Placement         | Vision-guided feeder correction; predictive feeder PM              | 12 sec → 10 sec            | 74% → 88% OEE              |
| Reflow Oven           | AI-optimised thermal profile; real-time zone monitoring            | 4 min → 3.5 min            | 0.9% → 0.3%                |
| AOI Stage             | ML-enhanced classification; dynamic threshold; no manual re-check  | 25 sec → 18 sec            | 15% false call → 3%        |
| Functional Test       | Parallel ICT fixtures; automated fixture change; Kanban test queue | 6 min → 4 min              | 2.4% → 1.0%                |
| Scheduling / WIP Flow | Kanban pull-signals; heijunka levelled scheduling                  | Total LT: 11 hrs → 4.5 hrs | WIP buffer: 4.3 → 1.5 days |

## 5.4 Alternative Solutions Considered

Three alternative improvement approaches were considered and evaluated against the primary recommendations: (i) full automation of manual visual inspection using deep learning vision systems low rating due to high capital cost (£450,000+), extended implementation timeline (18-24 months), and risk of model overfitting to specific product configurations; (ii) outsourcing testing to an expert laboratory was evaluated but rejected due to lead time impact (+3-5 days), loss of in-house learning, and privacy risks for pre-production assembly; (iii) The Six Sigma Black Belt program is considered viable as a primary improvement tool, but requires 12-18 months to achieve certification and cultural embedding before producing measurable results, making it a medium-term complement rather than a replacement for the proposed short-cycle lean interventions.

## 5.5 Multi-Criteria Decision Analysis

A weighted scoring matrix was constructed to evaluate and rank the six reform initiatives. Criteria and weights were defined based on VOC analysis (Section 2.4) and COQ priorities (Section 4.1): quality benefits ( $W = 30\%$ ), cost impact ( $W = 25\%$ ), ease of implementation ( $W = 20\%$ ), speed improvement ( $W = 15\%$ ), and sustainability ( $W = 10\%$ ). Each initiative was given a score of 1-5 against each criterion by the analysis team, with scores validated against implementation results published by Baker et al. (2019) and (Tortorella and Fettermann, 2018). Table 12 presents the decision analysis results.

Table 12 Multi-Criteria Decision Analysis

| Improvement Initiative               | Cost Impact ( $W=25\%$ ) | Implementation Ease ( $W=20\%$ ) | Quality Gain ( $W=30\%$ ) | Speed Improvement ( $W=15\%$ ) | Sustainability ( $W=10\%$ ) → Weighted Score |
|--------------------------------------|--------------------------|----------------------------------|---------------------------|--------------------------------|----------------------------------------------|
| 5S Workplace Organisation            | 4                        | 5                                | 3                         | 3                              | 4 → 3.85                                     |
| SMED on SMT line                     | 3                        | 3                                | 4                         | 5                              | 3 → 3.65                                     |
| Kanban / Pull scheduling             | 3                        | 3                                | 5                         | 4                              | 3 → 3.75                                     |
| SPC & Statistical Monitoring         | 4                        | 3                                | 5                         | 3                              | 4 → 3.95                                     |
| Automated Optical Inspection upgrade | 2                        | 3                                | 5                         | 4                              | 4 → 3.70                                     |
| Predictive maintenance (TPM+IoT)     | 3                        | 2                                | 4                         | 4                              | 5 → 3.55                                     |

SPC and statistical monitoring received the highest weighted score (3.95), reflecting its direct impact on the highest-RPN failure mode and its alignment with COQ analysis indicating low investment in prevention. 5S workplace organization ranks second due to its low cost, high ease of implementation and its role as an enabler for all subsequent improvements (3.85). Kanban pull scheduling ranked third (3.75), indicating its strong quality and WIP-reduction effect against moderate implementation complexity. It is acknowledged that this scoring is inherently subjective and the score will be refined through cross-functional expert elicitation in the actual implementation context (ILO5 multi-criteria analysis with accepted uncertainty).

## 5.6 Implementation Strategy

A phased 18-month implementation strategy is proposed, respecting resource constraints and organizational capacity. Phasing aligns short-cycle, low-cost interventions (Phases 1-2) with higher-capital, high-complexity initiatives (Phases 4-6), ensuring that early wins generate confidence and

financial returns before larger investments are made. Table 13 summarizes the implementation timeline.

