Jurnal Kejuruteraan 38(5) 2026: 2457-2468
https://doi.org/10.17576/jkukm-2026-38(5)-28

From Paper to Pixels: Improving RF Productivity with Digital Check Sheets and DMAIC

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Received 13 September 2025, Received in revised form 7 April 2026
Accepted 7 May 2026, Available online 30 August 2026

ABSTRACT

Manufacturing documentation often contributes to process inefficiencies, human error, and productivity constraints within the RF brazing workflow. This study aimed to improve manufacturing documentation at NGK Electronics Devices by replacing manual check sheets with a digital RF Brazing Checksheet System. Guided by the Lean Six Sigma DMAIC (Define, Measure, Analyze, Improve, Control) framework, the study adopted a mixed-methods approach involving observation, time tracking, and user feedback to evaluate the existing process. The main issues identified included lengthy documentation, inaccurate data entry, limited traceability, and inefficient retrieval of historical records. A digital check sheet incorporating autofill, field validation, and expiry alerts was subsequently developed and piloted over four weeks. Following implementation, form completion time decreased by more than 60%, error rates fell by over 80%, and technician workload was reduced. In addition, integrating real-time dashboards and feedback loops strengthened continuous improvement in line with Kaizen principles. The success of the system has prompted plans for broader deployment across additional product lines, including optical parts, as well as possible integration with digital work instructions (WORKI) to support fully paperless operations. The findings demonstrate that lean-driven digital transformation can modernize legacy documentation practices, improve data quality and accessibility, and enhance RF brazing throughput in manufacturing settings. This study also confirms the value of the DMAIC framework for designing, piloting, and sustaining digital interventions on the shop floor, resulting in measurable gains in accuracy, efficiency, and operator experience. Future work will evaluate cost savings, quality yield, and long-term sustainability metrics.

Keywords: Lean Six Sigma (LSS); Digital Transformation; Kaizen; Operational Excellence; DMAIC

INTRODUCTION

NGK Electronics Devices, Inc., a subsidiary of NGK Insulators, Ltd., is a mid-sized multinational producer of high-reliability ceramic packages and functional circuit boards used across automotive, telecommunications, and industrial electronics. Established in 1991 and headquartered in Yamaguchi, Japan, the company's portfolio spans ceramic materials, SMT chip packages, MEMS, Radio Frequency (RF) power devices, and functional circuit boards, supported by precision engineering and sustained R&D investment. Operating on a business-to-business model, NGK collaborates with tier-1 original equipment manufacturers to deliver durable, high-performance components. Within this context, NGK's Information Technology (IT) function has been advancing digital transformation by automating paper-based workflows through web-based solutions to improve efficiency, accuracy, and sustainability.

Despite advanced manufacturing capabilities, the RF brazing area relied heavily on manual checksheets for production documentation and control. Manual data entry contributed to spelling and transcription errors, inconsistent records, lengthy documentation cycles, and weak traceability, thereby impeding timely decision-making, reinforcing departmental silos, and increasing technician workload. These challenges mirror broader evidence that manufacturing digitalization efforts often fail to realize performance benefits when data capture remains fragmented, non-standardized, and weakly integrated with decision workflows (Sharma et al. 2024), and that quality management in the digital era increasingly depends on timely, shareable, and systematically structured operational data (Shim et al. 2025). Gaps in material tracking and quality control also intensified downtime and waste, reinforcing the need for connected, transparent process information flows aligned with Industry 4.0 priorities (Aziana et al. 2025; Babu 2025; Gomaa 2025; Vashishth et al. 2024).

Prior literature indicates that Lean Manufacturing (LM) techniques, such as poka-yoke, can reduce waste by approximately 10% (Suhaimi & Salleh, 2018), while digital Lean ("e-Lean") tools that embed mobile access and automation can increase efficiency by around 15% (Gomma 2025). More recent work further emphasizes that the digital transformation of Lean methods ("Lean 4.0") is an active research and practice area, yet organizations still face difficulties in operationalizing and managing digitally transformed Lean tools at scale (Schumacher et al. 2023). In parallel, the integration of Lean and Industry 4.0 is increasingly positioned as a route to improved operational performance through greater connectivity, visibility, and data-driven control (Costa et al. 2024).

Yet empirical studies that examine the design, deployment, and control of digital checksheets in high-reliability RF processes remain limited, particularly those that integrate Lean Six Sigma with Industry 4.0 enablers to deliver measurable gains in accuracy, traceability, and responsiveness. Recent syntheses show growing interest in aligning Industry 4.0 technologies (e.g., smart sensors, analytics, automation) with Lean Six Sigma DMAIC for stronger process improvement and control, while also highlighting that implementation roadmaps and validated task-level integration remain underdeveloped in many real industrial contexts (Pongboonchai-Empl et al. 2023).

This study addresses that gap by applying the Lean Six Sigma DMAIC (Define–Measure–Analyze–Improve–Control) framework across the end-to-end RF brazing manufacturing process, with the redesign of RF documentation and checksheets serving as the primary intervention to strengthen process control, traceability, and responsiveness at NGK. Specifically, we (i) document and analyze RF workflows to identify sources of inefficiency, variability, and waste; (ii) replace paper checksheets with a Lean-based, web-enabled digital checksheet system that embeds error-proofing, validation, and expiry alerts to reduce errors and workload while enhancing traceability; and (iii) institutionalize Kaizen-driven continuous improvement through real-time monitoring, feedback loops, and standardized reporting for root-cause analysis and process control consistent with quality's ongoing shift toward digitally enabled transparency and shared operational learning (Shin et al. 2025).

