ENHANCING PRODUCTION LINE PERFORMANCE THROUGH AN INTEGRATED OEE-FMEA MODEL: A CASE STUDY AT HOA SEN NGHE AN

Vu T. Hanh[1]*, Phan H. Hoang[2]

[1]The University of Danang - University of Science and Technology, Vietnam

[2]Industrial & Systems Engineering student, The University of Danang - University of Science and Technology, Vietnam

*Corresponding author: vthanh@dut.udn.vn

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Abstract - This study introduces an integrated methodology, combining Overall Equipment Effectiveness (OEE) and Failure Mode and Effects Analysis (FMEA), to enhance operational performance within the NOF1 production line at Hoa Sen Nghe An Co., Ltd. Production efficiency was quantified using the OEE framework across Availability, Performance, and Quality metrics, while failure modes were identified and prioritized via PFMEA and DFMEA, adhering to the AIAG & VDA 2022 standard. The methodology aligned quantitative performance data with structured risk analysis to formulate targeted corrective actions, addressing root causes based on Action Priority (AP) levels. Post-intervention analysis demonstrated a 6.6% improvement in OEE and a 67.6% reduction in defect rates. These results validate the efficacy of the integrated OEE-FMEA model as a proactive, data-driven strategy for optimizing equipment utilization, minimizing downtime, and improving product quality within the coated steel manufacturing sector.

Key words - Overall Equipment Effectiveness (OEE); Failure Mode and Effects Analysis (FMEA); Action Priority (AP); Risk prioritization; Process improvement; Galvanized steel production; TPM; AIAG & VDA 2022; Performance metrics; Manufacturing optimization.

1. Introduction and Literature Review

1.1. Context and Significance

The Fourth Industrial Revolution (Industry 4.0) is driving a paradigm shift in manufacturing, emphasizing intelligent systems, real-time data, and integrated process optimization. In this landscape, manufacturers are compelled to adopt systematic strategies not only to maximize equipment efficiency but also to reduce operational risks and ensure consistent product quality. As noted by Nakajima [1], optimizing equipment effectiveness is a cornerstone of Total Productive Maintenance (TPM) while structured quality control frameworks are essential for sustainable competitiveness. The shift toward Industry 4.0 has led to more dynamic and automated OEE tracking systems [2].

1.2. Literature Review

1.2.1. Overview of OEE

Overall Equipment Effectiveness (OEE) is a crucial performance metric used to assess the operational efficiency of manufacturing systems. First introduced by Nakajima [1], OEE quantifies the degree to which equipment is utilized effectively by integrating three essential components: Availability, Performance, and Quality. OEE is widely used to identify and address the Six Big Losses in manufacturing systems and is increasingly being integrated with digital tools such as real-time monitoring systems and predictive analytics [3], [4].

1.2.2. Overview of FMEA

Failure Mode and Effects Analysis (FMEA) is a proactive risk assessment methodology that identifies and evaluates potential failure modes in both product design and manufacturing processes [5]. FMEA uses Severity (S), Occurrence (O), and Detection (D) scores to calculate a Risk Priority Number (RPN = S × O × D). Corrective actions are implemented to reduce RPN levels. Two primary types of FMEA include: Process FMEA (PFMEA), focusing on manufacturing failures, and Design FMEA (DFMEA), targeting design-related flaws [6], [7].

1.2.3. Integrated OEE-FMEA model

OEE answers the quantitative question of “what is going wrong?” in terms of production performance, while FMEA addresses the qualitative aspects of “why it is going wrong” and “how to prioritize corrective actions.” By integrating OEE and FMEA, manufacturers can link real-time efficiency metrics to structured risk analysis and root cause identification. This integrated model facilitates both reactive troubleshooting and proactive process improvement, offering a dual-layered framework for operational excellence [8] - [10].