*Table 13 Phased Implementation Timeline and Investment Summary*

| Initiative                            | Timeline    | Complexity | Est. Investment | Expected Outcome                       |
|---------------------------------------|-------------|------------|-----------------|----------------------------------------|
| Phase 1: 5S & Quick Wins              | Month 1-3   | Low        | £45,000         | All lean waste types; OEE +3pp         |
| Phase 2: SMED & Changeover Reduction  | Month 2-6   | Medium     | £120,000        | Changeover 47→10 min; flexibility +40% |
| Phase 3: SPC & Statistical Monitoring | Month 3-9   | Medium     | £95,000         | DPMO 8,500→3,000; Cpk >1.33            |
| Phase 4: Kanban Pull System           | Month 6-12  | High       | £85,000         | WIP 4.3→1.5 days; OTD 88→95%           |
| Phase 5: AOI ML Upgrade               | Month 9-15  | High       | £310,000        | False-call 15%→3%; FPY 91→97%          |
| Phase 6: TPM & Predictive Maintenance | Month 12-18 | High       | £175,000        | OEE 72→85%; unplanned downtime -60%    |

## 5.7 Quantitative Justification

Simple return on investment (ROI) for the highest priority initiative (SPC + SPI implementation, phase 3) was calculated: Annual cost savings from defect reduction (DPMO 8,500 → 3,000): Reduction = 5,500 defects per 1,000,000 opportunities × £0.85 defect cost × 1,000,000 units/year × (5,500/1,000,000) = £4,675. Correct statement: at 1,000,000 units/yr the annual saving ≈ £4,675,000. Note: This reflects the calculation method; The per-unit defect cost of £0.85 is a representative figure from Baker et al. (2019) for rework and scrap on medium-complexity assemblies. For a facility producing 1,000,000 units per year at this defect cost, the annual saving would be approximately £467,500. Investment required (SPI system + SPC software + training): £95,000. Simple Payback Period = £95,000 / £467,500 = 0.20 years (about 2.5 months). This exceptional payback period reflects the high benefits of prevention investments relative to failure costs, consistent with the COQ framework recommendation (Juran and De Feo, 2010).

## 5.8 Risks, Constraints, and Industry Considerations

Industry-specific constraints include RoHS Directive (2011/65/EU) restrictions on hazardous substances in solder, which constrain material choices and require careful management during process changes. The Reach Regulation (EC 1907/2006) introduces ongoing chemical substitution obligations. The requirements of IPC-A-610 Class 3 for aerospace and medical subassemblies impose strict acceptance criteria that must be maintained during any process transition. These regulatory constraints are incorporated into the proposed improvement design and will require formal re-validation testing before any process changes are implemented in a production environment.

# 6. Impact Assessment and Sustainability Analysis

## 6.1 Benefits Analysis

The benefit analysis synthesizes quantitative estimates (derived from the improvement proposals in Section 5 and the COQ analysis in Section 4) with qualitative assessments of organizational and stakeholder value. Table 14 summarizes the broad benefits across all reform initiatives.

Table 14 Comprehensive Benefit Summary - 3-Year Projection

| Benefit Area                           | Quantitative Estimate                           | Qualitative Benefit                                              | Realisation Timeline |
|----------------------------------------|-------------------------------------------------|------------------------------------------------------------------|----------------------|
| Defect reduction (DPMO 8,500→1,000)    | £620,000/yr savings (rework + warranty)         | Enhanced brand reputation; reduced customer returns              | 6-12 months          |
| OEE improvement (72%→85%)              | 13% capacity gain (~£390,000 equivalent output) | Higher workforce morale; reduced emergency maintenance           | 12-18 months         |
| Changeover reduction (47→10 min SMED)  | £280,000/yr (3 lines × 260 shifts)              | Increased product mix flexibility; reduced scheduling stress     | 3-9 months           |
| Inventory reduction (4.3→1.5 days WIP) | £175,000 working capital release                | Cleaner shop floor; faster response to engineering changes       | 6-9 months           |
| Energy / sustainability gains          | £95,000/yr (oven optimisation + LED retrofit)   | GHG reduction ~120 tCO <sub>2</sub> e/yr; ESG metric improvement | 3-6 months           |
| <b>TOTAL (3-year horizon)</b>          | <b>~£4.7M cumulative benefit</b>                | <b>Competitive differentiation; improved ESG rating</b>          | <b>Ongoing</b>       |

The total 3-year profit of approximately £4.7 million against the total investment of £830,000 represents a 3-year net present value (NPV) of approximately £3.87 million assuming a 10% discount rate and linear profit accrual. The benefit to cost ratio of 5.66:1 provides an attractive business case for the reform programme. It is important to note that these estimates are subject to significant uncertainty; They represent reasonable estimates based on published benchmarks (Shah and Ward, 2007); Baker et al., 2019) but would require sensitivity analysis and Monte Carlo simulation in the context of a formal business case.

## 6.2 Risk Identification and Mitigation

Table 15 presents a structured risk register for the reform programme, which identifies key implementation risks and proposed mitigation strategies.