The resulting RF Brazing Checksheet System centralizes data capture and historical records, supports predictive maintenance signals, and provides dashboards for near-real-time visibility. By automating documentation and tightening process control, the system is designed to increase machine uptime, accelerate decision-making, and redeploy technician effort toward higher-value activities. These changes align with Lean principles (waste elimination, flow, built-in quality) and Industry 4.0 priorities (connectivity, transparency, and data-driven operations), which are increasingly discussed as complementary mechanisms when integration is explicitly modelled and operationalized (Costa et al. 2024; Schumacher et al. 2023). The initiative thus represents a shift from reactive, manual practices to proactive, digitized workflows. It offers a scalable blueprint for broader enterprise adoption beginning with RF manufacturing and extendable to adjacent product lines (e.g., optical components).

This paper makes three contributions. First, it provides an in-situ, DMAIC-based redesign of a legacy documentation process in RF brazing, detailing the design decisions and sociotechnical trade-offs of a digital checksheet solution. Second, it provides empirical evidence on operational outcomes relevant to high-reliability electronics manufacturing, including data accuracy, traceability, documentation time, and operator workload. Third, it distills implementation lessons for integrating Lean, Six Sigma, and Industry 4.0 in brownfield settings, including governance mechanisms that sustain gains via Control-phase routines.

The rest of the paper reviews related work on Lean digitalization and digital checksheets, explains the context and DMAIC methodology, details the system design and implementation, reports evaluation outcomes, and discusses implications, limitations, and future directions research.

RELATED WORK

Lean Six Sigma (LSS) and digital transformation have increasingly been positioned as complementary approaches for addressing inefficiencies rooted in manual processes, human error, and limited traceability in manufacturing. Recent studies indicate that integrating LSS with Industry 4.0 enablers such as connected data capture, analytics, and automation strengthens operational excellence by improving process capability, shortening cycle times, enhancing traceability, and accelerating corrective actions, especially when digital initiatives are structured around LSS problem-solving routines rather than implemented as standalone digitalization (Chiarini & Kumar 2021; Pongboonchai-Empl et al. 2023; Gomma 2025). This integration is particularly relevant for RF operations, where process consistency and data integrity are central to product reliability and compliance, and where the shift toward Quality 4.0 emphasizes the strategic value of digitized quality data and evidence-based control (Ranjith et al. 2022; Gomma, 2025). In such contexts, replacing paper-based documentation with a digital approach is not merely an administrative upgrade; it operationalizes real-time data availability, standardization, and traceable decision pathways that support continuous improvement and responsiveness (Komkowski et al. 2023; Pongboonchai-Empl et al. 2023).

LSS combines Lean's waste reduction with Six Sigma's defect minimization through the DMAIC (Define–Measure–Analyze–Improve–Control) roadmap. Contemporary LSS4.0 studies further emphasize that DMAIC remains a strong improvement architecture precisely because its measurement and control logic can be tightened by digital features such as automated validation rules, timestamps, audit trails, and connected dashboards, thereby reducing transcription errors and improving governance of process knowledge over time (Pongboonchai-Empl et al. 2023; Sordan et al. 2025; Themezhub, 2023). In parallel, Industry 4.0 technologies such as IoT connectivity and cloud platforms increasingly reinforce Quality 4.0 practices by enabling more reliable data capture, faster escalation, and evidence-based decision-making across functions (Oliveira et al. 2024; Rogala et al. 2024). Compared to broader programs such as TQM or JIT, DMAIC offers a targeted, metrics-driven mechanism that can be directly coupled with these digital affordances to sustain data-centric optimization and reinforce process control in precision manufacturing environments (Komkowski et al. 2023; Pongboonchai-Empl et al. 2023).

Empirical work on digitalizing manual workflows shows reductions in operator workload, improvements in data integrity, and gains in production reliability when automated checksheets enforce standardization and validation while providing immediate data access (Pongboonchai-Empl et al. 2023). IoT-connected dashboards further enable predictive maintenance and downtime reduction, fostering agile, information-rich shop floors—capabilities that are especially salient for RF manufacturing. Case-based evidence reports measurable benefits from LSS and digitalization, including defect reduction, cost savings, and quality improvements (Kumar et al. 2023), quality gains attributed to digital checksheets and productivity increases via Lean devices such as poka-yoke and line balancing (Farhan et al. 2018). Collectively, these results suggest the applicability of a combined LSS–digital approach to RF process efficiency and reliability, even as RF-specific, in-situ evaluations of digital checksheets remain comparatively scarce.

The broader LSS studies demonstrated benefits spanning shorter cycle times, improved OEE, higher customer satisfaction, safer workplaces, and stronger team member engagement outcomes that digital integration can further amplify by strengthening real-time visibility, coordination, and data-enabled decision-making in dynamic markets (Albliwi et al. 2015; Olayinka, 2021; Karim, 2025). Nonetheless, studies on LSS–digital (and Quality 4.0) implementation consistently show across a different spectrum, the insufficient leadership commitment, resistance to change, skills/training gaps, weak data architecture, and poor strategic alignment can limit impact or stall momentum (Pongboonchai-Empl et al. 2023; Dwivedy et al. 2025). Addressing these barriers typically requires visible executive sponsorship, structured capability building, robust data governance/architecture, and deliberate change management to institutionalize continuous improvement (Antony et al. 2022; Alsadi et al. 2025). Against these conditions, RF manufacturing provides a relevant context for examining how a DMAIC-guided digital approach to manufacturing documentation can translate established LSS principles into traceable, real-time, and sustainable process control.

