Reducing Manufacturing Waste in the Copper Industry through Lean Six Sigma and Value Stream Mapping: An Industrial Case Study in Malaysia

Muhammad Khairul Rezwan Abdul Rahman[1], Nor Hayati Saad[2], Isnaiddy Dalisan[3]

[12]Faculty of Mechanical Engineering, Universiti Teknologi MARA, Shah Alam, Selangor, Malaysia

[3]Quality Department, Metrod (M) Sdn. Bhd., Malaysia

DOI: https://doi.org/10.47772/IJRISS.2026.101000749

Received: 25 October 2026; Accepted: 30 October 2026; Published: 17 November 2026

ABSTRACT

Continuous copper rod manufacturing is highly sensitive to upstream process instability, yet Lean Six Sigma research has rarely examined continuous metallurgical processes. This study evaluates the effectiveness of Value Stream Mapping (VSM) in reducing waste and enhancing operational performance in the upstream Continuous Casting and Rolling (CCR) process of a Malaysian copper manufacturer. An industrial case study was conducted using VSM as the primary analytical tool, supported by the Define, Measure, Analyse, Improve and Control (DMAIC) framework. SAP production records, including coil-by-coil rod reports, were cross-validated against SCADA data and shop-floor observations to map the current state, quantify value-added time, prioritise defects using Pareto and Ishikawa analyses, and evaluate Overall Equipment Effectiveness (OEE). Five targeted Kaizen interventions were implemented across the Loader, Melting Furnace, Casting Wheel, Rolling Mill and Coiler workstations. A comparison between the baseline (Week 10, 718 coils) and post-improvement (Week 41, 673 coils) periods revealed a statistically significant 17% relative reduction in the copper rod downgrade rate (31.34% to 26.00%; $p = 0.028$), alongside an increase in OEE from 63.49% to 67.58%, primarily driven by improved quality performance. The Future State VSM projected a 40% reduction in production process lead time, from 32.02 to 19.21 hours. Chemical-impurity downgrades decreased from 16.7% to 3.0% following material verification at the Loader, while pallet-related defects were eliminated at the Coiler. However, oxygen-, surface- and peeling-related defects increased. Based on copper prices and exchange rates matched to the respective assessment dates, the estimated 139.9 tonnes of weekly downgrades avoided represent an economic benefit of RM 0.15–0.30 million, after accounting for market price fluctuations. Given the single-site design, longer-term performance monitoring and multi-site validation are recommended.

Keywords: Value stream mapping, Lean Six Sigma, DMAIC, copper rod manufacturing, waste reduction

I. INTRODUCTION

A. Background of Continuous Copper Manufacturing

Continuous Casting and Rolling (CCR) is a widely adopted upstream process for copper rod production due to its high productivity, stable metallurgical characteristics, and suitability for large-scale electrical conductor manufacturing (Chia & Adams, 1981; Sachin & Dileeplal, 2017; Salwin et al., 2021; Sinha & Adams, 1993; Ware, 2007). In this process, copper cathodes are continuously melted, cast, hot-rolled, and coiled into 8 mm copper rods, which subsequently serve as feedstock for downstream rod breakdown and wire drawing operations. As the CCR process operates as an integrated and continuous system, any instability at upstream stages directly propagates to downstream product quality, process continuity, and delivery reliability. Despite advancements in automation, instrumentation, and process control, continuous copper manufacturing remains vulnerable to quality degradation associated with chemical impurity, oxygen concentration variation, and surface-related defects (Abdelwahed et al., 2024; Alexandrov et al., 2022; González et al., 2024; Haddi et al., 2011; Jones et al., 2021; Larsson et al., 2019; Liu et al., 2021). Metallurgical studies have demonstrated that

fluctuations in furnace atmosphere, molten metal handling, solidification conditions, and rolling stability significantly influence rod integrity and downstream drawability performance (Jones et al., 2021; Larsson et al., 2019; Liu et al., 2021). In addition, compliance with international technical standards such as ASTM B115, ASTM B49, and ASTM B3 imposes stringent constraints on process stability and operational flexibility, thereby intensifying the importance of systematic waste reduction and process control (ASTM International, 1995, 2010, 2017). Company A, the industrial case organization examined in this study, operates a CCR production line supplying copper rod to both domestic and export markets. Although the organization is certified under ISO 9001 and ISO 14001 quality and environmental management systems, internal production records extracted from the SAP system (System, Applications, and Products in Data Processing) indicate persistent operational and quality challenges. Historical trends of wire break incidents over a three-year period are summarized in Table 1, providing empirical motivation for the present investigation.

TABLE 1 Company A Wire Breaks Summary

Year	**2022**	**2023**	**2024**
No. of Wire Breaks	38 breaks	65 breaks	52 breaks

B. Problem Statement

Detailed analysis of Company A's CCR operations revealed three dominant performance gaps. First, manufacturing and production lead times were disproportionately extended by non-value-added activities, including waiting for quality clearance, internal material transfer delays, and asynchronous production confirmation within the SAP system (Nurhidayah et al., 2025). These delays contributed significantly to extended order fulfilment cycles despite relatively stable processing times. Second, copper rod downgrade rates consistently exceeded internal quality targets. SAP-based defect classification records identified chemical impurity, oxygen variation, and surface-related defects as the primary contributors to downgrade events. These quality losses resulted in material reclassification, rework, and yield reduction, negatively affecting downstream wire drawing operations. Third, Overall Equipment Effectiveness (OEE) values remained persistently below commonly referenced industrial benchmarks. Losses in availability, performance, and quality were observed across multiple CCR workstations, indicating systemic inefficiencies rather than isolated equipment failures.

Shop-floor observations further revealed handling abnormalities, coil strapping inconsistencies, and surface damage during material transfer and storage. Visual evidence of these abnormalities was documented during Gemba observations, as illustrated in Figure 1. Figure 2 shows the CCR and RBD lines that were observed.



Figure 1: Observed Abnormalities in Copper Manufacturing Plant

From an industrial perspective, these inefficiencies led to increased material loss, higher energy consumption, elevated operating costs, and reduced delivery reliability. Consequently, Company A required an improvement approach capable of visualizing end-to-end material and information flow, quantifying waste in time-based terms, and guiding structured improvement actions beyond conventional machine-level optimization.

C. Limitations of Conventional Approaches

Conventional improvement initiatives in continuous manufacturing environments typically emphasize localized equipment troubleshooting, preventive maintenance activities, or compliance-driven audits. While

such approaches may temporarily improve specific performance indicators, they often fail to address flow-related waste embedded across interconnected production stages. Value Stream Mapping (VSM) has been widely recognized as an effective Lean tool for visualizing material and information flow, distinguishing value-added and non-value-added activities, and identifying dominant sources of waste (Batwara et al., 2023;

Rother & Shook, 1999; Salwin et al., 2021, 2023). Separately, Six Sigma methodologies provide a structured framework for data-driven problem solving, process variation reduction, and performance control through the DMAIC cycle (Mittal et al., 2023; Odeyinka et al., 2024; Setiawan, 2025). However, most documented applications of Lean Six Sigma focus on discrete or batch manufacturing environments (Mittal et al., 2023; Sachin & Dileeplal, 2017; Salwin et al., 2021). Empirical studies addressing continuous metallurgical processes, particularly with VSM positioned as the primary analytical method rather than a supporting visualization, remain limited. Moreover, the integration of enterprise resource planning systems such as SAP (Chaudhari & Nemade, 2024) and real-time SCADA data into VSM-based analysis is rarely documented with sufficient operational detail, limiting industrial reproducibility and practical relevance.

D. Research Objectives and Methodological Positioning

To address the identified gaps, this study adopts Value Stream Mapping as the main analytical and improvement methodology, with the Lean Six Sigma DMAIC framework serving as a supporting structure for disciplined execution, measurement, and control. The overall research workflow follows a structured sequence aligned with the 9-step VSM methodology, integrated with DMAIC phases. The specific objectives of this study are:

1. To map the Current State of the CCR production process using the VSM methodology and quantify lead time value-added and waste categories (RO1).

2. To apply DMAIC-supported analysis to prioritize defects, validate root causes, and assess equipment effectiveness using SAP- and SCADA-based data (RO2).

3. To develop and implement targeted Kaizen improvement actions and evaluate impact on lead time, defect rate, and Overall Equipment Effectiveness (RO3).

E. Contribution of the Study

This work contributes to both academic literature and industrial practice in three ways. First, it provides empirical evidence of VSM-led waste reduction in a continuous copper manufacturing environment, extending Lean Six Sigma applications beyond discrete manufacturing contexts. Second, it demonstrates the structured integration of SAP and SCADA production data into VSM timelines for quantitative waste analysis. Third, it offers a replicable methodological framework aligning VSM 9-steps with DMAIC execution for adoption in other continuous manufacturing systems.



Figure 2: CCR Machine (Top) and RBD Machine (Bottom)

II. METHODOLOGY

A. Overall Research Framework

The overall research methodology is structured according to the research flow illustrated in Figure 3. The framework integrates the 9-step Value Stream Mapping (VSM) methodology as the primary analytical tool, while the DMAIC functions as supporting execution and control structure. The study begins with problem definition, research objectives, research questions, and scope determination, followed by a structured literature review and methodology design. The analytical core of the study consists of the sequential VSM steps, which form the backbone of the investigation. The DMAIC phases are embedded alongside selected VSM steps to ensure disciplined execution, data validation, improvement implementation, and sustainability. Importantly, VSM remains the dominant method for waste identification and flow optimization, while DMAIC acts as a governance and control mechanism, rather than replacing VSM as the main analytical framework.

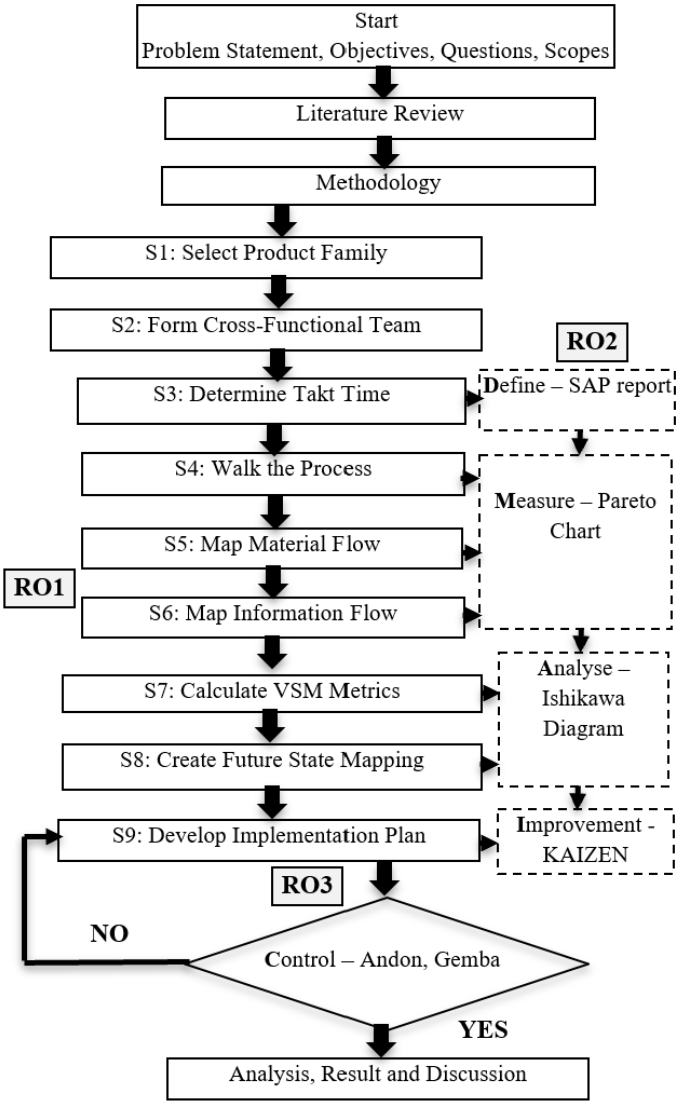


Figure 3: Research Process Flow

B. Mapping of VSM 9 Steps to DMAIC Phases

The detailed alignment between the VSM 9-step methodology and the DMAIC phases is summarized in Table 2, which serves as the methodological bridge between Lean flow analysis and Six Sigma structured improvement. This structured alignment ensures methodological rigor while preserving VSM as the primary improvement driver, with DMAIC providing systematic validation and sustainability.