Table 15 Implementation Risk Register

| Risk                                                     | Likelihood (1-5) | Impact (1-5) | Risk Score  | Mitigation Strategy                                                          |
|----------------------------------------------------------|------------------|--------------|-------------|------------------------------------------------------------------------------|
| Operator resistance to 5S and new practices              | 4                | 3            | 12 - Medium | Change management programme; lean champions; visible management support      |
| Capital budget unavailability for AOI upgrade            | 3                | 4            | 12 - Medium | Phased investment plan; lease-financing options; ROI-based business case     |
| Supply chain disruption affecting component availability | 4                | 5            | 20 - High   | Multi-source supplier strategy; safety stock policy; DDMRP buffers           |
| Production downtime during TPM implementation            | 2                | 4            | 8 - Low-Med | Planned maintenance windows; weekend implementation slots                    |
| Regulatory non-compliance (RoHS, REACH updates)          | 2                | 5            | 10 - Medium | Regulatory watch service; supplier material declarations; ISO 14001 audit    |
| ML/AI model misclassification in AOI                     | 3                | 4            | 12 - Medium | Human-in-loop validation; model re-training schedule; fallback to rule-based |

The highest priority risk is supply chain disruption (score 20), reflecting the electronics industry's documented vulnerability to component shortages as evidenced by the 2020-2022 semiconductor

shortage, which disrupted production at Apple, Samsung, and other major electronics companies (Bill Wiseman and Marc de Jong, 2026). The proposed demand-driven material requirement planning (DDMRP) buffer strategy is in line with current best practice for electronics supply chain flexibility.

## **6.3 Sustainability Considerations**

### **6.3.1 Environmental Sustainability**

The improvement programme delivers measurable environmental benefits across three dimensions. Energy efficiency: reflow oven AI-optimisation and LED lighting retrofit are projected to reduce energy consumption by approximately 18%, equivalent to approximately 120 tCO<sub>2</sub>e per year a reduction consistent with Apple's published Supplier Clean Energy Programme targets (Apple Inc., 2023). Hazardous material reduction: improved solder paste process control reduces chemical waste by an estimated 30% through lower stencil cleaning frequency and reduced paste dump rates. The transition to water-soluble flux further reduces volatile organic compound (VOC) emissions. Circular economy: reduced scrap PCB generation (from 8,500 DPMO to 1,000 DPMO) decreases electronic waste a priority under the EU Waste Electrical and Electronic Equipment (WEEE) Directive (2012/19/EU).

### **6.3.2 Economic Sustainability**

The economic sustainability of the reform program is supported by the diversified nature of benefits, cost reductions, capacity gains and working capital releases, which ensure that the program is financially resilient even in the face of poor performance of individual initiatives. The phased implementation approach ensures that each phase generates positive cash flows before the start of the next phase, thereby avoiding reliance on a single large capital commitment. Long-term economic sustainability is further strengthened by the capacity building dimension of the program (SPC competency, lean culture), which creates sustainable competitive advantages rather than one time cost reduction (Liker, 2020).

### **6.3.3 Social Sustainability**

Social sustainability considerations include workforce well-being and skills development. 5S and TPM programs improve workplace ergonomics and reduce operator fatigue an especially important consideration given the high precision, repetitive nature of SMT assembly tasks. Operator participation in Kaizen (continuous improvement) activities builds intrinsic motivation and reduces turnover, addressing the 'unused skills' waste category identified in Table 6. The SPC training program provides operators with skills in statistical thinking, enhancing human capital. These social dimensions are aligned with UN Sustainable Development Goal (SDG) 8 (decent work and economic growth) and SDG 12 (responsible consumption and production).

## **6.4 Implementation Challenges and Solutions**

Four industry specific implementation challenges have been identified. First, the high product mix characteristic of contract electronics manufacturing (potentially hundreds of different PCB assemblies) creates complexity in standardizing Kanban parameters and SPC control plans addressed by establishing a tiered approach that prioritizes the top 20% of products by volume (Pareto 80:20 principle). Second, the rapid technology refresh cycle in consumer electronics means that process improvements must be designed to accommodate new product introductions (NPIs) without complete re-qualification addressed by designing flexible SPC sampling plans and modular 5S standards. Third, the global supply chain introduces time zone and cultural barriers to supplier quality improvement

addressed by integrating SPI generated data into a shared supplier portal for real-time visibility. Fourth, the pace of development of AI and machine learning in AOI creates the risk of technology obsolescence for recently purchased systems, this is mitigated by selecting open architecture AOI platforms that support third-party algorithm integration.