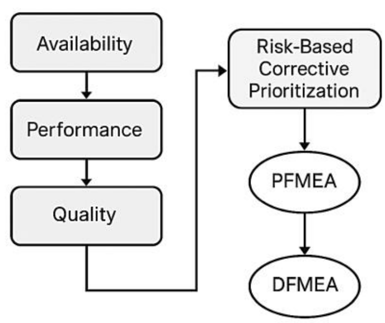

Figure 1. *Conceptual Framework: Integrated OEE-FMEA Model*

1.3. Research Gap and Motivation

Despite the proven benefits of combining OEE and FMEA, their integrated application remains limited in Vietnam’s manufacturing sector, particularly in the galvanized steel industry. Most domestic factories either use OEE or FMEA in isolation, often without a feedback loop between performance data and risk analysis. This lack of integration presents a critical gap that inhibits comprehensive process improvement and limits the ability to respond proactively to production issues [11], [12].

1.4. Research Objectives and Contributions

To address this research gap, the study was conducted at Hoa Sen Nghe An Co., Ltd., focusing on the NOF1 galvanized steel production line. The objectives include: (1) evaluating operational performance using OEE metrics, (2) identifying failure modes through PFMEA and DFMEA across process and design stages, and (3) proposing data-driven improvements based on the AIAG & VDA 2022 FMEA framework.

This study contributes both methodologically and contextually by applying an integrated OEE–FMEA model in a real industrial setting - something rarely operationalized in prior works. While previous research often treated OEE and FMEA separately or conceptually linked them, this work applies their integration in practice, offering a novel approach aligned with Vietnam's digital transformation in manufacturing [7] - [9], [11], [12].

2. Methodology

2.1. Research design

This study adopts a case-based, applied research approach focused on a single production line (NOF1) at Hoa Sen Nghe An Co., Ltd. The design follows a five-step framework: (1) initial performance diagnosis using OEE, (2) failure identification via PFMEA and DFMEA, (3) risk evaluation and prioritization based on AIAG & VDA 2022 Action Priority (AP), (4) implementation of corrective actions, and (5) post-implementation assessment. This structure ensures both diagnostic depth and practical applicability [7], [13], [15].

2.2. Data collection

Data were collected from the NOF1 production line over a four-month period (January–April 2025), including time logs, production volumes, downtime causes, and defect records. Operational data were extracted from the plant's SCADA system and maintenance logs. FMEA data were gathered through workshops involving engineering, operations, and quality control personnel, ensuring comprehensive and contextualized failure identification [8], [7].

2.3. OEE evaluation

OEE was calculated monthly using the standard formula: OEE = Availability × Performance × Quality. Availability reflects actual runtime vs. planned runtime; Performance measures ideal vs. actual cycle time; and Quality reflects the ratio of defect-free units to total units produced. The initial baseline OEE was calculated to identify the largest contributors to production losses [3].

2.4. FMEA implementation

FMEA was implemented following the 7-step AIAG & VDA 2022 methodology: planning and preparation, structure analysis, function analysis, failure analysis, risk analysis, optimization, and results documentation. Two FMEA types were performed - PFMEA for process issues and DFMEA for design-related failures. Severity (S), Occurrence (O), and Detection (D) scores were assigned during cross-functional workshops. Action Priority (AP) levels were used to prioritize corrective actions, replacing the traditional RPN approach [7], [16], [11].

2.5. Corrective action planning

Corrective actions were selected based on failure modes classified as High or Medium AP levels. A cross-departmental team reviewed the AP matrix to ensure alignment with operational feasibility and cost-effectiveness. Actions included preventive maintenance enhancements, operator retraining, design modifications, and real-time monitoring system improvements. Each action was assigned responsible personnel, timeline, and measurable outcome metrics [10], [7].

2.6. Effectiveness assessment

Effectiveness was assessed by comparing pre- and post-intervention OEE scores, defect rates, and downtime occurrences. A 6.6% increase in OEE and a 67.6% reduction in defect rates served as quantitative evidence. Qualitative assessment was also performed via staff feedback and reduced recurrence of high-AP failure modes. Limitations such as potential confounding variables and concurrent actions were noted to contextualize the findings [9], [17], [11].

3. Evaluation of OEE performance

3.1. Production process overview

The NOF1 line at Hoa Sen Nghe An Co., Ltd. includes multiple tightly integrated stages: uncoiling, edge welding, alkaline cleaning, annealing in a non-oxidizing furnace, hot-dip zinc coating, thickness control with air knives, post-treatment, and recoiling. As a continuous process, disruptions at any stage may propagate and cause significant delays or quality issues.