C. Application of VSM Steps 1–3 (Define)

Step 1(S1): Select Product Family

The selected product family for this study was 8 mm copper rod produced via the Continuous Casting Rod (CCR) line. This product was chosen due to its high production volume, critical downstream dependency, and historical quality issues, particularly recurring wire break incidents observed in downstream processes.

Step 2 (S2): Form Cross-Functional Team

A cross-functional team was established, comprising personnel from production, quality assurance, maintenance, SAP planning, and SCADA operations. This ensured that both material flow and information flow perspectives were comprehensively captured during mapping, analysis, and improvement implementation.

Step 3 (S3): Determine Takt Time

Customer demand data were extracted from the SAP production planning module. Takt time was calculated to establish the required production pace and to identify mismatches between customer demand and actual process capability. This step defines the baseline performance expectations used throughout the study. Collectively, these three steps constitute the Define phase of DMAIC, establishing scope, objectives, and performance targets.

TABLE 2 Mapping Of VSM 9 Steps To Dmaic Phases

VSM	Description	DMAIC	Description
1. Select Product Family	Identify high-volume products with major impact (for example, 8 mm copper rod)	Define	Establish SAP report based on VOC
2. Form Cross-Functional Team	Assemble Lean, QA, SCADA, SAP, and production team		
3. Determine Takt Time	Calculating pace required to meet customer demand		
4. Gemba Walk (Walk the Line)	Observe real production flow, delays, and operator input	Measure	Baseline current process performance vs. takt time, lead time, yield
5. Map Material Flow	Visualize movement of copper from cathode to rod		Document VA/NVA/NNVA activity, use for process time analysis
6. Map Information Flow	Trace how data flows through SAP and SCADA		Identify delays and disconnects in planning, tracking, and alert systems
7. Calculate VSM Metrics	Compute lead time, cycle time, O.E.E, rework rate, inventory	Analyze	Use Pareto, cause-effect diagrams, and root cause validation for bottlenecks
8. Create Future State Map	Design improved flow with Lean tools (Kanban, SMED, IoT)	Improve	Implement solutions (for example, automation, SOP changes, integration upgrades)
9. Develop Implementation Plan	Define action items, responsibilities, training, rollout	Control	Sustain improvements using SPC, SAP dashboards, audit schedules

D. Application of VSM Steps 4–6 (Measure)

Step 4 (S4): Gemba Walk (Walk the Process)

Direct shop-floor observations were conducted across all upstream CCR workstations. The objective of this

step was to observe actual production flow, operator practices, waiting periods, and informal work arounds that are typically not captured in system-level data.

Step 5 (S5): Map Material Flow

Material movement from copper cathode charging through melting, casting, rolling, and coiling was observed in detail. Intermediate buffers, handling points, inventory accumulation, and waiting locations were explicitly identified to visualize physical flow inefficiencies across the value stream.

Step 6 (S6): Map Information Flow (RO1)

Information flow related to production scheduling, quality release, and production confirmation was mapped using SAP transaction timestamps and SCADA system signals. Delays and disconnects between physical processing and information updates were explicitly identified. These steps form the Measure phase of DMAIC, during which baseline lead time, yield, and flow performance were established using both observational and system-generated data.

E. Application of VSM Step 7 (Analyze)

Step 7 (S7): Calculate VSM Metrics

Using the SAP-based timeline data (Table 3), key performance metrics were computed, including total production lead time, defect (rod downgrade) rate, and Overall Equipment Effectiveness (OEE). Defect prioritization was conducted using Pareto analysis, while cause–effect (Ishikawa) analysis was applied to validate root causes associated with dominant bottlenecks and defect categories. This step aligns with the Analyse phase of DMAIC, where quantitative evidence is used to identify critical waste sources and quality drivers.

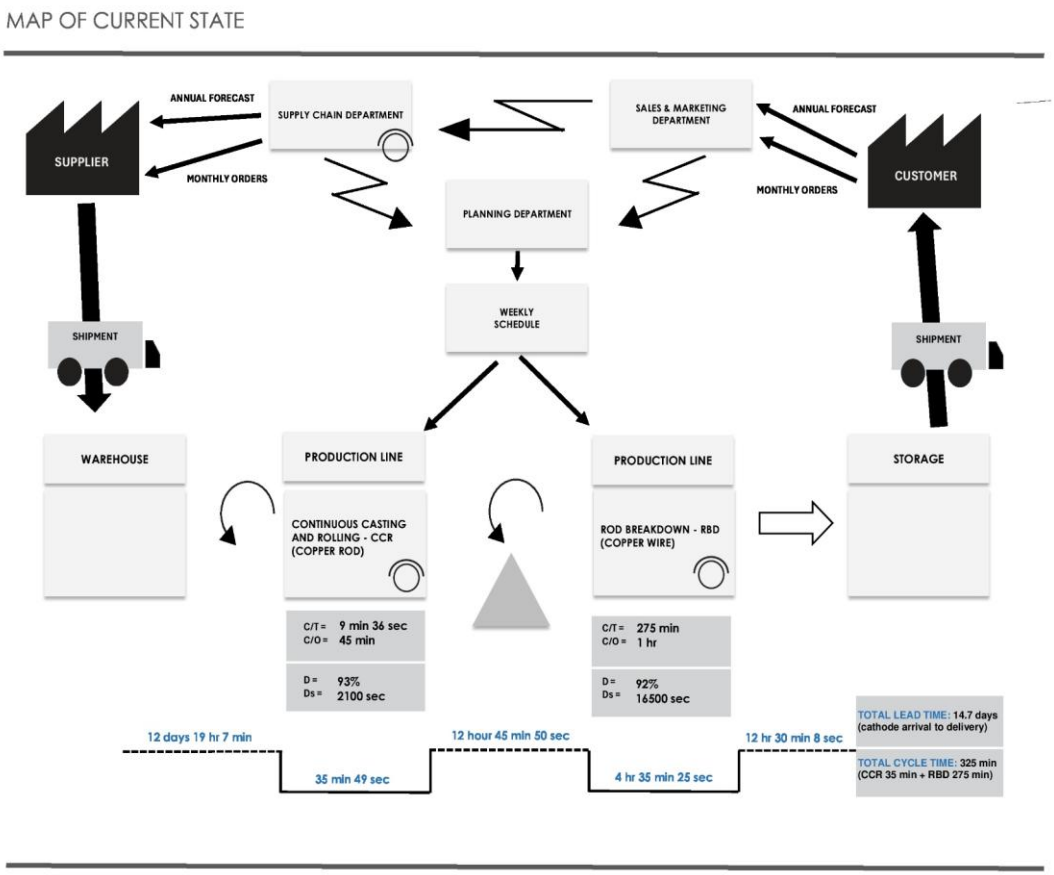


Figure 4: Current State Value Stream Mapping (CCR Process)

TABLE 3 SAP-Based VSM Timeline Summary (Week 10, Before Improvement)

Steps	Description	SAP User	Date	Time	Delay from Previous Steps
1	Sales Order Created	–	28.01.2025	–	–
2	Expected Delivery Date	–	04.03.2025	–	–
3	Cathode Arrival	DEK20640	19.02.2025	18:35:50	–
4	Cathode Transfer to CCR	–	03.03.2025	13:43:20	12 days, 19 hr
5	CCR Start	PANNIR	04.03.2025	9:34:23	19 hr 51 min
6	CCR Rod Output Confirmed	PAR20699	04.03.2025	10:10:12	35 min 49 sec
7	QC Rod	DUR60343	04.03.2025	10:13:11–	13 min 24 sec
8	Coil to Interval Area	DIP60411	05.03.2025	0:13:40	13 hr 47 min
9	RBD Start	YOG60412	05.03.2025	12:59:30	12 hr 45 min
10	RBD Wire Drawing End	DIP80088	05.03.2025	17:34:55	4 hr 35 min
11	QC Wire	UTT60406	05.03.2025	17:34:55	46 sec
12	Sent to Logistics	RUB20607	06.03.2025	6:05:49	12 hr 30 min
13	Container Loading Start	NYA20682	06.03.2025	8:48:17	2 hr 42 min
14	Delivery Completed	NYA20682	06.03.2025	10:58:41	2 hr 10 min

F. Application of VSM Steps 8–9 (Improve and Control)

Step 8 (S8): Create Future State Mapping (RO2)

Based on the gaps identified between the Current State and desired flow conditions, a Future State Value Stream Mapping was developed (refer to Figure 4 for the current state of VSM). Lean tools such as Kanban, SMED, and poka-yoke were selected to address dominant waste categories affecting material flow, information flow, and equipment stability.

Step 9 (S9): Develop Implementation Plan and Control (RO3)

Improvement actions were implemented through structured Kaizen activities. Control mechanisms, including Andon systems, standardized work instructions, SAP dashboards, Statistical Process Control (SPC), and periodic Gemba audits, were established to sustain performance gains. These steps correspond to the Improve and Control phases of DMAIC, ensuring that improvements were both implemented and maintained over time.

G. Research Design and Study Scope

This study adopted an industrial case study design conducted within the upstream Continuous Casting Rod (CCR) process of Company A. The scope covered production activities from copper cathode charging to 8 mm rod coiling, involving five upstream workstations: Loader, Melting Furnace, Casting Wheel, Rolling Mill, and Coiler. Value Stream Mapping was selected as the primary analytical method due to its ability to visualize interconnected material and information flows and to quantify time-based waste (Batwara et al., 2023; Rother & Shook, 1999; Salwin et al., 2021, 2023). The Lean Six Sigma DMAIC framework was employed as a supporting execution structure (Mittal et al., 2023; Odeyinka et al., 2024; Setiawan, 2025).

H. Data Collection and Sources

Multiple data sources were utilized to ensure comprehensive process visibility and data triangulation. Production data were extracted from the SAP ERP system (Figure 5), including production confirmation timestamps, material movement records, quality release times, and output quantities (Chaudhari & Nemade, 2024; Nurhidayah et al., 2025). Process parameters such as furnace temperature, oxygen concentration, and equipment status were obtained from the SCADA system (Jones et al., 2021; Larsson et al., 2019). Quality-related data included rod downgrade classifications and inspection records aligned with ASTM standards

(ASTM International, 1995, 2010, 2017). Coil-level data for both reference weeks were taken from the SAP rod reports, which record each coil's timestamp, grade, quality remark and net weight (718 coils in Week 10 and 673 coils in Week 41), together with the daily production reports and downtime logs.