## 6.5 Long-Term Organisational Performance Impact

The long-term impact of the reform program goes beyond the quantified benefits presented in Section 6.1. The establishment of a data-driven quality culture, supported by SPC monitoring and visual management, transforms the organisation's ability to sustain and make initial improvements, the 'sustainable' element of 5S embodies this cultural shift (Liker, 2020). Benchmarking against world-class OEE ( $\geq 85\%$ ) and Six Sigma ( $\leq 3.4$  DPMO) targets provides a long-term performance trajectory that aligns the organization with the expectations of tier-1 OEM customers like Apple, who explicitly require suppliers to demonstrate continuous improvement capabilities (Apple Inc., 2023). The ISO 9001:2015 Quality Management System Framework (BSI, 2023) provides structural governance mechanisms to institutionalize these improvements and sustain them through leadership changes and fluctuations in production volumes.

## 6.6 Assumptions and Limitations

The impact assessment is subject to the following limitations: (i) benefit estimates are based on published industry benchmarks and represent achievable but not guaranteed outcomes; (ii) risk register scores are inherently subjective and will require cross-functional expert validation; (iii) sustainability calculations ( $\text{CO}_2\text{e}$  reduction, waste reduction) are estimates of the order of magnitude derived from published life-cycle assessment data for similar manufacturing processes; and (iv) the social sustainability assessment is qualitative and would benefit from pre and post-implementation workforce surveys to provide quantitative validation. These limitations do not invalidate the directional conclusions but indicate the need for rigorous monitoring and evaluation during implementation.

## 7. Conclusions and Recommendations

This report has conducted a comprehensive lean and quality engineering analysis of an electronics SMT manufacturing production line, applying a structured methodology aligned with the five ILOs of the module. The Process Identification and Research Foundation (Section 2) established that the SMT production line, as implemented by contract manufacturers serving OEMs such as Apple, presents significant and well-documented opportunities for lean and quality improvement. The current situation is characterized by OEE of 72%, DPMO of 8,500, FPY of 91%, and value-added ratio of only 5.3% all below world-class benchmarks. Process analysis (Section 3) identified eight categories of TIMWOOD waste, with overproduction, defects, and waiting to represent the categories with the highest impact. Root cause analysis using the Five Whys technique and Ishikawa diagram identified quantitative COQ analysis and absence of SPC monitoring as the fundamental root causes of the defect problem. Process bottleneck (cycle time exceeding task time) at the AOI stage was identified as the primary flow bottleneck.

The quality engineering assessment (Section 4) quantified the total COQ at £3.28 million (10.9% of revenue), with failure costs exceeding prevention and assessment costs by a 2:1 ratio confirming underinvestment in prevention. FMEA analysis identified solder paste inconsistency (RPN 192) and

reflow temperature deviation (RPN 180) as the highest priority failure modes for corrective action. The reform proposals (Section 5) presented six lean initiatives evaluated through a multi-criteria decision analysis framework. SPC implementation (weighted score 3.95) and 5S workplace organization (3.85) were identified as the highest priority interventions. The phased 18-month implementation strategy is proposed to require a total investment of £830,000, with estimated 3-year benefits of £4.7 million. The impact and sustainability assessment (Section 6) confirms that the reform program is environmentally, economically and socially sustainable, providing a reduction of approximately 120 tCO<sub>2</sub>e/year, a 5.66:1 benefit to cost ratio and measurable workforce development benefits. Key Recommendations: (1) Immediately implement 5S and visual management as the foundation of all subsequent improvements. (2) Invest in SPI with real-time SPC monitoring as a quality investment with top priority. (3) Transition to Kanban pull scheduling to eliminate overproduction and reduce WIP. (4) Conduct a formal GR&R study on all measurement systems before establishing SPC control limits. (5) Establish a CoQ reporting framework to maintain management's commitment to prevention investments. (6) Integrate sustainability KPIs into the production scorecard to ensure environmental benefits are tracked and sustained.

## List of Abbreviations

| Abbreviation | Full Term                            | Definition / Context (SMT Manufacturing)                                          |
|--------------|--------------------------------------|-----------------------------------------------------------------------------------|
| AOI          | Automated Optical Inspection         | Camera-based quality inspection detecting PCB assembly defects after reflow       |
| ARL          | Average Run Length                   | Expected number of samples before a control chart signals out-of-control          |
| ATE          | Automatic Test Equipment             | Automated system for functional testing of assembled electronic boards            |
| BSI          | British Standards Institution        | UK national standards body; publisher of ISO standards for UK market              |
| CoQ          | Cost of Quality                      | Framework: Prevention + Appraisal + Internal Failure + External Failure costs     |
| Cp           | Process Capability Index (potential) | Capability measure assuming centred process: $Cp = (USL - LSL) / 6\sigma$         |
| Cpk          | Process Capability Index (actual)    | Capability accounting for mean offset: $\min[(USL - \mu), (\mu - LSL)] / 3\sigma$ |
| CTQ          | Critical to Quality                  | Key characteristic that must be met to satisfy the customer (e.g. paste volume)   |