METHODOLOGY

CONTEXT AND BASELINE PROCESS MAPPING (PRE-DIGITAL)

NGK's RF brazing area operated a manual, paper-based checksheet system spanning planners, MQC, operators, technicians, inspectors, and supervisors. Materials and lot data from the MCFrame (ERP) system were printed onto token cards and physically routed to the relevant roles. Technicians hand-entered production details; inspectors and supervisors verified and signed forms, which were then filed in cabinets. Direct observations and shadowing revealed systemic limitations: handwriting errors and skipped fields; manual expiry checks; manual ribbon-usage calculations; slow audit retrieval of archived records; lack of real-time visibility into lot status and material consumption; and a heavy dependence on the physical movement of token cards. Excel logs maintained by some roles were siloed and not integrated with enterprise systems. These findings informed the Define and Measure phases.

STUDY DESIGN: LEAN SIX SIGMA (DMAIC)

This study employed the Lean Six Sigma DMAIC (Define–Measure–Analyze–Improve–Control) framework to redesign RF documentation and control as follows:

1. Define. Problem statements and project scope were established based on baseline observations, and defect logs, with a focus on documentation accuracy, timeliness, traceability, and auditability. Key issues in RF documentation—manual entries, human errors, illegible handwriting, delayed reporting, and poor traceability—were identified. Usability testing confirmed user frustrations with time-consuming data entry, difficulty in interpreting handwritten data, and delays in retrieving past records. These findings established the scope: replacing paper checksheets with a digital system to automate data capture, standardize records, and enable real-time monitoring.

2. Measure. Baseline performance was quantified through time studies, error audits, simulated record retrievals, and user feedback sessions. Primary metrics included: (i) checksheet completion time; (ii) error frequency (incorrect/missing lot and expiry data, incomplete fields); (iii) expiry-control non-conformances; (iv) record-retrieval time for audits; and (v) qualitative usability feedback (workload, clarity, accessibility).

During the measure phase, baseline data were collected over a four-week observation period, extending beyond the initial two-week pilot described in the Improve phase. This longer window was deliberately selected to capture variation across multiple RF brazing shifts, production lots, and operator rotations, ensuring the baseline reflected real operating conditions rather than a short snapshot. In doing so, the four-week period provided coverage of multiple production cycles, incorporated differences in operator behaviours and documentation practices, reduced the risk of short-term observation bias, and enabled a more representative assessment of the manual system's baseline performance—thereby strengthening the robustness and generalizability of the findings.

Within this four-week measure phase window, several complementary assessments were conducted to establish a reliable baseline of the manual checksheet system. First, a time study directly measured the completion time of 60 manual checksheets during routine production (approximately 15 forms per week across different operators and shifts), capturing natural variation in technician experience, production complexity, and workload conditions. Second, an error audit was conducted on 100 randomly selected completed checklists from archived records over the same period, enabling quantification of error frequency and identification of recurring data-quality issues. To reflect the practical demands of supervisory traceability, 20 record-retrieval simulations were also carried out, timing how long it took to locate archived forms from physical filing cabinets under typical audit conditions. Finally, user perspectives were triangulated through shadowing, and usability sessions involving technicians, planners, MQC staff, supervisors, and engineers (n = 18 across roles), ensuring the baseline captured both measured performance and day-to-day operational realities.

1. Analyze. Root causes were identified using a fishbone (Ishikawa) analysis across the following categories: People, Machine, Method, Measurement, and Environment, complemented by the 5 Whys method. Recurrent causes included inconsistent handwriting, lack of standardized data rules, absence of in-process validation, fragmented data storage, and fragile paper archiving.

2. Improve. An interventional web-based RF Brazing Checksheet System was designed to address root causes through mandatory field validation, expiry alerts, auto-timestamps, dropdowns/autofill, user authentication with activity logs, centralized storage, and real-time dashboards for lot/material tracking.

3. Control. A sustainment plan defines KPIs, control charts/monitoring cadences, SOPs, role-specific work instructions, training, and feedback mechanisms to institutionalize gains and enable continuous improvement.

Prior to data collection, ethical and professional standards were maintained throughout the project. Access to confidential data was obtained through prior approvals, all findings were anonymized, and the system was designed to track process accuracy rather than personal information. Regular, structured engagement with technicians and IT supported usability, compliance, and integration readiness, enabling a user-driven design approach and facilitating uptake.

DATA COLLECTION

Data were gathered via: (i) time tracking documentation steps; (ii) error audits of completed checksheets; (iii) usage/expiry logs for compliance events; (iv) simulated audit retrievals to measure access latency; and (v) usability sessions (on-site observation) with technicians, MQC, supervisors, and engineers. A consolidated data dictionary defined each metric, its unit, sampling plan, and acceptance criteria. A summary of measures and methods, such as completion time/time study, error rate/error audit, expiry issues/log review, retrieval time/simulation, and observation notes, is presented in Table 1.

The observation was conducted through continuous shadowing of each key role technician, planner, MQC, material operator, supervisor, and engineer across two full production shifts (day and night) to capture how the manual check sheet workflow operated in real conditions. During shadowing, the team documented role-specific tasks, including technicians completing checksheets (often after production), planners printing and routing token cards, MQC manually verifying lot identity and expiry without alerts, and supervisors searching for past records for planning and approvals. In parallel, form-completion and record-retrieval activities were manually timed, and field notes were recorded on interruptions, double-handling of information, and movement/travel required to locate documents and coordinate across functions.

TABLE 1. Data Collection Method of RF Brazing Checksheet System

Parameter	Purpose	Method
Completion time	Identify documentation inefficiency	Time tracking
Error rate	Measure data quality	Error audit
Expiry tracking issues	Compliance gaps	Usage logs
Record retrieval time	Access delays	Simulated retrieval
Usability feedback	User experience	Testing sessions
Incomplete fields	Documentation completeness	Sheet audit

Throughout the data collection, the Measure phase showed major inefficiencies: forms took 8–12 minutes to complete, 25% contained errors, record retrieval exceeded 15 minutes, and manual expiry checks posed compliance risks. User feedback also highlighted handwriting issues, slow documentation, and difficulty accessing records, reinforcing the need for a digital solution.