I. Activity Classification Criteria

All process activities were classified as Value-Added (VA), Non-Value-Added (NVA), or Necessary but Non-Value-Added (NNVA) using standardized definitions summarized in Table 4.

TABLE 4 Activity Classification Criteria

Activity Type	Description	Examples in Company A	Improvement Implications
Value-Added (VA)	Directly transforms raw material into product	Charging, Melting, Casting, Rolling, Coiling, Wire Drawing	Benchmark for PCE (Process Cycle Efficiency); improve by reducing cycle variability
Non-Value Added (NVA)	Pure waste; provides no transformation or compliance benefit	Waiting, Queueing, Staging Delays, Manual Re-checks	Primary target for removal under DMAIC Improve phase
Necessary Non-Value Added (NNVA)	Required under current operational constraints	Cooling, QC Inspection, Safety Checks	Reduced through stability, automation, and standardized methods

J. Supporting DMAIC Execution and SMED Analysis

While VSM served as the primary tool, DMAIC provided structured execution support. Changeover time reduction initiatives followed the SMED principle of converting internal setup activities to external ones and streamlining the remaining internal activities.

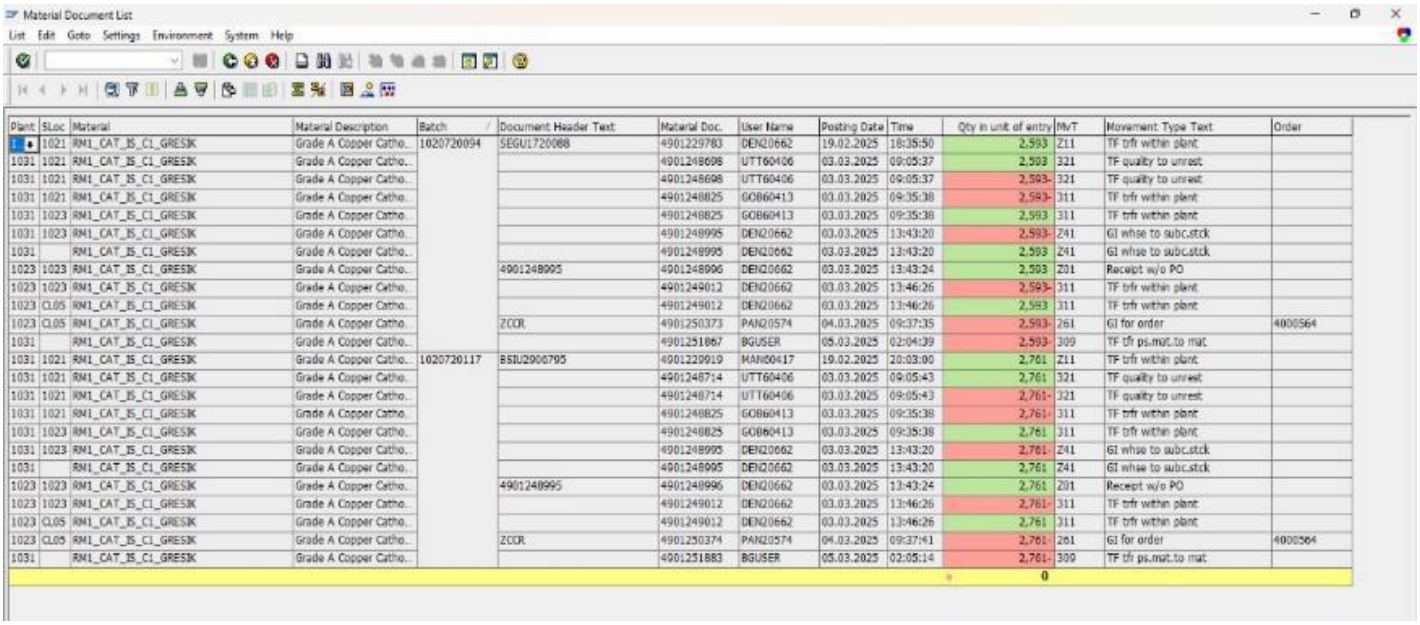
K. Performance Evaluation Criteria

Improvement effectiveness was evaluated using three key metrics: production process lead time, rod downgrade rate, and Overall Equipment Effectiveness (OEE). Baseline and post-improvement performance were compared using descriptive and time-based analysis aligned with the VSM structure. To ensure that every reported value is comparable, the defect and OEE indicators were computed for the same two reference weeks, Week 10 (baseline, before improvement) and Week 41 (after improvement), using the same SAP and SCADA sources and the same denominators. (i) Manufacturing lead time (MLT) is the elapsed time from cathode arrival to delivery completion, and production process lead time (PPLT) is the elapsed time from CCR start to wire quality release, both taken from SAP transaction timestamps for a traced baseline order (Table 3). Post-improvement lead times are reported as Future State VSM projections, because a validated post-improvement SAP order trace was not available; the value-added ratio is VA% = (total value-added time ÷ lead time) × 100. (ii) The rod downgrade rate is the number of downgraded coils divided by the total number of coils produced in the week (Tables 6 and 9), while the tonnage-based defect rate is (total output − good output) ÷ total output × 100. (iii) OEE = Availability × Performance × Quality. All three components were computed from the coil-by-coil SAP rod reports in the same way for both weeks: planned production time is the run window from the first to the last coil of the week; downtime is the sum of coil-to-coil intervals longer than 20 min, less one median coil interval (about 10 min); Availability = operating time ÷ planned production time; Performance = actual output rate during operating time ÷ the design casting rate of 25 t/h; and Quality = good (non-downgraded) net output ÷ total net output (Table 12). Downtime was derived from the timestamps rather than from the manual downtime logs, because the post-improvement log recorded only 2.52 h of stoppages whereas the coil timestamps show about 10 h. The contribution of each Kaizen action was estimated by linking it to its target indicator (the Contribution of Individual Kaizen Actions subsection). Financial impact was valued at the LME copper cash-settlement price converted to ringgit at the USD/MYR rate of the same date, with price effects separated from the operational effect (see the Financial Impact Analysis subsection). Because the rod

downgrade rate is recorded per coil, the change between Week 10 (n = 718 coils) and Week 41 (n = 673 coils) was tested with a two-sided two-proportion z-test ($\alpha = 0.05$), reported with the 95% confidence interval of the difference and confirmed by Fisher's exact test; the same test was applied to each major downgrade category, with Holm correction for multiple comparisons. The Week 41 rate was also assessed against p-chart control limits ($\pm 3\sigma$) derived from the Week 10 baseline. OEE is a weekly aggregate with one observation per period and is therefore reported descriptively, and post-improvement lead time is a projection that cannot be tested statistically.

L. Ethical and Operational Considerations

Organizational approval was obtained prior to data collection. All production data were anonymized, and improvement activities complied with safety, quality, and operational requirements. No experimental modifications affecting product compliance with ASTM standards were introduced.


Material Document List

List Edit Goto Settings Environment System Help

Plant	SLoc	Material	Material Description	Batch	Document Header Text	Material Doc.	User Name	Posting Date	Time	Qty in unit of entry	MvT	Movement Type Text	Order
1031	1021	RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..	1020720094	SEGU1720088	4901229783	DEN20662	19.02.2025	18:35:50	2,593	Z11	TF trfr within plant	
1031	1021	RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..			4901248698	UTT60406	03.03.2025	09:05:37	2,593	321	TF quality to unrest	
1031	1021	RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..			4901248698	UTT60406	03.03.2025	09:05:37	2,593-	321	TF quality to unrest	
1031	1021	RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..			4901248825	GOB60413	03.03.2025	09:35:38	2,593-	311	TF trfr within plant	
1031	1023	RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..			4901248825	GOB60413	03.03.2025	09:35:38	2,593	311	TF trfr within plant	
1031	1023	RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..			4901248995	DEN20662	03.03.2025	13:43:20	2,593-	Z41	GI whse to subc.stck	
1031		RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..			4901248995	DEN20662	03.03.2025	13:43:20	2,593	Z41	GI whse to subc.stck	
1023	1023	RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..		4901248995	4901248996	DEN20662	03.03.2025	13:43:24	2,593	Z01	Receipt w/o PO	
1023	1023	RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..			4901249012	DEN20662	03.03.2025	13:46:26	2,593-	311	TF trfr within plant	
1023	CL05	RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..			4901249012	DEN20662	03.03.2025	13:46:26	2,593	311	TF trfr within plant	
1023	CL05	RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..		ZCOR	4901250373	PAN20574	04.03.2025	09:37:35	2,593-	261	GI for order	4000564
1031		RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..			4901251867	BGUSER	05.03.2025	02:04:39	2,593-	309	TF tfr ps.mat.to mat	
1031	1021	RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..	1020720117	BSIU2906795	4901229919	MAN60417	19.02.2025	20:03:00	2,761	Z11	TF trfr within plant	
1031	1021	RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..			4901248714	UTT60406	03.03.2025	09:05:43	2,761	321	TF quality to unrest	
1031	1021	RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..			4901248714	UTT60406	03.03.2025	09:05:43	2,761-	321	TF quality to unrest	
1031	1021	RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..			4901248825	GOB60413	03.03.2025	09:35:38	2,761-	311	TF trfr within plant	
1031	1023	RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..			4901248825	GOB60413	03.03.2025	09:35:38	2,761	311	TF trfr within plant	
1031	1023	RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..			4901248995	DEN20662	03.03.2025	13:43:20	2,761-	Z41	GI whse to subc.stck	
1031		RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..			4901248995	DEN20662	03.03.2025	13:43:20	2,761	Z41	GI whse to subc.stck	
1023	1023	RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..		4901248995	4901248996	DEN20662	03.03.2025	13:43:24	2,761	Z01	Receipt w/o PO	
1023	1023	RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..			4901249012	DEN20662	03.03.2025	13:46:26	2,761-	311	TF trfr within plant	
1023	CL05	RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..			4901249012	DEN20662	03.03.2025	13:46:26	2,761	311	TF trfr within plant	
1023	CL05	RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..		ZCOR	4901250374	PAN20574	04.03.2025	09:37:41	2,761-	261	GI for order	4000564
1031		RM1_CAT_IS_C1_GRES3K	Grade A Copper Catho..			4901251883	BGUSER	05.03.2025	02:05:14	2,761-	309	TF tfr ps.mat.to mat	
										0			

Figure 5: SAP Material Movement Interface (Shown for Illustration)

III. RESULTS

A. Current State Analysis (Before Improvement)

The Current State Value Stream Mapping (VSM) revealed substantial inefficiencies within the upstream CCR process. Based on SAP-derived event timestamps and shop-floor observations, the production process lead time (PPLT), from CCR start to wire quality release, was 32.02 h, of which only 5.42 h were value-added. This resulted in a value-added ratio (VA%PPLT) of 16.91%, as calculated using Eq. (1). Over the full manufacturing lead time (MLT) from cathode arrival to delivery, 352.38 h (14.7 days), the value-added share was only 1.54% (Table 3). The visual representation of material and information flow is shown in Figure 4. The measured current-state lead times and the projected future-state values are summarised in Table 5, while the proportional distribution of lead time components is illustrated in Figure 6. Major bottlenecks identified included:

- 12 days 19 h of cathode waiting in the warehouse before transfer to the CCR
- 13 h 47 min of coil waiting between rod QC and transfer to the interval area, followed by a 12 h 45 min queue before RBD start
- 12 h 30 min of waiting between wire QC and release to logistics