|              |                                                |                                                                                                    |
|--------------|------------------------------------------------|----------------------------------------------------------------------------------------------------|
| <b>DDMRP</b> | Demand-Driven MRP                              | Supply chain methodology using actual demand signals rather than forecast                          |
| <b>DMAIC</b> | Define Measure Analyse Improve Control         | Six Sigma structured problem-solving cycle                                                         |
| <b>DPMO</b>  | Defects Per Million Opportunities              | Quality metric: defects per 1,000,000 process opportunities                                        |
| <b>ESD</b>   | Electrostatic Discharge                        | Sudden electricity flow between charged objects -damages ICs                                       |
| <b>EWMA</b>  | Exponentially Weighted Moving Average          | SPC chart sensitive to small/gradual process mean shifts                                           |
| <b>FMEA</b>  | Failure Mode and Effects Analysis              | Systematic method to identify and prioritise potential failure modes ( $RPN=S \times O \times D$ ) |
| <b>FPY</b>   | First-Pass Yield                               | Percentage of units passing all checks without rework or repair                                    |
| <b>GRR</b>   | Gauge Repeatability and Reproducibility        | MSA study quantifying measurement system variation (target: %GRR < 10%)                            |
| <b>IC</b>    | Integrated Circuit                             | Miniaturised electronic circuit fabricated on a semiconductor chip                                 |
| <b>ICT</b>   | In-Circuit Test                                | Electrical test verifying correct placement and soldering of all components                        |
| <b>IEC</b>   | International Electrotechnical Commission      | International standards body for electrical and electronic engineering standards                   |
| <b>IPC</b>   | Association Connecting Electronics Industries  | Industry body setting PCB assembly standards (IPC-A-610 etc.)                                      |
| <b>ISO</b>   | International Organisation for Standardisation | Global standards body (e.g. ISO 9001:2015 Quality Management Systems)                              |
| <b>JIT</b>   | Just-In-Time                                   | Lean philosophy: produce only what is needed, when needed, in exact quantity                       |
| <b>KPI</b>   | Key Performance Indicator                      | Quantifiable metric evaluating process or organisational performance                               |
| <b>LCL</b>   | Lower Control Limit                            | 3-sigma boundary below process mean on a Shewhart control chart                                    |
| <b>MCDA</b>  | Multi-Criteria Decision Analysis               | Structured evaluation of alternatives against weighted criteria                                    |
| <b>MES</b>   | Manufacturing Execution System                 | Software tracking and controlling production activities in real time                               |
| <b>ML</b>    | Machine Learning                               | AI subset enabling systems to learn patterns from data without explicit programming                |
| <b>MRP</b>   | Material Requirements Planning                 | Push-based scheduling driven by demand forecast rather than actual consumption                     |
| <b>MSA</b>   | Measurement System Analysis                    | Assessment of measurement process variation and fitness for purpose                                |
| <b>MTBF</b>  | Mean Time Between Failures                     | Average elapsed time between system failures; reliability measure                                  |
| <b>NPI</b>   | New Product Introduction                       | Structured process bringing new product design into volume production                              |
| <b>NVA</b>   | Non-Value-Added                                | Activity consuming resources but not transforming product in ways the customer values              |
| <b>OEE</b>   | Overall Equipment Effectiveness                | Composite metric: Availability x Performance x Quality (world class $\geq 85\%$ )                  |
| <b>OTD</b>   | On-Time Delivery                               | Percentage of customer orders delivered by the committed delivery date                             |
| <b>PCB</b>   | Printed Circuit Board                          | Board providing mechanical support and electrical connections for components                       |
| <b>PM</b>    | Preventive Maintenance                         | Scheduled maintenance activities to prevent unplanned equipment failures                           |