Furthermore, the On-site observations during RF brazing shifts confirmed inefficiencies in the manual checksheet process. Roles such as technicians, planners, MQC staff, material operators, supervisors, and engineers were shadowed to study interactions with the paper system. Findings showed technicians often made rushed, handwritten entries post-production; MQC manually verified expiry without alerts; material operators duplicated data in isolated Excel files; and supervisors spent time searching for records. Using task timing, field notes, and on-site observation, it was recorded that form completion exceeded 10 minutes, retrieval of archived records took over 15 minutes, and about 25% of forms contained errors. Feedback highlighted handwriting issues, audit delays, and skipped expiry checks, reinforcing baseline inefficiencies and the need for digital transformation, leading into the Analyze phase.

The Analyze phase identified root causes of inefficiencies such as delayed documentation, frequent errors, poor traceability, and slow record retrieval in the manual checksheet process. Data showed form completion averaged 10 minutes, 25% contained errors, expired materials were used due to a lack of tracking, and record retrieval took up to 15 minutes. Fishbone and 5 Whys analysis were used to pinpoint these issues, as shown in Figures 1a and 1b.

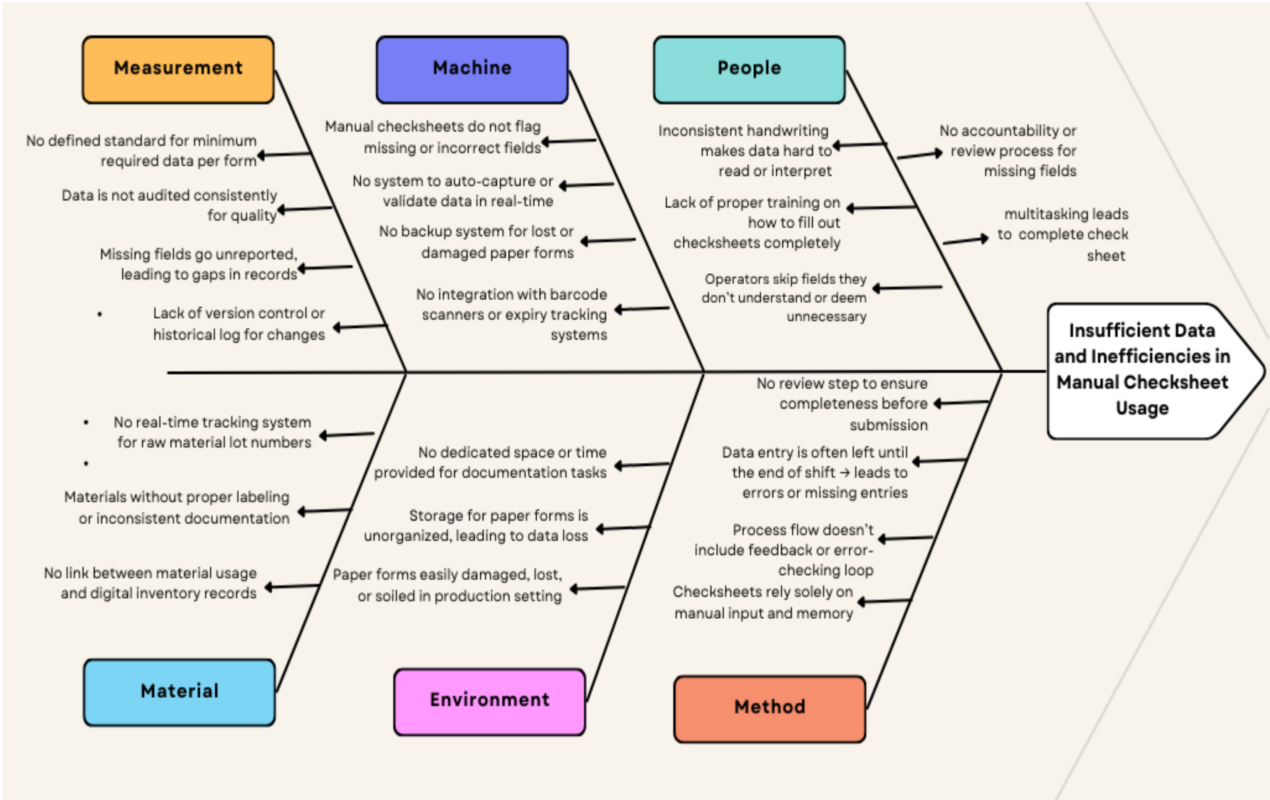

FIGURE 1a. Fishbone Diagram

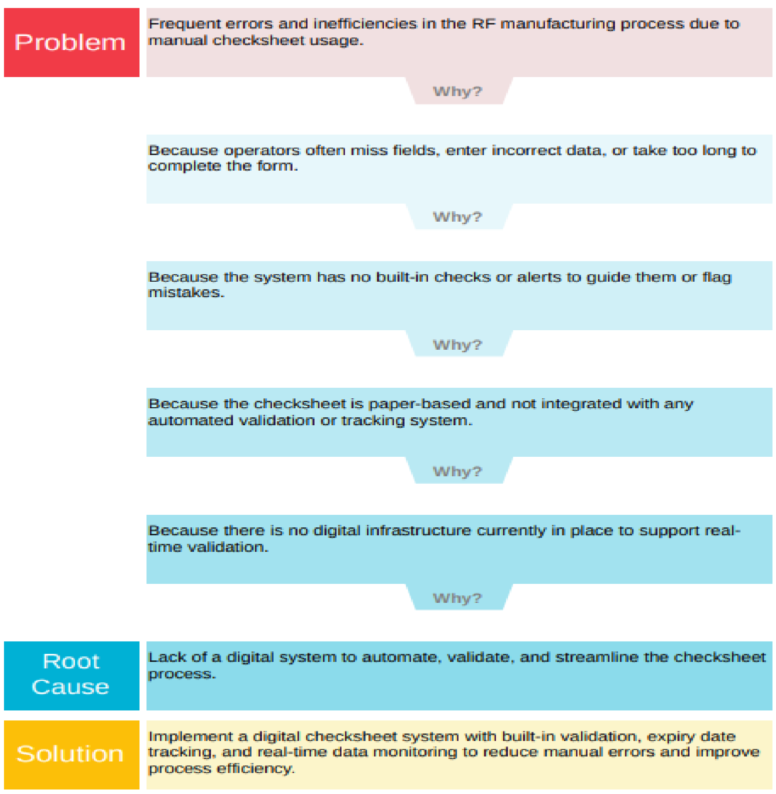

FIGURE 1b. 5 Whys Analyses

Figure 1a–1b presents fishbone diagrams mapping six root-cause categories: People, Machine, Method, Material, Measurement, and Environment, that drive inefficiencies in manual checksheets, including inconsistent handwriting, insufficient training, lack of real-time validation, process gaps, weak material tracking, missing data standards, and fragile paper storage. The 5 Whys analysis converges on a single core cause: the absence of a digital system to automate, validate, and streamline the checksheet process. Together, these analyses show the inefficiencies are systemic—spanning human, technical, and procedural factors—and underscore the urgency of a digital solution in the Improve phase.

INTERVENTION DESIGN AND IMPLEMENTATION (DIGITIZATION)

In the Improve phase, a digital checksheet system was implemented to address the identified root causes, eliminating errors, shortening documentation time, enhancing real-time monitoring, and strengthening traceability. Core features comprised mandatory field validation, expiry alerts, automatic timestamps, centralized storage, dropdowns/autofill, and user login tracking.

During a two-week pilot, the time to complete the form decreased from 10 minutes to under 4 minutes; data errors dropped by more than 80%; expiry alerts improved material traceability; and user feedback confirmed greater efficiency and reduced workload. An iterative feedback loop then introduced clearer field labels, quick-search functions, and user training. Together, these changes resolved the prior issues and established a foundation for continuous improvement aligned with Lean Six Sigma principles, preparing the project for the Control phase.

The Control phase ensured the sustainability of the improvements achieved in the Improve phase. Key strategies included training operators, supervisors, and quality staff for consistent system use, establishing a helpdesk for support, and developing Standard Operating Procedures (SOPs) for data entry, expiry handling, and verification. Performance was tracked using KPIs such as form completion time, data accuracy, and user activity, with weekly reviews for deviations and retraining needs. Monthly audits verified data integrity and compliance, while a built-in feedback form promoted continuous improvement. These measures embedded the digital checksheet into daily operations and reinforced its role in maintaining efficiency and traceability.