TABLE 5 Lead Time And Value-Added Ratio: Current State (Measured) And Future State (Projected)

Lead time measure	Current state, Week 10 (measured)	Future state (projected)	Change
Manufacturing lead time, MLT (cathode arrival to delivery)	352.38 h (14.7 days)	228.0 h (9.5 days)	−35.3%
Production process lead time, PPLT (CCR start to wire QC release)	32.02 h	19.21 h	−40.0%
Value-added time (CCR and RBD processing)	5.42 h	5.42 h	Unchanged
Value-added ratio of PPLT, VA%PPLT	16.91%	28.19%	+11.28 pp
Value-added ratio of MLT, VA%MLT	1.54%	2.38%	+0.84 pp

$$VA\%_{PPLT} = (5.4164 \div 32.0217) \times 100 = 16.91\% \quad \text{Eq. (1)}$$

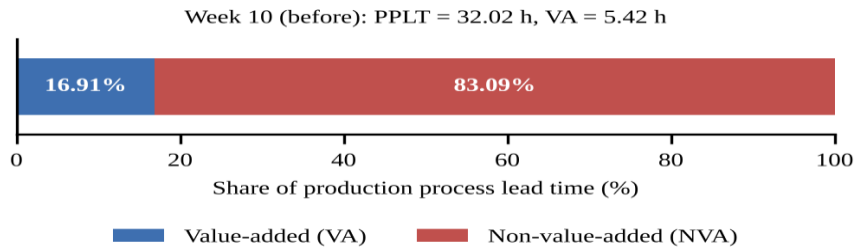


Figure 6: Percentage Distribution of Lead Time Components (Week 10, Before Improvement)

B. Defect Characterization and Prioritization

Baseline defect analysis identified a rod downgrade rate of 31.34% (225 downgraded coils out of 718 coils produced in Week 10). Chemical impurity alone accounted for 53% of downgrades, and the top three categories for 72%. A Pareto analysis was conducted to prioritise improvement focus areas, with results tabulated in Table 6 and visualized in Figure 7. Chemical impurity defects were identified as the dominant contributor, followed by surface flaws and oxygen variation. Within the Ishikawa framework, impurity-related issues fell predominantly under the Manpower, Material, Measurement and Method categories.

TABLE 6 Pareto Table Analysis For Rod Downgrades (Week 10, Before Improvement)

Type of Downgrade Defects	#	Cumulative Total	Cumulative %
High Impurity	120	120	53.33%
Surface Flaw	23	143	63.56%
Oxygen Hi-Low	20	163	72.44%
Plant Start/Stop	15	178	79.11%
Management Decision	15	193	85.78%
Pallet Issue	14	207	92.00%
Peeling	7	214	95.11%
Bad Coiling	6	220	97.78%
Unstable Pool	2	222	98.67%
Wax Mark	1	223	99.11%
Tundish Temp High	1	224	99.56%
Bar Temp Hi-Low	1	225	100.00%
Total	225	718 coils produced	31.34% reject rate

Source: coil-by-coil SAP rod report, 3–9 March 2025 (Week 10).

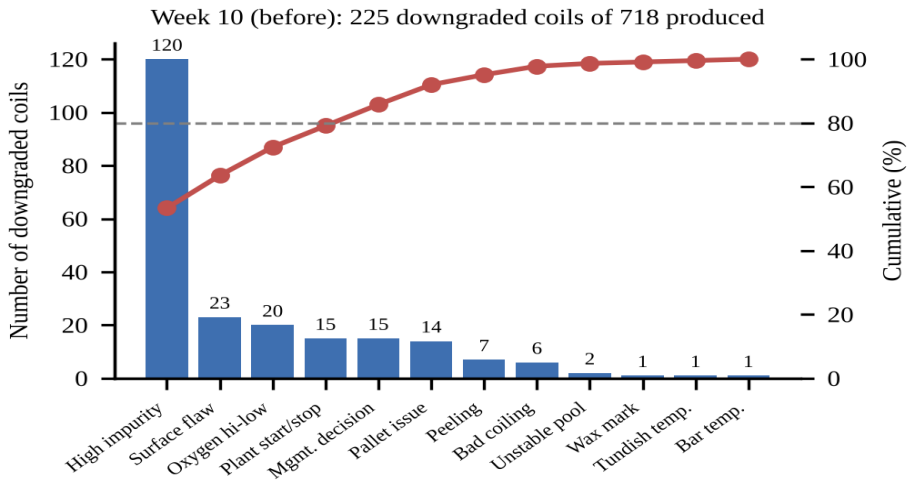


Figure 7: Pareto Chart for Rod Downgrades (Week 10, Before Improvement)

Within the Ishikawa framework, impurity-related issues fell predominantly under the Material and Method categories (Figure 8). The inconsistent application of verification steps and the lack of real-time material grading allowed contaminated scrap to be charged into the furnace.

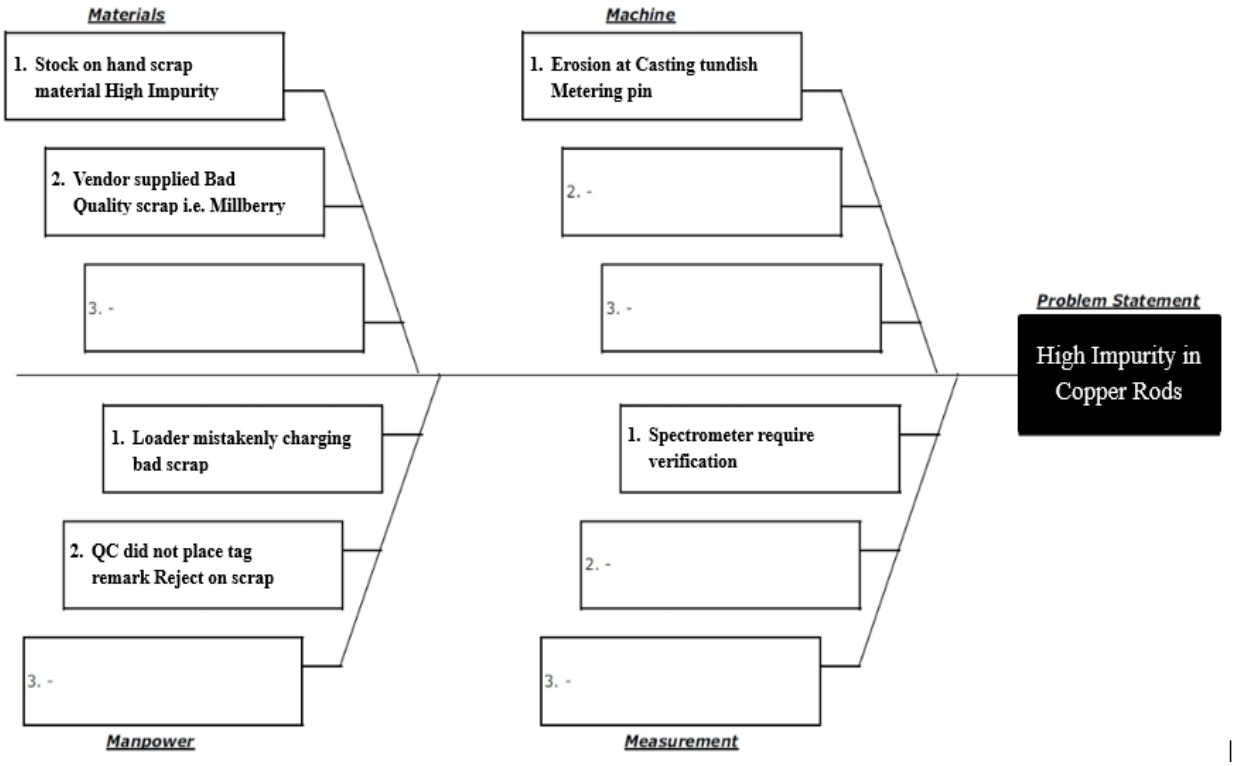


Figure 8: Root Cause Diagram for High Chemical Impurity

Root-cause mapping associated this defect with both the Machine and Manpower dimensions. Machine-related issues included SCU moisture contamination, delayed analyser calibration, and inconsistent CO flow control. From the manpower perspective, the absence of real-time SPC visualization prevented operators from responding promptly to atmospheric deviations. Kaizen 2 (from Kaizen 1-5) addressed these failures through structured SPC chart implementation, enhanced visual management, and recalibrated furnace sensors, although oxygen-related downgrades had not yet decreased by Week 41 (the Contribution of Individual Kaizen Actions subsection; Figure 9).

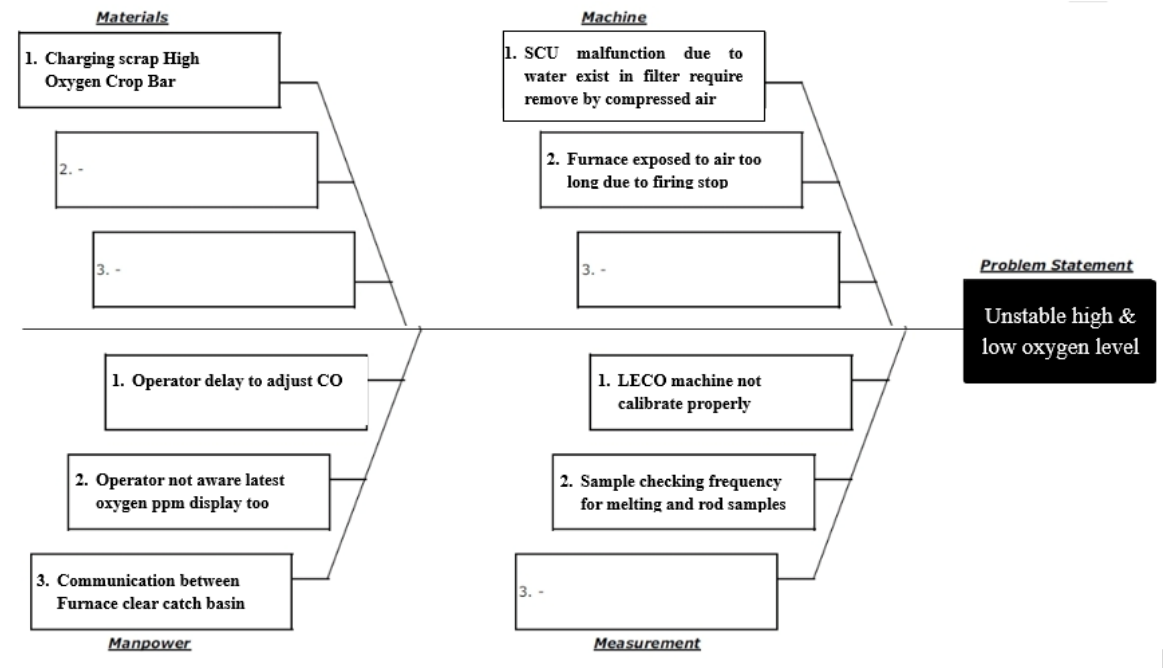


Figure 9: Root Cause Diagram for Unstable Oxygen Content

Within the Ishikawa model, surface flaws fell under the Machine category due to tool wear and under the Method category due to inconsistent maintenance routines (Figure 10). Kaizen 4 targeted these issues through Kanban-controlled roll storage, comprehensive labelling, and Standardized Work for roll replacement, although the expected reduction in surface flaws was not yet visible in the Week 41 data (the Contribution of Individual Kaizen Actions subsection).