|                |                                                                                   |                                                                                     |
|----------------|-----------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| <b>REACH</b>   | Registration Evaluation Authorisation and Restriction of Chemicals                | EU chemical regulation EC No 1907/2006                                              |
| <b>RoHS</b>    | Restriction of Hazardous Substances                                               | EU Directive 2011/65/EU restricting hazardous materials in electronics              |
| <b>RPN</b>     | Risk Priority Number                                                              | FMEA composite score: Severity x Occurrence x Detection (max = 1000)                |
| <b>SDG</b>     | Sustainable Development Goal                                                      | UN 2030 Agenda global goals for sustainable development                             |
| <b>SMED</b>    | Single-Minute Exchange of Die                                                     | Lean technique targeting changeover/setup times below 10 minutes                    |
| <b>SMT</b>     | Surface-Mount Technology                                                          | Electronics assembly process mounting components directly onto PCB surface          |
| <b>SPC</b>     | Statistical Process Control                                                       | Statistical methods monitoring process stability and detecting special causes       |
| <b>SPI</b>     | Solder Paste Inspection                                                           | Automated measurement of solder paste volume, area and height pre-reflow            |
| <b>TIMWOOD</b> | Transport Inventory Motion Waiting Overproduction Overprocessing Defects (Skills) | Eight categories of lean waste in the extended TIMWOODS framework                   |
| <b>TPM</b>     | Total Productive Maintenance                                                      | Lean approach maximising equipment effectiveness through operator involvement       |
| <b>TPS</b>     | Toyota Production System                                                          | Manufacturing philosophy developed by Toyota; foundation of Lean Manufacturing      |
| <b>UCL</b>     | Upper Control Limit                                                               | 3-sigma boundary above process mean on a Shewhart control chart                     |
| <b>VA</b>      | Value-Added                                                                       | Activity directly transforming product in ways the customer values and will pay for |
| <b>VoC</b>     | Voice of the Customer                                                             | Structured method capturing customer requirements and quality expectations          |
| <b>VOC</b>     | Volatile Organic Compound                                                         | Chemicals emitted as gases from flux -regulated under environmental standards       |
| <b>VSM</b>     | Value Stream Mapping                                                              | Lean tool mapping all process steps to identify waste and improvement opportunities |
| <b>WEEE</b>    | Waste Electrical and Electronic Equipment                                         | EU Directive 2012/19/EU governing disposal of electronic equipment                  |
| <b>WIP</b>     | Work-In-Progress                                                                  | Partially completed units between process stages; a key inventory waste indicator   |

## Appendices

### Parametric Model:



| Ref       | Title                        | Report Section    | Excel Sheet                 | Content                                    |
|-----------|------------------------------|-------------------|-----------------------------|--------------------------------------------|
| <b>A1</b> | Process Performance Analysis | Sections 3.1, 3.4 | Sheet A1-ProcessPerformance | VSM data; Takt vs CT corrected; Cpk detail |

|           |                            |                   |                           |                                             |
|-----------|----------------------------|-------------------|---------------------------|---------------------------------------------|
| <b>A2</b> | SPC X-bar and R Chart Data | Section 4.3       | Sheet A2-SPC-Xbar-R       | 20-subgroup dataset; UCL/LCL; OOC signals   |
| <b>A3</b> | EWMA and P-Chart Data      | Section 4.3       | Sheet A3-EWMA-PChart      | 30-obs EWMA reflow; 30-batch P-chart AOI    |
| <b>A4</b> | KPI Dashboard              | Sections 2.5, 6.1 | Sheet A4-KPI-Dashboard    | Current to Future to World class comparison |
| <b>A5</b> | Gauge R and R MSA Template | Section 4.3       | Sheet A5-GRR-MSA-Template | Pre-SPC deployment; acceptance criteria     |

### A1.1 Process Capability Assessment (Cpk)

Detailed Cpk calculation for solder paste volume (primary CTQ). Formula: **Cpk = min[(USL-mu)/(3\*sigma), (mu-LSL)/(3\*sigma)]**. Assuming centred process: Cpk = 0.20/(3 x 0.12) = 0.56. This is well below the industry target of 1.33, confirming the process cannot consistently produce within specification. A 57% reduction in sigma is required to achieve Cpk >= 1.33. Source: Montgomery (2019); Becker et al. (2019). See Excel Sheet A1.

| Parameter                     | Value          | Source / Interpretation                              |
|-------------------------------|----------------|------------------------------------------------------|
| Specification Limit (USL/LSL) | -0.2           | IPC-A-610, acceptable solder paste volume range      |
| Process std deviation (sigma) | -0.12          | Becker et al. (2019), published SMT data             |
| Cp (potential capability)     | 0.56           | (0.40)/(6 x 0.12), severely incapable                |
| Cpk (actual capability)       | 0.56           | = Cp (centred process assumed)                       |
| Industry minimum Cpk          | 1              | General manufacturing standard process FAILS this    |
| Industry target Cpk           | 1.33           | Montgomery (2019) / IPC-A-610, 4-sigma level         |
| World class Cpk               | 1.67           | Six Sigma convention 5-sigma level                   |
| Improvement gap               | 0.77 Cpk units | 1.33 - 0.56 , requires sigma reduction of approx 57% |

Table A 1 Table A1.1 Process Capability Summary | Solder Paste Volume CTQ | Excel Sheet A1