Therefore, digital transformation was necessary because manual systems could no longer meet the rising production demands. Inefficiencies, delays, and a lack of automation led to handwriting errors, poor traceability, and slow decision-making. Guided by Lean Six Sigma's DMAIC methodology, we developed a web-based RF Brazing Checksheet System with automated email alerts for expiries and verifications, real-time dashboards for material tracking, auto-calculations to eliminate errors, and centralised storage for instant retrieval. This system eliminates paper-based processes and improves audit readiness. The DMAIC phases—Define, Measure, Analyze, Improve, Control—systematically addressed each gap; fishbone and 5 Whys analyze informed solutions such as automated validation and expiry tracking. Pilot testing, user feedback, and ongoing audits provided the control mechanisms to sustain gains, demonstrating a low-risk, data-driven transformation aligned with Lean principles of waste elimination and continuous improvement.

RESULTS AND DISCUSSION

The Define, Measure, and Analyze phases documented the manual workflow, revealing inefficiencies: average form completion time of 8–12 minutes, ~25% error rate, and delayed record retrieval. Via Analysis phase in DMAIC, the root causes were traced to the absence of a digital system, highlighting human error, lack of validation, poor storage, and inconsistent data handling.

Baseline assessment of the manual checksheet from the audit of 100 archived manual checksheet showed substantial operational and data-quality gaps: each form required 8–12 minutes to complete; 25% of forms contained errors or missing information; there were no expiry alerts, leading to mistakes in identifying expired materials; audit retrieval relied on manual searches that took up to 15 minutes per form; and technicians reported repetition, illegible handwriting, and delays. Table 2 shows the specific error type and its description.

TABLE 2. Manual Checksheet error type and its description

Error Type	Percentage of Total Errors	Description
Missing Mandatory Fields	32%	Skipped lot numbers, ribbon batch codes, or expiry dates
Incorrect Lot/Material Entry	24%	Transcription errors from token cards
Expiry Misidentification	18%	Expired materials recorded as valid
Illegible Handwriting	15%	Data difficult to interpret during audits
Calculation Errors	11%	Manual ribbon usage miscalculations

Collectively, the baseline assessment of the manual checksheet system indicates excessive cycle time, elevated compliance risk, weak traceability, and low user satisfaction—together underscoring the need to replace paper-based checklists with a digital, validated, and traceable workflow. The observed error patterns point to systemic weaknesses rather than isolated mistakes: errors rose noticeably during high-workload shifts, particularly when end-of-day documentation backlogs accumulated; technicians often completed forms after production, increasing reliance on memory and recall-based entry errors; the absence of a standardized lot-number format led to inconsistent notation and reduced data integrity; expiry verification depended largely on visual inspection without alerts, heightening compliance exposure; and manual calculations introduced variability and avoidable arithmetic mistakes. Taken together, these issues reinforce that the manual process is structurally prone to delay, inconsistency, and preventable non-compliance, strengthening the justification for digitalization.