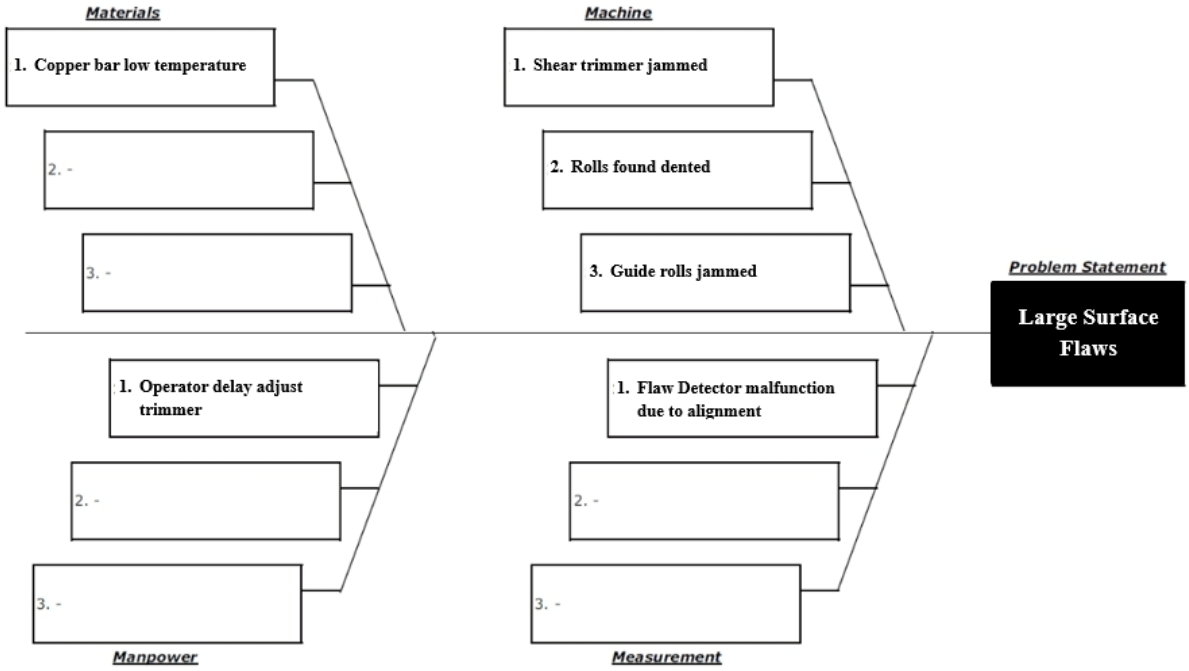


Figure 10: Root Cause Diagram for Large Surface Flaw

C. Kaizen Improvement Implementation (Kaizen 1–5)

Based on the Current State VSM findings, five targeted Kaizen initiatives were implemented across upstream workstations. Each Kaizen action directly addressed waste sources identified during the VSM and Analyse phases. Figure 11 shows the before-and-after conditions at each upstream workstation, where Standardized Work, SPC, SMED, Kanban and Poka-yoke tools were applied.

Kaizen (workstation)	Before improvement	After improvement
Kaizen 1: Loader	 Operator charge first, keep many tags  Scrap unknown quality status	 Operator practice scan to check  Scrap material visually no QC tag
Kaizen 2: Melting furnace	 Rod oxygen report in table with no range  Unused split screen for extra monitor	 
Kaizen 3: Casting wheel	 Gap to big between platform & machine  Casting pit entrance too narrow	 
Kaizen 4: Rolling mill	 	 
Kaizen 5: Coiler	 	 

Kaizen 1: Loader Workstation – Standardize Work SOP

Focused on standardizing scrap and cathode verification procedures at the Loader workstation. Visual inspection criteria, material tagging, and handling rules were formalized to prevent contaminated or mixed material from entering the melting furnace.

Kaizen 2: Melting Furnace – Oxygen Control Using SPC

Implemented Statistical Process Control (SPC) to monitor oxygen concentration within defined control limits. Calibration of oxygen measurement instruments and standardized response actions improved furnace atmosphere stability.

Kaizen 3: Casting Wheel – SMED Changeover Reduction

Applied Single-Minute Exchange of Die (SMED) principles to reduce casting changeover time. Work sequencing, ergonomic access, and preparation activities were revised to minimize internal setup time.

Kaizen 4: Rolling Mill – Kanban-Based Roll Management

Introduced a Kanban-based system for roll usage and replacement management at the rolling mill. Improved roll condition monitoring and inventory control were intended to reduce surface defects associated with roll wear.

Kaizen 5: Coiler – Poka-Yoke for Strapping Alignment

Implemented poka-yoke at the coiler to prevent strapping misalignment and handling damage. Mechanical guides and limit adjustments ensured consistent coil positioning.

D. Post-Improvement Performance Evaluation

Following Kaizen implementation, the post-improvement week (Week 41, 6–11 October 2025) was compared with the baseline week (Week 10, 3–9 March 2025) using the coil-by-coil SAP rod reports. The Future State VSM (Figure 12) projects a 40% reduction in production process lead time, from 32.02 h to 19.21 h; this is a design target, because a validated post-improvement SAP order trace was not available. The rod downgrade rate decreased from 31.34% (225 of 718 coils) to 26.00% (175 of 673 coils), a 17% relative reduction; on a tonnage basis, downgraded output fell from 31.11% to 25.88% of net output, raising the quality yield from 68.89% to 74.12% (Table 7). Overall Equipment Effectiveness improved from 63.49% to 67.58% (+4.09 percentage points), driven by the quality component (see Figures 12, 13 and 14 and Tables 7, 8 and 9).

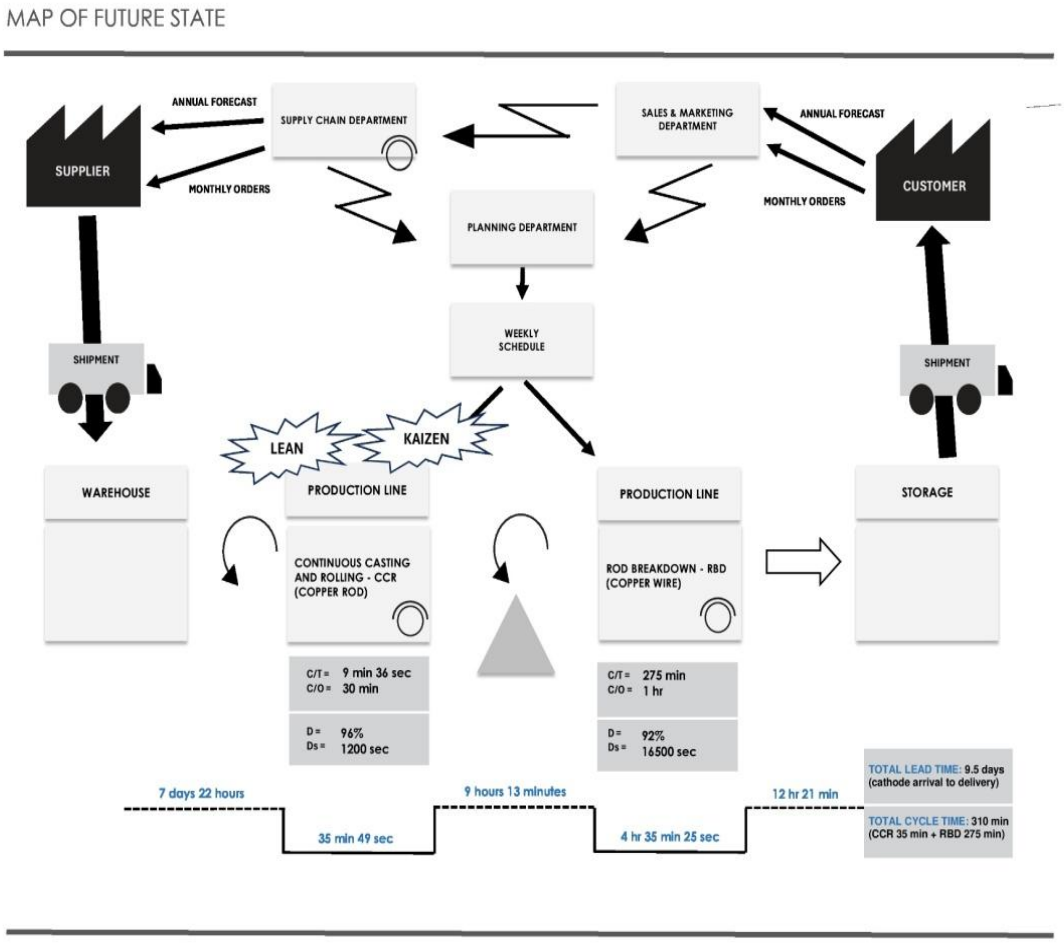


Figure 12: Future State Value Stream Mapping (CCR Process, Projected)

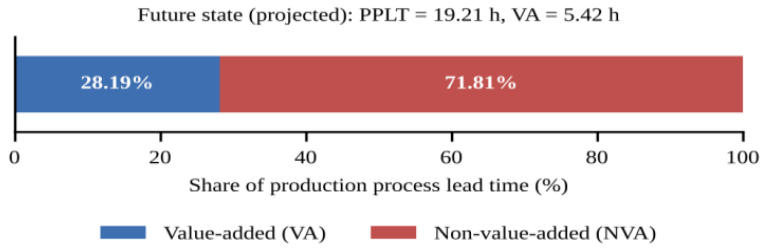


Figure 13: Projected Distribution of Lead Time Components (Future State)

TABLE 7 Weekly Production Yield Before And After Improvement

Week	Coils	Net output (kg)	Downgraded (kg)	Good output (kg)	Quality yield (%)
Week 10 (3–9 Mar 2025)	718	2,900,046	902,324	1,997,722	68.89%
Week 41 (6–11 Oct 2025)	673	2,671,948	691,427	1,980,521	74.12%

Downgraded = net weight of coils with a quality remark other than OK. Week 41 includes coil 347 (4,123 kg), which is missing from the appendix listing; its weight is reconstructed from the daily production total and it is counted as a chemical-impurity downgrade, consistent with the SAP downgrade summary.

TABLE 8 Summary Of Key Performance Indicators Before And After Improvement

Metric	Week 10 (Before)	Week 41 (After)	Change
Run window, first to last coil	125.87 h	117.23 h	−8.64 h
Coils produced	718	673	−6.3%
Net rod output	2,900.05 t	2,671.95 t	−7.9%
OEE	63.49%	67.58%	+4.09 pp
Availability	92.63%	91.46%	−1.17 pp
Performance	99.49%	99.68%	+0.19 pp
Quality (net tonnage)	68.89%	74.12%	+5.23 pp
Defect rate (tonnage basis)	31.11%	25.88%	16.8% reduction
Rod downgrade rate (coil basis)	31.34%	26.00%	17.0% reduction

TABLE 9 Pareto Table Analysis For Rod Downgrades (Week 41, After Improvement)

Type of Downgrade Defects	#	Cumulative Total	Cumulative %
Surface Flaw	43	43	24.57%
Oxygen Hi-Low	37	80	45.71%
Twist Pluck Peeling	33	113	64.57%
Chemical Impurity	20	133	76.00%
Plant Start/Stop	12	145	82.86%
Bar Temp High	10	155	88.57%
Tundish Temp High	7	162	92.57%
Bad Coiling	6	168	96.00%
Coil Overweight	5	173	98.86%
Phosphorus Shot	2	175	100.00%
Total	175	673 coils produced	26.00% reject rate

Source: coil-by-coil SAP rod report, 6–11 October 2025 (Week 41); includes coil 347 (see Table 7).