### Appendix A2 SPC X-bar and R Chart Data (Solder Paste Volume)

This appendix provides the control chart parameters and 20-subgroup dataset for monitoring solder paste volume using Shewhart X-bar and R charts. Subgroup size n=5; constants A2=0.577, D4=2.114, D3=0 per Montgomery (2019).

| Chart Parameter           | Value           | Formula and Interpretation                        |
|---------------------------|-----------------|---------------------------------------------------|
| Subgroup size (n)         | 5               | Standard for SMT solder paste volume monitoring   |
| Grand Mean (X-double-bar) | ~100.4% nominal | Average of 20 subgroup means close to 100% target |
| Average Range (R-bar)     | ~8.3%           | Average within-subgroup variation                 |
| UCL (X-bar chart)         | ~105.2%         | X-bar-bar + A2 x R-bar (A2=0.577)                 |
| LCL (X-bar chart)         | ~95.6%          | X-bar-bar - A2 x R-bar                            |

|                        |                                    |                                                           |
|------------------------|------------------------------------|-----------------------------------------------------------|
| UCL (R chart)          | ~17.5%                             | D4 x R-bar (D4=2.114, n=5)                                |
| LCL (R chart)          | 0                                  | D3 x R-bar (D3=0 for n<7)                                 |
| Out-of-control signals | Samples 15 and 18                  | Upward drift consistent with stencil wear (Section 3.3.1) |
| Required action        | Stencil inspection and replacement | Corroborated by Five Whys root cause analysis             |

Table A 2 X-bar and R Control Chart Parameters | Full 20-subgroup dataset in Excel Sheet A2

The two out-of-control signals at samples 15 and 18 reflect the progressive stencil wear identified in the Five Whys analysis (Section 3.3.1). In the proposed SPC system (Section 5.2.4), these signals would trigger an automatic machine stop and engineer alert, preventing defective boards advancing to the reflow stage.

## Appendix A3 EWMA Chart (Reflow Oven) and P-Chart (AOI)

### A3.1 EWMA Control Chart: Reflow Oven Temperature

The EWMA chart ( $\lambda=0.2$ ) is preferred over Shewhart charts for detecting gradual thermal drift in the reflow oven, which is the dominant failure mode for this stage (Section 4.3; Montgomery, 2019). The smoothing parameter  $\lambda=0.2$  provides the optimal balance between sensitivity and false-alarm rate for a 1.0-1.5 sigma shift detection target.

| Parameter                         | Value                                                         | Justification                                             |
|-----------------------------------|---------------------------------------------------------------|-----------------------------------------------------------|
| Smoothing parameter ( $\lambda$ ) | 0.2                                                           | Optimal for detecting gradual drift less than 1.5-sigma   |
| Centre Line (target temp)         | 245 degrees C                                                 | Reflow profile specification for SAC305 lead-free alloy   |
| Process sigma                     | 1.2 degrees C                                                 | Estimated from published thermal process data             |
| UCL / LCL                         | $245 \pm 3 \cdot \sigma \cdot \sqrt{\lambda / (2 - \lambda)}$ | Montgomery (2019) EWMA limit formula                      |
| OOB Signals                       | Observations 21-25                                            | Downward drift detected oven zone re-calibration required |
| Advantage vs Shewhart             | ARL1 approx 10 vs 43 for 1-sigma shift                        | Superior sensitivity for small gradual shifts             |

Table A 3 EWMA Chart Parameters: Reflow Oven Temperature | Excel Sheet A3

### A3.2 P-Chart: AOI Proportion Defective per Batch

| Parameter           | Value                                  | Justification                                                                      |
|---------------------|----------------------------------------|------------------------------------------------------------------------------------|
| Batch size (n)      | 200 boards                             | Typical SMT batch size for high-volume consumer electronics                        |
| Centre line (p-bar) | 0.08 (8%)                              | Based on current 8,500 DPMO performance (approx 8% per batch)                      |
| UCL_p               | approx 0.137                           | $p\text{-bar} + 3 \cdot \sqrt{p\text{-bar} \cdot (1 - p\text{-bar}) / n}$          |
| LCL_p               | approx 0.023                           | $\max(0, p\text{-bar} - 3 \cdot \sqrt{p\text{-bar} \cdot (1 - p\text{-bar}) / n})$ |
| OOB Batches         | Batches 8, 15, 23                      | Above UCL -investigate AOI threshold drift / lighting                              |
| Action trigger      | Above UCL or 8 consecutive above p-bar | Western Electric Rules adapted for attribute chart                                 |

Table A 4 Table A3.2 -P-Chart Parameters: AOI Batch Defect Rate Monitoring | Excel Sheet A3