To explain why these issues persisted, the Fishbone (refer to Figure 1a) and 5 Whys analyses (refer to Figure 1b) traced the observed error patterns to a small set of root causes embedded in the manual workflow. In particular, the process lacked in-process validation, allowing incomplete or inconsistent entries to pass unchecked; it provided little automation to support calculations, expiry verification, or standardized formatting; it relied on fragmented data storage across physical folders, which weakened traceability and slowed retrieval; and it remained heavily dependent on handwriting and manual checking, increasing variability and making errors more likely under time pressure.

A Lean-based, web-enabled RF Brazing Checksheet system was developed to replace the manual, paper-based process with a centralized platform that improves efficiency, reduces errors, and provides real-time visibility. Informed by insights from the DMAIC Define and Measure phases, the system incorporates automated validations, expiry alerts, automatic time-stamping, and rapid record retrieval. In a two-week pilot, average form completion time fell from 10 minutes to under 4 minutes; data errors declined by more than 80% through validation logic; technician workload decreased by eliminating handwriting and manual checks; and real-time traceability improved, streamlining audits and reviews. Table 3 below summarizes the improvements achieved through the digital check sheet system.

TABLE 3. Comparison of key performance indicators before and after digital checksheet implementation

KPI	Manual System	Digital System	Improvement
Form-filling Completion Time	8–12 minutes	Less than 4 minutes	~60% faster
Data Entry Errors	~25% error rate	<5% error rate	80%+ error reduction
Technician Workload	High (repetitive writing tasks)	Lower (dropdowns, autofill)	Improved efficiency
Traceability & Record Access	Manual search (10–15 mins)	Instant digital access	Enhanced traceability
Expiry Tracking	Manual checking	Automated alerts	Reduced the risk of expired material use
User Satisfaction	Moderate	High (based on feedback survey)	Positive user experience

System digitization improved data handling, reduced manual workload, and enabled faster, more reliable decision-making, demonstrating how Lean digital tools can modernize manufacturing and align with Industry 4.0.

On a different note, Kaizen-driven continuous improvement used real-time data from the digital check sheet to improve RF manufacturing. Four reinforcing routines were implemented: (i) weekly data reviews, where supervisors tracked material delays, process issues, and equipment performance; (ii) system-log analysis, using validation flags and input-time metrics to identify recurring errors and bottlenecks; (iii) an in-app feedback form that enabled operators to report issues and suggest improvements immediately; and (iv) targeted training, with updated materials addressing common input errors and improving user proficiency. Together, these measures provided accurate, timely data for root-cause analysis, supported waste reduction, and strengthened decision-making. These measures reinforced Kaizen by using accurate data for root cause analysis, waste reduction, and ongoing process optimization. Kaizen principles were operationalized using real-time data from the digital check sheet to drive continuous improvement in RF manufacturing. The system enabled accurate data capture for root-cause analysis, waste reduction, and timelier, evidence-based decision-making. Post-implementation, it supported ongoing operational monitoring and performance reviews, and institutionalized weekly data reviews, system-log analysis, a digital feedback channel, and targeted training.

During a two-week pilot in the RF brazing area, technicians, planners, MQC staff, supervisors, and engineers used the system. At the same time, data on form completion time, error rates, traceability, and user feedback were captured through real-time observation, system logs, and post-observation analysis. Weekly tracking enabled trend analysis and iterative refinement, demonstrating the digital system improvements relative to the manual baseline. Table 4 highlights significant improvements in speed, accuracy, workload, and user satisfaction following the implementation of the digital checksheet system.

TABLE 4. Manual vs Digital Checksheet Performance Comparison (Key KPIs)

KPI	Manual Checksheet	Digital Checksheet	Interpretation
Form-filling Completion Time	12 minutes	4 minutes	Time to fill in one form
Data Entry Errors	25% error rate (per 100)	5% error rate	Error rate in submitted forms
Technician Workload	10 (high workload score)	4 (lower is better)	Effort rating (scale 1–10)
Traceability & Access	15 min (manual retrieval)	3 min (digital search)	Time to retrieve past records
Expiry Tracking	15 (risk/difficulty score)	3 (with alerts)	Score reflecting tracking difficulty
User Satisfaction	10	35	Feedback score based on user reactions

Eleven participants (mean age of 29 years) tracked KPIs on weekly dashboards and showed clear improvements in error rates and form-completion times. Data was collected over a four-week observation period (extended from the initial two-week pilot) involving technicians, planners, MQC staff, supervisors, and engineers. Real-time system logs, direct observations, and manual timing corroborated the digital system's positive impact. The error rate dropped from 25% to under 5%, driven by validation features, while the form completion time decreased from 10 minutes to under 4 minutes due to automation (see Figures 2 and 3).