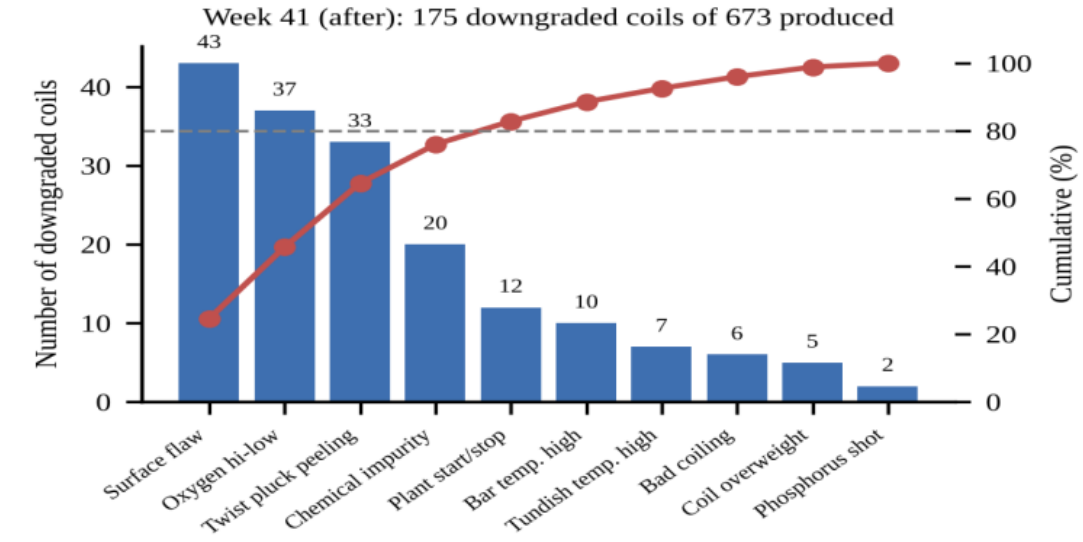


Figure 14: Pareto Chart for Rod Downgrades (Week 41, After Improvement)

E. Statistical Validation of the Defect Reduction

To test whether the reduction in rod downgrades exceeded normal week-to-week variation, the coil-level downgrade proportions of the two reference weeks were compared using the coil-by-coil SAP rod reports (Table 10). The downgrade rate fell from 31.34% (225 of 718 coils) to 26.00% (175 of 673 coils), a difference of 5.33 percentage points (95% CI: 0.59 to 10.08), which is statistically significant (two-proportion $z = 2.20$, $p = 0.028$; Fisher's exact test $p = 0.028$). The relative risk of a coil being downgraded after improvement was 0.83 (95% CI: 0.70 to 0.98). On a p-chart built from the Week 10 baseline (centre line 31.34%; for $n = 673$ coils, LCL = 25.97% and UCL = 36.70%), the Week 41 rate of 26.00% lies at the lower control limit, so the shift is statistically significant but modest and should be confirmed over further weeks. At category level, chemical impurity downgrades fell from 16.71% to 2.97% of coils ($p < 0.001$), and pallet/strapping and management-decision downgrades were eliminated (14 and 15 coils to 0; Fisher's exact $p < 0.001$). In contrast, surface flaw downgrades increased from 3.20% to 6.39% ($p = 0.005$), peeling-related downgrades from 0.97% to 4.90% ($p < 0.001$), and oxygen-related downgrades from 2.79% to 5.50% ($p = 0.011$). All of these changes remain significant after Holm correction for eight comparisons. The net improvement is therefore driven by the categories targeted by material verification at the Loader (Kaizen 1) and packing control at the Coiler (Kaizen 5), while surface-, peeling- and oxygen-related defects require further attention. OEE was captured as a single weekly aggregate in each period and post-improvement lead time is a projection, so neither could be tested statistically; both are reported descriptively and extending the comparison to multiple production weeks before and after improvement is recommended.

TABLE 10 Statistical Comparison Of Coil Downgrade Rates, Week 10 Versus Week 41

Downgrade category	Week 10, n (% of 718 coils)	Week 41, n (% of 673 coils)	p-value
All downgrades	225 (31.34%)	175 (26.00%)	0.028*
Chemical impurity	120 (16.71%)	20 (2.97%)	< 0.001*
Pallet/strapping	14 (1.95%)	0 (0.00%)	< 0.001*[a]
Management decision	15 (2.09%)	0 (0.00%)	< 0.001*[a]
Surface flaw	23 (3.20%)	43 (6.39%)	0.005* (increase)
Peeling / twist pluck peeling	7 (0.97%)	33 (4.90%)	< 0.001* (increase)
Oxygen high-low	20 (2.79%)	37 (5.50%)	0.011* (increase)

Plant start/stop	15 (2.09%)	12 (1.78%)	0.679
Bad coiling	6 (0.84%)	6 (0.89%)	0.91

*Significant at α = 0.05 (two-proportion z-test); all rows marked * remain significant after Holm correction for eight comparisons. [a]Fisher's exact test, used because of a zero count. Source: coil-by-coil SAP rod reports for 3–9 March 2025 (Week 10) and 6–11 October 2025 (Week 41).

F. Contribution of Individual Kaizen Actions

Because the five Kaizen actions were implemented in the same period, their individual effects could not be isolated experimentally. Instead, each Kaizen was linked, through the Ishikawa analysis, to the indicator it was designed to change, and its contribution to quality was estimated as the number of downgraded coils avoided in Week 41 relative to the Week 10 rate of the targeted categories: avoided coils = (p_Week10 − p_Week41) × 673 (Table 11). On this basis, the 35.9 coils avoided in Week 41 relative to the baseline rate can be decomposed by Kaizen. Kaizen 1 (material verification at the Loader) delivered the largest gain, with 92.5 fewer chemical impurity downgrades, and Kaizen 5 (strapping poka-yoke at the Coiler) avoided a further 12.7 coils by eliminating pallet/strapping defects. Kaizen 3 (ergonomic SMED at the casting wheel) targets a reduction in casting changeover from 45 to 30 min (−33%) in the Future State VSM; however, measured availability did not improve (92.63% to 91.46%), because two long stoppages on 8 and 10 October 2025 outweighed the fall in the number of stoppages from 11 to 6. In contrast, Kaizen 2 and Kaizen 4 had not yet produced a measurable effect by Week 41: oxygen-related downgrades rose by an estimated 18.3 coils, surface flaw and peeling downgrades by 47.9 coils, and categories not targeted by any Kaizen by 3.2 coils. The gross gain from Kaizen 1 and Kaizen 5 (105.2 coils) was therefore largely offset by these increases. Because the average coil mass was similar in both weeks (4.04 t and 3.97 t per coil), the coil-based estimates can be read approximately in tonnes. The projected lead time reduction, by contrast, comes entirely from shorter waiting between stages, since value-added processing time is unchanged (Table 5); it depends on the flow and scheduling changes in the Future State VSM rather than on any single Kaizen.

TABLE 11 Contribution Of Individual Kaizen Actions, Week 10 Versus Week 41

Kaizen (workstation)	**Target indicator**	**Week 10 → Week 41**	**Estimated effect**
Kaizen 1 (Loader)	Chemical impurity downgrades	16.71% → 2.97% of coils	92.5 coils avoided ($p < 0.001$)
Kaizen 2 (Melting furnace)	Oxygen high-low downgrades	2.79% → 5.50% of coils	18.3 coils added; no reduction yet ($p = 0.011$)
Kaizen 3 (Casting wheel)	Casting changeover time (target); availability (measured)	45 → 30 min (target); 92.63% → 91.46%	Changeover −33% (target); availability −1.17 pp
Kaizen 4 (Rolling mill)	Surface flaw and peeling downgrades	4.18% → 11.29% of coils	47.9 coils added; no reduction yet ($p < 0.001$)
Kaizen 5 (Coiler)	Pallet/strapping and bad coiling downgrades	2.79% → 0.89% of coils	12.7 coils avoided ($p = 0.009$)
Not targeted	Plant start/stop, management decision, temperature and other categories	4.87% → 5.35% of coils	3.2 coils added ($p = 0.688$)
Net effect	All downgrades	31.34% → 26.00% of coils	35.9 coils avoided ($p = 0.028$)

Avoided coils = (Week 10 rate − Week 41 rate) × 673 coils; a positive value is an improvement. p-values from the two-proportion z-test (Table 10). Kaizen 3 changeover values are the current-state value and the future-state target from the VSM data boxes (Figures 4 and 12); availability is measured from coil timestamps (Table 12).

G. Sustainability of Improvements

In the Control phase, visual management, SPC monitoring, standardised work documentation, preventive maintenance scheduling and routine Gemba audits were put in place to hold the gains. The post-improvement evaluation (Week 41) was taken 31 weeks after the baseline (Week 10), so the gains were still present some seven months after the project began. However, continuous weekly data between and after these two points were not analysed, so long-term sustainment has not yet been demonstrated statistically. To make sustainment measurable, a control plan was defined with the Week 41 performance as the new baseline (Table 15): each indicator has a target or control limit, a monitoring method and frequency, and a defined reaction, so that regression can be detected and acted on. The Andon board used for real-time monitoring is shown in Figure 15.



Figure 15: Andon Board Monitoring Production Status

IV. DISCUSSION

A. Interpretation of Lead Time Reduction

The projected 40% reduction in production process lead time (from 32.02 h to 19.21 h) rests on eliminating the dominant non-value-added activities identified through the Current State VSM (Table 5, Figure 4). As illustrated in the lead time distribution (Figures 6 and 13), waiting for quality release, internal transportation, and coordination delays constituted the largest proportion of waste prior to improvement. By applying VSM as the primary analytical tool, the study was able to visualize time-based inefficiencies that were not apparent through conventional machine-level performance indicators. This finding is consistent with prior studies that highlight the effectiveness of VSM in identifying flow-related waste across complex production systems (Batwara et al., 2023; Rother & Shook, 1999; Salwin et al., 2021, 2023). If realised, this would show that significant lead time reduction can be achieved in continuous manufacturing environments without major capital investment, if material and information flows are synchronized; verifying it with post-improvement SAP order data is therefore a priority for future work.

B. Effectiveness of Kaizen Interventions on Defect Reduction

The 17% reduction in rod downgrade rate (from 31.34% to 26.00% of coils produced) reflects the effectiveness of targeted Kaizen actions derived from Pareto-based defect prioritization (Table 6, Figure 7). Chemical impurity, surface flaws and oxygen variation were the dominant quality loss categories, accounting

for 72% of total downgrades. Kaizen 1 directly addressed upstream material consistency and delivered the largest single gain (Table 11), while Kaizen 2 addressed furnace oxygen stability, aligning with metallurgical studies that emphasize the sensitivity of copper rod quality to raw material consistency and oxygen control (Abdelwahed et al., 2024; González et al., 2024; Haddi et al., 2011; Jones et al., 2021; Larsson et al., 2019). The quality benefit of Kaizen 2 was not yet visible in Week 41, which suggests that SPC-based furnace control needs a longer stabilisation period before its effect on downgrades appears.