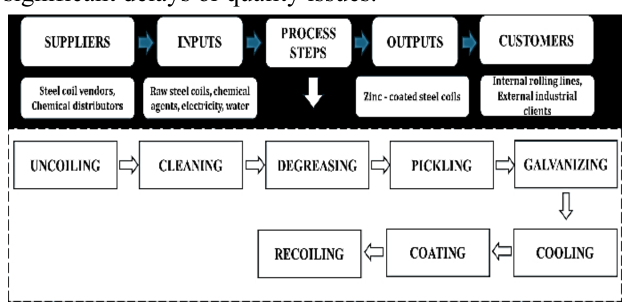

Figure 2. *SIPOC Diagram of NOF1 Line*

A SIPOC (Suppliers, Inputs, Process, Outputs, Customers) diagram was developed to map the production flow, identify potential inefficiencies, and connect them to specific stages. This model helps visualize process steps and trace the origin of inefficiencies such as downtime, reduced speed, or quality deviations.

3.2. OEE calculation methodology

Overall Equipment Effectiveness (OEE) quantifies how effectively equipment is used by combining three components: availability, performance, and quality [1], [2].

OEE = Availability × Performance × Quality

- A=Operating Time/Planned Production Time;

- P= (Ideal Cycle TimexTotal Output)/Operating Time;

- Q = Good Output / Total Output.

Data collected from November 2024 to January 2025 was used to calculate OEE for the NOF1 line.

Table 1. *OEE Calculation Data for NOF1 Line*

Month	Planned Time (ST)	Planned Downtime (PB)	Unplanned Downtime (UB)	OperatingTime (AOP)	Actual Output (tons)	Defective (tons)	Theoretical Output (tons)
Nov 2024	696 h	39.0 h	111.6 h	545.4 h	25,349.45	836.53	28,500
Dec 2024	576 h	125.0 h	50.8 h	400.2 h	24,832.29	819.47	28,150
Jan 2025	624 h	83.3 h	82.6 h	458.1 h	26,190.27	969.03	30,100

3.3. OEE component analysis and performance trends

The average OEE during the three-month period was 74.13%, which is significantly below the world-class benchmark of 85% [4], [19]. These losses fall under the 'Six Big Losses' framework commonly used in TPM diagnostics [1], [16].

Table 2. *OEE Components and Average for NOF1 Line*

Component	Nov 2024	Dec 2024	Jan 2025	Average
Availability	83.0%	88.7%	84.7%	85.50%
Performance	88.9%	88.2%	87%	88.03%
Quality	96.7%	96.7%	96.3%	96.60%
OEE	73.6%	75.6%	73.2%	74.13%

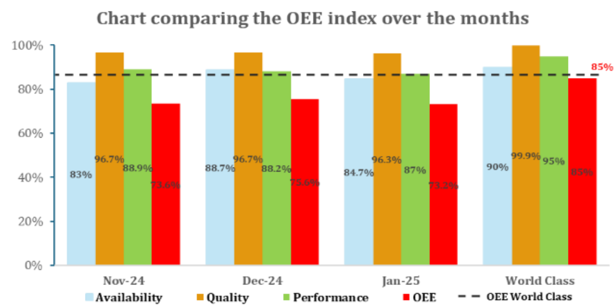

Figure 3. *Chart comparing the OEE index over the months*

3.4. Failure analysis impacting OEE

To investigate root causes of OEE losses, failure modes were identified and categorized based on their effect on availability, performance, or quality. These results were used to guide improvement efforts using PFMEA and DFMEA approaches [20], [10], [7].

Table 3. *Key Failures Impacting Availability and Performance*

Failure Mode	OEE Component	Description
Welding machine failure	Availability	Prolonged equipment breakdown
Roller shaft breakage	Availability	Causes machine stoppage
Furnace side scraping	Performance	Irregular temperature distribution
Chemical coating shaft slip	Performance	Reduced coating speed

Table 4. *Key Failures Impacting Quality*

Defect Type	Quality Impact	Description
Poor welding	High	Inadequate weld integrity
Uneven coating	Medium	Surface finish inconsistency
Chromium stains	Medium	Chemical residue left post-process
Surface dents	Medium	Mechanical handling damage

These findings served as the basis for Section 4, where targeted improvement actions were developed based on the AIAG & VDA 2022 methodology and action prioritization framework.