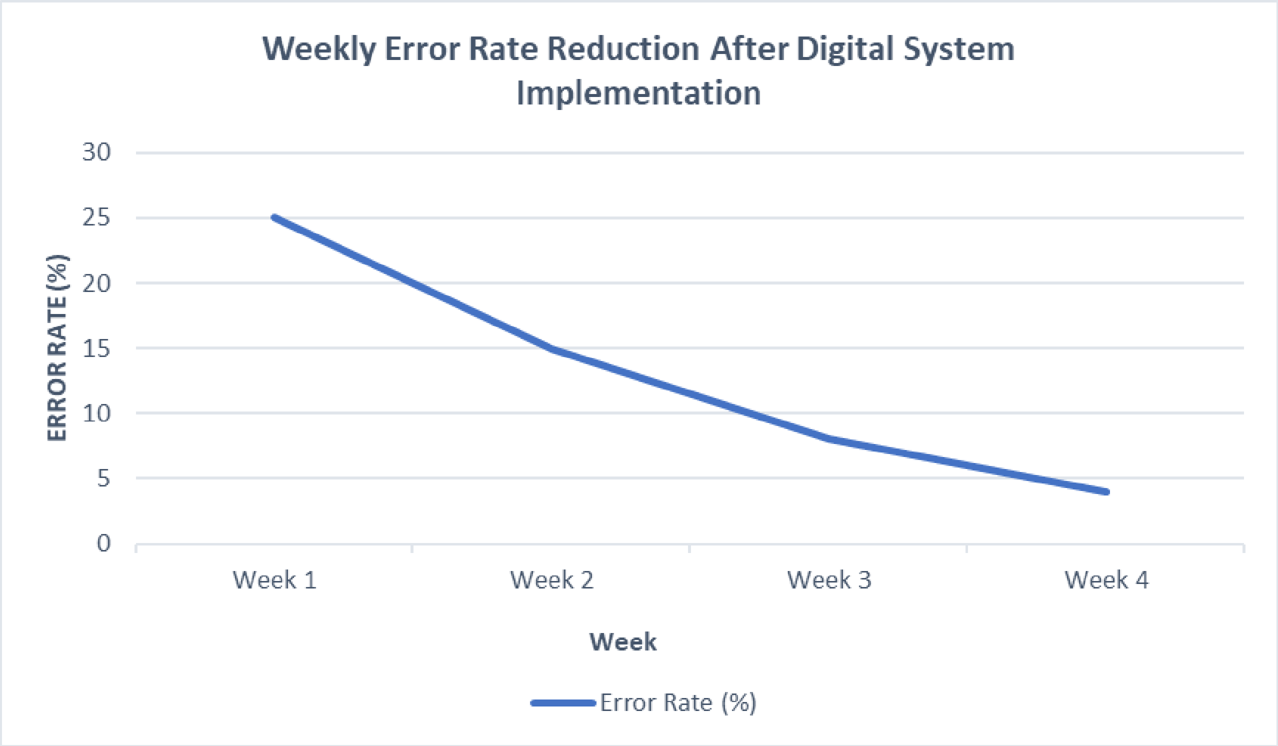

FIGURE 2. Error Rate Reduction

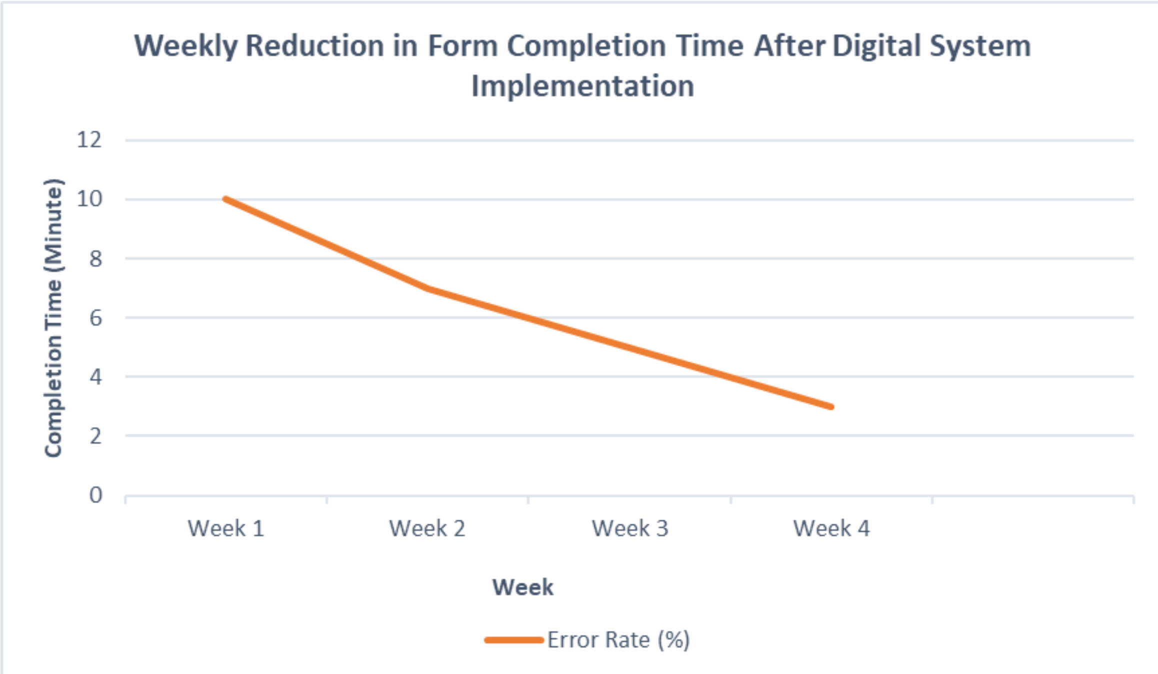

FIGURE 3. Form-filling Completion Time

Eleven participants (mean age of 29 years, mean Although the continuous improvement loop was initiated, realizing the full benefits of Kaizen will require longer observation windows and richer time-series data. Three constraints shaped the evaluation: limited time for trend analysis; a learning curve as operators adapted to the new system, which affected feedback consistency; and the inability to implement all user suggestions within the project timeframe. Even so, the project effectively leveraged system telemetry and user input to drive incremental improvements. While only partially achieved during the study period, sustained use, iterative releases, and periodic retraining are expected to further enhance quality, reduce waste, and support long-term operational excellence.