Kaizen 3 and Kaizen 4 focused on casting and rolling stability, where surface integrity is strongly influenced by changeover practices and roll condition management (Alexandrov et al., 2022; Liu et al., 2021). The elimination of packaging-related defects through Kaizen 5 further illustrates the importance of downstream handling control in preserving upstream quality improvements. Compared with prior Lean Six Sigma applications reported in discrete manufacturing environments (Mittal et al., 2023; Sachin & Dileeplal, 2017; Salwin et al., 2021), the results demonstrate that defect reduction in continuous metallurgical processes requires upstream-focused interventions rather than isolated inspection-based controls.

C. Improvement in Overall Equipment Effectiveness (OEE)

The improvement in Overall Equipment Effectiveness (Table 12, Figure 16) from 63.49% to 67.58% came almost entirely from the quality component, which rose from 68.89% to 74.12% as downgrades fell. Performance was already close to the design casting rate of 25 t/h in both weeks (99.49% and 99.68%), so speed losses were not a material constraint. Availability fell slightly, from 92.63% to 91.46%: the number of stoppages longer than 20 min fell from 11 to 6, consistent with the Kaizen 3 changeover target, but two long stoppages on 8 and 10 October 2025 (about 4.2 h and 4.5 h) increased total downtime from 9.28 h to 10.01 h, so availability is the next improvement priority. The observed OEE improvement aligns with findings reported in prior DMAIC-based studies, where structured waste elimination and process stabilization led to measurable equipment performance gains (Mittal et al., 2023; Odeyinka et al., 2024; Setiawan, 2025). The present study extends this evidence by showing that, in a continuous casting line already running close to its design rate, VSM-led improvement raises OEE mainly through quality rather than speed.

TABLE 12 Detailed Overall Equipment Effectiveness (OEE)

Metric	Week 10 (Before)	Week 41 (After)	Change
Planned production time, run window (h)	125.87	117.23	−8.64
Stoppages longer than 20 min (n)	11	6	−5
Downtime (h)	9.28	10.01	0.73
Operating time (h)	116.59	107.22	−9.37
Availability (%)	92.63	91.46	−1.17
Net output (t)	2,900.05	2,671.95	−228.098
Actual rate during operation (t/h)	24.87	24.92	0.05
Design casting rate (t/h)	25	25	
Performance (%)	99.49	99.68	0.19
Good output (t)	1,997.72	1,980.52	−17.201
Quality (%)	68.89	74.12	5.23
OEE (%)	63.49	67.58	4.09

Source: coil-by-coil SAP rod reports. Downtime = sum of coil-to-coil intervals longer than 20 min, less one median coil interval (9.98 min in Week 10 and 9.90 min in Week 41).

The Week 41 OEE components in Table 12 were calculated from the coil-by-coil SAP rod report as follows:

$$AvailabilityW41 = (107.22 \div 117.23) \times 100\% = 91.46\% \quad (2)$$

PerformanceW41 = (24.92 ÷ 25.00) × 100% = 99.68% (3)

QualityW41 = (1,980.521 ÷ 2,671.948) × 100% = 74.12% (4)

OEEW41 = 0.9146 × 0.9968 × 0.7412 × 100% = 67.58% (5)

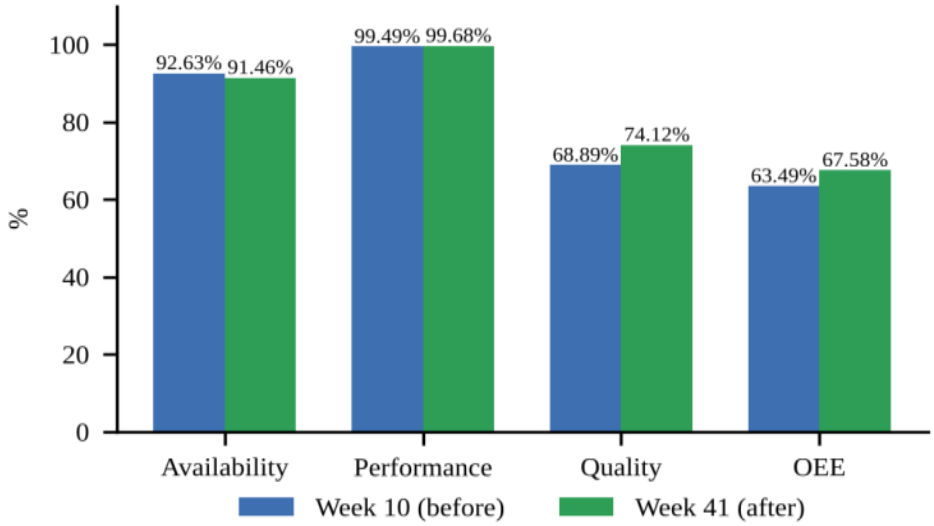


Figure 16: OEE Improvement Before vs After

D. Role of VSM as Primary Method and DMAIC as Supporting Framework

A key contribution of this study lies in the methodological positioning of VSM as the primary improvement tool, with DMAIC serving as a supporting execution framework. The 9-step VSM approach enabled comprehensive visualization and quantification of waste across the entire CCR process, while DMAIC provided a disciplined structure for measurement, analysis, improvement, and control. This integration addresses limitations identified in previous studies, where VSM was often treated as a preliminary mapping exercise rather than a central analytical method (Batwara et al., 2023; Rother & Shook, 1999; Salwin et al., 2023). The structured alignment between VSM steps and DMAIC phases (Table 2, Figure 3) enhanced traceability between identified waste, Kaizen actions, and performance outcomes. Furthermore, the integration of SAP and SCADA data into VSM timelines (Table 3) enhanced measurement accuracy and reproducibility, addressing a common limitation in qualitative VSM applications (Chaudhari & Nemade, 2024; Nurhidayah et al., 2025).

E. Financial Impact Analysis

To make the financial evaluation transparent and traceable, copper was valued at the London Metal Exchange (LME) copper cash-settlement price and converted to ringgit at the USD/MYR exchange rate of the same date. The mid-week trading day of each reference week was used: 5 March 2025 for Week 10 and 8 October 2025 for Week 41 (Table 13). Between these dates, the LME price rose from USD 9,541.00/t to USD 10,738.00/t (+12.5%), while the ringgit strengthened from 4.4285 to 4.2160 per USD (−4.8%); the ringgit price of copper therefore rose by 7.1%, from RM 42,252/t to RM 45,271/t.

TABLE 13 Copper Price, Exchange Rate And Metal Value On Matched Dates

Item	Week 10 (Before)	Week 41 (After)	Change
Price reference date (mid-week)	5-Mar-25	8-Oct-25	–
LME copper cash-settlement (USD/t)	9,541.00	10,738.00	12.50%

USD/MYR exchange rate (same date)	4.4285	4.216	−4.8%
Copper price (RM/t)	42,252	45,271	7.10%
Good output (t)	1,997.72	1,980.52	−17.201 t
LME metal value of good output (RM million)	84.41	89.66	+5.25 (price +5.98; volume −0.73)
Downgraded output (t)	902.324	691.427	−210.897 t
Downgraded share of net output	31.11%	25.88%	−5.23 pp

Sources: LME copper cash-settlement prices (Westmetall, 2025); USD/MYR daily rates (ValutaFX, 2025a, 2025b). Metal value excludes the rod premium and conversion costs.

Two effects were separated so that market movements are not reported as improvement benefits. First, the LME metal value of good output rose by RM 5.25 million in the week, from RM 84.41 million to RM 89.66 million. Good output was almost unchanged (1,997.722 t versus 1,980.521 t), so this increase consists of a price effect of RM 5.98 million, partly offset by a volume effect of −RM 0.73 million. It reflects market conditions rather than the Kaizen actions and is therefore not claimed as a benefit of the study. Second, the operational benefit comes from the lower downgrade share. Had the Week 10 downgrade share of 31.11% applied to the Week 41 output of 2,671.948 t, 831.36 t would have been downgraded, compared with the actual 691.43 t, so 139.93 t of downgrades were avoided in the week. Because downgraded rod keeps most of its metal value, the financial loss per downgraded tonne is the selling-price discount or reprocessing cost, not the full copper price. Table 14 therefore values the avoided tonnes across a range of discounts at constant prices: at the Week 10 price, each 1% discount is worth about RM 59,100 per week, so a discount of 2.5% to 5% corresponds to RM 0.15 million to RM 0.30 million per week. This price-neutral value is the financial benefit attributable to the improvement programme.

TABLE 14 Price-Neutral Value Of Avoided Downgrades (139.93 T Per Week)

Assumed loss per downgraded tonne (% of copper price)	**At Week 10 price (RM/week)**	**At Week 41 price (RM/week)**	**Indicative annual value at Week 10 price (RM million, 52 weeks)**
1.00%	59,122	63,347	3.07
2.50%	147,805	158,367	7.69
5.00%	295,611	316,733	15.37
10.00%	591,221	633,466	30.74

Avoided downgrades = (31.11% × 2,671.948 t) − 691.427 t = 139.93 t per week. Value = 139.93 t × assumed loss × copper price (RM/t). Annual values assume 52 operating weeks at Week 41 performance and are indicative only.

F. Industrial Implications and Study Limitations

From an industrial perspective, the findings demonstrate that substantial performance improvements can be achieved in continuous copper manufacturing through systematic flow analysis and targeted Kaizen implementation. The approach is particularly relevant for energy-intensive industries operating under strict quality standards such as ASTM B115, B49, and B3 (ASTM International, 1995, 2010, 2017). The financial value of these improvements, separated from copper price and exchange rate movements, is given in the Financial Impact Analysis subsection (Tables 13 and 14). Despite these promising results, several limitations should be acknowledged. First, the study was conducted at a single production site with specific operational characteristics, which may limit generalizability to other continuous manufacturing contexts with different scale, technology, or market conditions. Second, the before-and-after comparison of defects and OEE rests on one reference week in each period, and the lead time improvement is a Future State projection based on one traced baseline order that has not yet been verified with post-improvement SAP order data. As an observational design without a control line, concurrent changes in cathode and scrap mix, product mix, staffing or market conditions may also have influenced the results, and longer-term monitoring is needed to confirm retention and

detect regression. Third, the Kaizen actions targeted the upstream CCR workstations; rod breakdown and wire drawing were mapped for lead time but not improved, so interdependencies across the wider value chain were not optimised. Fourth, the financial estimate depends on the copper price, the exchange rate and the downgrade discount; the sensitivity range in Table 14 should be refined with the plant's actual discount data, and absolute values may differ under different market conditions. Finally, the post-improvement downtime log under-recorded stoppages, so downtime was derived from coil timestamps, and one coil record (coil 347 of Week 41) was missing from the appendix listing and was reconstructed from the daily production total; a standard data protocol is recommended for future studies.

Regarding transferability, the VSM–DMAIC framework does not depend on site-specific equipment. It requires a continuous casting and rolling line or a comparable continuous metal-forming process, time-stamped production confirmations in an ERP system such as SAP, and process data from SCADA or an equivalent historian. Plants that meet these conditions can reproduce the analysis by applying the same nine VSM steps, the same indicator definitions (Performance Evaluation Criteria subsection) and the same statistical tests (Statistical Validation subsection). To establish reproducibility and wider applicability, three steps are recommended: (i) extending monitoring to at least 12 weeks before and 12 weeks after improvement and analysing the weekly downgrade rate and OEE as an interrupted time series; (ii) replicating the study on other CCR or SCR lines that differ in capacity, cathode and scrap mix, and technology; and (iii) pooling multi-site results under a common data protocol, so that the effect of each Kaizen action can be compared across plants.