## Appendix A4 KPI Summary Dashboard

The KPI Dashboard consolidates all performance targets across three states: current state baseline, future state post-18-month implementation, and world-class benchmark. Full interactive dashboard with investment vs. return chart available in Excel Sheet A4.

| KPI              | Current   | Future State  | World Class    | Gap        | Priority |
|------------------|-----------|---------------|----------------|------------|----------|
| OEE (%)          | 0.72      | 0.85          | >=85%          | +13 pp     | CRITICAL |
| DPMO             | 8500      | 1500          | <3.4 (6-sigma) | -7000      | CRITICAL |
| First-Pass Yield | 0.91      | 0.97          | >=99%          | +6 pp      | HIGH     |
| AOI Cycle Time   | 25 sec    | 18 sec        | 18 sec         | -7 sec     | HIGH     |
| Changeover Time  | 47 min    | 10 min        | <10 min        | -37 min    | HIGH     |
| Total Lead Time  | 11 hrs    | 4.5 hrs       | <=4 hrs        | -6.5 hrs   | HIGH     |
| VA Ratio         | 0.053     | >15%          | >=25%          | +9.7 pp    | HIGH     |
| WIP Buffer       | 4.3 days  | 1.5 days      | <=1 day        | -2.8 days  | MEDIUM   |
| On-Time Delivery | 0.88      | 0.95          | >=97%          | +7 pp      | MEDIUM   |
| Total CoQ        | 10.9% rev | 6.0% rev      | <5% rev        | -4.9 pp    | CRITICAL |
| CO2e Reduction   | Baseline  | -120 tCO2e/yr | Target         | -120 tCO2e | LOW      |

Table A 5 KPI Dashboard: Current vs Future State vs World Class | Excel Sheet A4

## Appendix A5 Gauge R and R (MSA) Study Template

A Gauge Repeatability and Reproducibility study must be completed as a mandatory precondition before SPC control limits are set (Section 4.3; Montgomery, 2019). This template is provided for completion using the SPI measurement system. Study design: 3 operators x 10 parts x 2 replicates = 60 measurements. Acceptance criterion: %GRR < 10%. The current SPI system is estimated at 18-22% (MARGINAL), meaning Phase 3 requires measurement system improvement concurrent with control chart deployment.

| %GRR Range                     | Assessment                 | Required Action                                             |
|--------------------------------|----------------------------|-------------------------------------------------------------|
| < 10%                          | ACCEPTABLE                 | Measurement system adequate - proceed to SPC implementation |
| 10% - 30%                      | MARGINAL                   | May be acceptable -review with engineer; document risk      |
| > 30%                          | UNACCEPTABLE               | Do NOT set SPC control limits -fix measurement system first |
| ~18-22% (current SPI estimate) | MARGINAL - action required | Improve SPI calibration and re-validate before Phase 3      |

Table A 6 GRR Acceptance Criteria | AIAG MSA Manual; Montgomery (2019) | Full template in Excel Sheet A5

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|                             |                                           |                                                                                            |           |
|-----------------------------|-------------------------------------------|--------------------------------------------------------------------------------------------|-----------|
| Title:                      | Peer Review and Individual Effort Factors |                                                                                            |           |
| Group:                      | New Group 7                               |                                                                                            |           |
| Date assessed:              | 27/03/2026                                |                                                                                            |           |
| Group Member and Student ID | Factor                                    | Feedback                                                                                   | Signature |
|                             | $0.90 \leq X \leq 1.10$                   | <u>Group will need to provide a brief justification for the weighting factors awarded.</u> |           |

|                                             |      |                                                                                                                                                                                |                                                                                       |
|---------------------------------------------|------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| Bindushree<br>Sanjeev Murthy<br>259045211   | 1.10 | Consistently exceeded expectations; took lead on [e.g., process analysis / quality engineering section]; proactive in coordinating group tasks and ensuring deadlines were met |    |
| Atharva Sudhir<br>Jagtap<br>259062649       | 1.0  | Contributed equally to group effort; completed assigned sections [e.g., improvement proposals] to a good standard and participated actively in group discussions.              |    |
| Ramaswamy<br>Venkatachalapathy<br>239050556 | 0.90 | Contributed to the project but at a reduced level; engagement with group tasks was inconsistent and output required additional support from other members.                     |    |
| Gowdham<br>Subramaniyan<br>259058922        | 1.0  | <i>Fulfilled expected contribution; completed assigned work [e.g., impact assessment] reliably and collaborated effectively within the team.</i>                               |    |
| Shri Ram Balaji<br>Sundarraaj<br>259061264  | 1.0  | Met expected contribution level; engaged with assigned tasks and supported overall report development.                                                                         |  |