Empirical evidence from past studies consistently shows that manual, paper-based quality documentation is structurally prone to transcription variability, delayed verification, and weak traceability because records are often completed retrospectively, rely on handwriting, and lack systematic controls at the point of data capture. Few studies emphasize that Industry 4.0 performance gains come from connectivity, intelligence, and automation that enable reliable, real-time data capture and timely decision-making, rather than from fragmented, manually checked documentation (Vashishts et al. 2024; Sharma et al. 2024; Kaur, 2025). In line with this, "digitizing" paper into static digital forms may improve storage and retrieval, but it does not necessarily prevent omissions, inconsistent formats, or calculation mistakes. The stronger performance improvements reported for smart manufacturing solutions arise when digital systems embed standardized inputs, automation, and integrated data flows, such as RFID-enabled traceability and connected manufacturing architectures, thereby reducing reliance on human memory and manual inspection (Akinlabi et. al, 2020). Consistent with these principles, the RF Brazing Checksheet System is positioned as a validated and traceable workflow such as mandatory field checks, controlled input formats, auto-calculation, expiry alerts, and authenticated logging, which explains why the observed reductions in documentation time (~60%) and data-entry errors (>80%) are plausibly larger than what would be expected from paper redesign or basic form digitization alone.

In a nutshell, under the manual baseline, checksheet completion typically required 8–12 minutes per form, with an estimated ~25% data-entry error rate and 10–15 minutes needed to retrieve archived records, contributing to high technician workload due to repetitive handwriting and manual checking, and exposing compliance risk due to the absence of expiry alerts. After the implementation of RF Brazing Checksheet System, completion time improved by ~60–67% (from ~12 minutes to <4 minutes), error rates reduced by >80% (from ~25% to <5%), and record retrieval time improved by ~70–80% (from up to 15 minutes to <3 minutes). Technician workload was reduced by approximately ~60% through autofill, dropdown controls, and removal of repetitive writing, while expiry-related compliance risk was substantially reduced through automated alerts and validation.

Overall, the project outcomes align closely with prior work on Lean Six Sigma (LSS) and digital transformation, which argues that digitizing frontline quality routines strengthens standardization, data integrity, and decision speed—often translating into measurable quality and productivity gains (Albliwi et al. 2015; Dornelles et al. 2022). Consistent with Pongboonchai-Empl et al. (2023), who reported sizable quality gains from digitization, error rates in this study fell from 25% to <5%. The productivity improvements similarly echo prior Lean/standard-work evidence: pre-filled and digitized entries reduced checksheet completion time from 12 to 4 minutes, aligning with the broader view that digital tools can amplify Lean outcomes by reducing non-value-added effort and improving process visibility (Chavez et al. 2024; Farhan et al. 2018). Likewise, the reduction in record-retrieval time from 15 minutes to 3 minutes aligns with findings from past studies that faster access to reliable shop-floor data strengthens responsiveness and supports evidence-based problem-solving (Antony et al. 2023; Dornelles et al. 2022). Kaizen practices, which apply real-time data and rapid feedback, also mirror the wider LSS emphasis on iterative refinement anchored in measurement and learning cycles (Antony et al. 2017; Pongboonchai-Empl et al. 2023).

Implementation revealed practical constraints repeatedly highlighted in some studies, particularly resistance to change, capability gaps, and data/technology readiness issues (Albliwi et al. 2015; Alsadi et al. 2025; Shamsuzzaman et al. 2020). In this study, resistance to new tools was addressed through onboarding, train-the-trainer sessions, quick-reference guides, and in-UI tooltips; limited feedback participation was offset by weekly review meetings that encouraged verbal input; short data-collection windows were managed by prioritizing high-frequency metrics and proposing extended monitoring; policy restrictions were navigated by focusing on editable areas while documenting change requests for approval; and technical limits were bridged with pragmatic workarounds (e.g., tooltips, formatting) that simulated advanced features. Collectively, these mitigations reflect commonly recommended enablers such as visible sponsorship, deliberate change management, and structured capability building which are needed to institutionalize continuous improvement when Lean practices are digitally enabled (Alsadi et al. 2025; Antony et al. 2023; Shamsuzzaman et al. 2020).

CONCLUSION

Overall, this project shows that applying the Lean Six Sigma (LSS) DMAIC framework to NGK Electronics Devices' RF brazing documentation can effectively convert a manual, paper-based workflow into a digital, controlled process that addresses persistent inefficiencies in accuracy, cycle time, and traceability. The improvements were quantified: checksheet completion time decreased from 12 minutes to under 4 minutes, data errors dropped from 25% to under 5%, and record-retrieval time was reduced to under 3 minutes. These outcomes provide concrete evidence that Lean-guided digitalization can deliver immediate, measurable operational benefits in RF manufacturing contexts.

Beyond performance gains, this project highlights the conditions required to sustain such improvements. Change management anchored in training, practical job aids, and active user engagement helped mitigate resistance and reinforce a culture of continuous improvement. Root-cause techniques, including fishbone analysis and the 5 Whys, supported targeted interventions grounded in observed process failures rather than assumptions. Importantly, the solution was developed with scalability in mind: digitized work instructions and a structured data foundation position the organization for broader rollout, tighter process control, and future extensions such as deeper system integration and analytics-enabled Kaizen.

In sum, coupling LSS with digital checksheets improved efficiency, accuracy, and traceability while maintaining strong ethical safeguards and collaborative practice. Collectively, these capabilities strengthen RF process control today and provide a practical pathway toward sustained operational excellence and Industry 4.0 readiness.

ACKNOWLEDGEMENT

Authors would like to acknowledge Universiti Sains Malaysia for supporting this work.

DECLARATION OF COMPETING INTEREST

None.

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