TABLE 15 Proposed Control Plan For Sustaining The Improvements

Indicator	Target / control limits (Week 41 baseline)	Control method and frequency	Reaction if out of control
Coil downgrade rate	p-chart: centre 26.0%, UCL 31.1%, LCL 20.9% ($n \approx 673$ coils per week)	Weekly SAP downgrade report plotted on the Andon board	Cross-functional root-cause review; re-audit Kaizen 1 and Kaizen 5 controls
Chemical impurity downgrades	≤ 3% of coils	Scan-verify-load audit at the Loader each shift (Kaizen 1); weekly SAP count	Quarantine untagged scrap; retrain operators
Rod oxygen content	Within furnace SPC limits for the ASTM B49 grade	Real-time SPC chart on the furnace display for every coil (Kaizen 2)	Adjust furnace atmosphere; recalibrate oxygen analyser
Surface flaw and peeling downgrades	Back to the Week 10 level (≤ 4.2% of coils)	Kanban roll-life tracking at every roll change (Kaizen 4); weekly SAP count	Inspect roll condition and roll-change records
OEE and casting changeover	OEE ≥ 67.6%; availability ≥ 92%; changeover ≤ 30 min	Weekly SAP/SCADA OEE dashboard; SMED checklist at each changeover (Kaizen 3)	Loss analysis by availability, performance and quality
Production process lead time	≤ 19.2 h from CCR start to wire QC release	Monthly SAP timestamp audit of sample orders	VSM review of waiting points

p-chart limits = $26.0\% \pm 3\sqrt{(0.26 \times 0.74 / 673)}$. Targets are proposed from Week 41 performance and should be reviewed after 12 weeks of monitoring.

V. CONCLUSION AND FUTURE RECOMMENDATION

This study investigated waste reduction in an upstream Continuous Casting Rod (CCR) process through the application of Value Stream Mapping (VSM) as the primary improvement methodology, supported by the Lean Six Sigma DMAIC framework. Using a single-site industrial case study, the research demonstrated that significant performance improvements can be achieved in continuous copper manufacturing by focusing on end-to-end flow rather than isolated machine-level optimisation. The Current State VSM revealed extensive non-value-added activities embedded within the production system, resulting in low Process Cycle Efficiency and prolonged lead time.

By visualising material and information flow across multiple upstream workstations, dominant sources of waste related to waiting, quality release delays, and coordination inefficiencies were identified. Figure 12 illustrates the Future State Value Stream Map, which sets the projected flow targets. These findings validated the suitability of VSM as a central analytical tool for diagnosing flow-related inefficiencies in continuous metallurgical processes. Guided by the VSM analysis, five targeted Kaizen improvement actions were implemented across material handling, melting, casting, rolling, and coiling operations. The structured execution of these actions within the DMAIC Improve and Control phases resulted in a measurable reduction in the defect rate and an improvement in Overall Equipment Effectiveness, with a projected reduction in lead time. Between Week 10 and Week 41, the rod downgrade rate fell by 17% (31.34% to 26.00% of coils produced; $p = 0.028$) and OEE rose from 63.49% to 67.58%, mainly through quality, while the Future State VSM projects a 40% reduction in production process lead time (32.02 h to 19.21 h). The results confirm that upstream stabilisation and flow synchronisation play a critical role in improving quality and equipment performance in continuous manufacturing environments.

From a methodological perspective, this study contributes empirical evidence supporting the positioning of VSM as the main improvement method, with DMAIC serving as a supporting execution framework. This integrated approach enhances traceability between waste identification, improvement actions, and performance outcomes, addressing limitations observed in prior Lean Six Sigma applications that treat VSM as a secondary or purely visual tool. In practical terms, the findings provide a replicable framework for manufacturers operating energy-intensive continuous processes under strict quality standards. Because the evidence comes from a single site and a comparison of two reference weeks, the results should be read as a well-documented industrial case rather than a general rule. Future research should verify the projected lead time with post-improvement SAP order data, extend monitoring to at least 12 weeks before and after improvement using the control plan in Table 15, replicate the framework on other CCR and SCR lines, and include downstream rod breakdown and wire drawing, to confirm the sustainability, reproducibility and wider applicability of the VSM–DMAIC framework across the copper value chain.

ACKNOWLEDGEMENTS

The authors thank the management and staff of Company A for their research support and cooperation. All facts and figures, including the name of the company, are subject to a non-disclosure agreement. This research was supported by the Institute of Postgraduate Studies (IPSis), Universiti Teknologi MARA (UiTM).

DECLARATIONS

A. Ethical approval

This industrial case study did not involve experiments on human participants or animals. Organisational approval was obtained from Company A before data collection, and all production data were anonymised.

B. Conflict of interest

The third author is employed by the case organisation. The authors declare no other conflict of interest.

C. Data availability

The production data are subject to a non-disclosure agreement with Company A and are not publicly available. The aggregated data that support the findings are reported in the tables of this article.

REFERENCES

1. Abdelwahed, M. S., Alghamdi, A., & Eltaher, M. A. (2024). Improving product quality of wire drawing process using design of experiments. Journal of Computational Applied Mechanics, 55(1), 8–25. https://doi.org/10.22059/JCAMECH.2024.372017.957

2. Alexandrov, S., Hwang, Y.-M., & Tsui, H. S. R. (2022). Determining the drawing force in a wire drawing process considering an arbitrary hardening law. Processes, 10(7), Article 1336. https://doi.org/10.3390/pr10071336
3. ASTM International. (1995). Standard specification for soft or annealed copper wire (ASTM B3-95).
4. ASTM International. (2010). Standard specification for electrolytic copper cathode (ASTM B115-10).
5. ASTM International. (2017). Standard specification for copper rod for electrical purposes (ASTM B49-17).
6. Batwara, A., Sharma, V., Makkar, M., & Giallanza, A. (2023). Towards smart sustainable development through value stream mapping – A systematic literature review. Heliyon, 9(5), Article e15852. https://doi.org/10.1016/j.heliyon.2023.e15852
7. Chaudhari, S., & Nemade, G. (2024). Optimizing manufacturing operations: A comprehensive study of SAP ERP with an emphasis on SAP MM. International Journal of Engineering Research & Technology, 13(9), Article IJERTV13IS090019. https://www.ijert.org/optimizing-manufacturing-operations-a-comprehensive-study-of-sap-erp-with-an-emphasis-on-sap-mm
8. Chia, E. H., & Adams, R. D. (1981). The metallurgy of Southwire's continuous rod. JOM, 33(2), 68–74. https://doi.org/10.1007/BF03354529
9. González, Á., Cruchaga, M., Celentano, D., & Ponthot, J.-P. (2024). Damage prediction in the wire drawing process. Metals, 14(10), Article 1174. https://doi.org/10.3390/met14101174
10. Haddi, A., Imad, A., & Vega, G. (2011). Analysis of temperature and speed effects on the drawing stress for improving the wire drawing process. Materials & Design, 32(8–9), 4310–4315. https://doi.org/10.1016/j.matdes.2011.04.010
11. Jones, T. D. A., Strachan, R. I., Mackie, D. M., Cooper, M., Frame, B., & Vorstius, J. B. (2021). Computational fluid dynamic simulations of solidification for enhancing speed of continuous cast copper. Engineering Science and Technology, an International Journal, 24(1), 92–104. https://doi.org/10.1016/j.jestch.2020.12.009
12. Larsson, J., Jansson, A., & Karlsson, P. (2019). Monitoring and evaluation of the wire drawing process using thermal imaging. The International Journal of Advanced Manufacturing Technology, 101, 2121–2134. https://doi.org/10.1007/s00170-018-3021-7
13. Liu, Y., Peng, Y., & Qu, X. (2021). Mechanism of and key technologies for copper bonding in the hot rolling of SCR continuous casting and rolling. Applied Sciences, 11(22), Article 11023. https://doi.org/10.3390/app112211023
14. Mittal, A., Gupta, P., Kumar, V., Al Owad, A., Mahlawat, S., & Singh, S. (2023). The performance improvement analysis using Six Sigma DMAIC methodology: A case study on Indian manufacturing company. Heliyon, 9(3), Article e14625. https://doi.org/10.1016/j.heliyon.2023.e14625
15. Nurhidayah, F. A., Chumaidiyah, E., & Suhendra, A. A. (2025). Design of ERP production planning module to optimize the use of System Application and Processing (SAP) software using business process improvement and Activate SAP methodology at PT. XYZ. International Journal of Inventive Engineering and Sciences, 12(1), 15–19. https://doi.org/10.35940/ijies.H1094.12010125
16. Odeyinka, O. F., Ipinnimo, O., & Ogunwolu, F. (2024). Parametric multi-level modeling of Lean Six Sigma. Journal of Engineering and Applied Science, 71, Article 193. https://doi.org/10.1186/s44147-024-00528-1
17. Rother, M., & Shook, J. (1999). Learning to see: Value stream mapping to add value and eliminate muda. Lean Enterprise Institute.
18. Sachin, S., & Dileeplal, J. (2017). Six Sigma methodology for improving manufacturing process in a foundry industry. International Journal of Advanced Engineering Research and Science, 4(5), 131–136. https://doi.org/10.22161/ijaers.4.5.21
19. Salwin, M., Jacyna-Gołda, I., Bańka, M., Varanchuk, D., & Gavina, A. (2021). Using value stream mapping to eliminate waste: A case study of a steel pipe manufacturer. Energies, 14(12), Article 3527. https://doi.org/10.3390/en14123527
20. Salwin, M., Pszczółkowska, K., Pałęga, M., & Kraslawski, A. (2023). Value-stream mapping as a tool to improve production and energy consumption: A case study of a manufacturer of industrial hand tools. Energies, 16(21), Article 7292. https://doi.org/10.3390/en16217292

21. Setiawan, S. A. (2025). Implementation of Six Sigma methodology to reduce high defect rate in rubber processing industry. European Journal of Business and Management Research, 10(1), 118–126. https://doi.org/10.24018/ejbmr.2025.10.1.2538
22. Sinha, U., & Adams, R. (1993). Southwire Continuous Rod process: Innovations for quality improvements. Wire Journal International, 26(6), 66.
23. ValutaFX. (2025a). US dollar (USD) to Malaysian ringgit (MYR) exchange rate on 2025-03-05. Retrieved November 3, 2026, from https://www.valutafx.com/history/usd-myr-2025-03-05
24. ValutaFX. (2025b). US dollar (USD) to Malaysian ringgit (MYR) exchange rate on 2025-10-08. Retrieved November 3, 2026, from https://www.valutafx.com/history/usd-myr-2025-10-08
25. Ware, P. W. (2007). The SCR® process produces high quality copper rod around the world. Canadian Institute of Mining, Metallurgy and Petroleum. https://onemine.org/documents/the-scr-process-produces-high-quality-copper-rod-around-the-world
26. Westmetall. (2025). LME copper cash-settlement prices, 2025 [Data set]. Retrieved November 3, 2026, from https://www.westmetall.com/en/markdaten.php?action=table&field=LME_Cu_cash&year=2025