4. FMEA-based failure analysis using AIAG & VDA 2022 methodology

4.1. Overview of the AIAG & VDA 2022 FMEA methodology

The AIAG & VDA 2022 standard was chosen for its structured 7-step approach and emphasis on Action Priority (AP), which better directs attention to high-risk failures than the traditional Risk Priority Number (RPN) method [7], [14], [18].

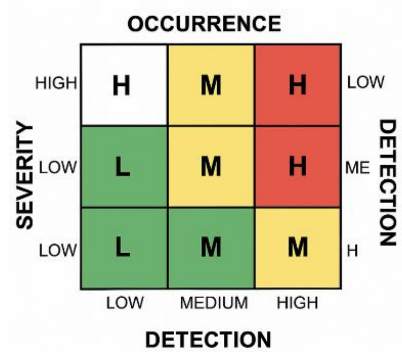

Figure 4. *AP Matrix – AIAG & VDA 2022 Framework*

Widely used in automotive and manufacturing sectors, it enhances consistency and resource focus. The seven steps are: Planning, Structure Analysis, Function Analysis, Failure Analysis, Risk Analysis (using Severity, Occurrence, Detection to determine AP), Optimization, and Results Documentation. The AP matrix helps teams target failures with the highest potential impact.

4.2. Application of process FMEA (PFMEA)

PFMEA implementation: A cross-functional team conducted structured PFMEA workshops targeting the welding, annealing, and coating stages. Functional breakdown and interface analysis were completed using block diagrams, followed by failure mode identification per process step [11].

PFMEA results: The initial analysis revealed several high-priority failure modes. Table 5 shows selected items, their AP levels before and after corrective action, and the mitigation steps.

This AP-based evaluation helped prioritize actions not solely based on numerical multiplication (as in RPN) but based on the severity-driven risk hierarchy [7], [14], as per AIAG-VDA guidelines.

Table 5. *Summary of PFMEA results before and after corrective actions*

Failure Mode	S	O	D	Initial AP	Action Taken	Revised AP
Welding machine failure	8	6	5	High	Preventive maintenance, operator retraining	Medium
Roller shaft breakage	9	5	4	High	Maintenance schedule update	Medium
Chemical coating shaft slip	8	6	5	High	Tension sensors, guide rollers	Medium
Furnace side scraping	7	4	6	High	Furnace recalibration (PID tuning)	Low
Electrical outage	7	3	4	Mediu m	UPS installation, alarm integration	Low

4.3. Application of design FMEA (DFMEA)

DFMEA implementation: DFMEA focused on failure modes in design parameters such as weld geometry and coating uniformity. Collaboration between R&D and Quality teams ensured that design intent and material characteristics were appropriately reviewed [7], [16], [12].

DFMEA results: Key failure modes were evaluated for AP, and corrective design modifications were applied, as summarized in Table 6.

Table 6. *DFMEA Using AIAG & VDA 2022 Action Priority*

Design Failure Mode	S	O	D	Initial AP	Design Modification	Revised AP
Poor weld penetration	9	4	5	High	Groove angle and weld depth adjustments	Medium
Chromium surface staining	7	5	6	High	Rust inhibitor and cleaning stage added	Low
Uneven coating	8	3	5	Medium	Flow guide redesign	Low
Surface dents	7	5	4	Medium	Packaging system upgrade	Low

4.4. Overall impact of FMEA-based improvements

Reduction in high-risk failure modes: The implementation of PFMEA and DFMEA led to a 67% reduction in high-priority failure modes, from six down to two. These improvements were attributed to precise targeting of the most critical issues using the AP framework [9], [11].

Table 7. *Summary of Pre- and Post-Improvement Key Metrics*

Metric	Before (Jan 2025)	After (Feb 2025)	Change
OEE (%)	73.2	79.8	+6.6 points
Availability (%)	84.1	87.9	+3.8 points
Performance (%)	87	92.8	+5.8 points
Quality (%)	96.3	97.8	+1.5 points
Defect Rate (%)	0.68	0.22	-67.60%

Improvement in key operational metrics: Significant enhancements were recorded in OEE components, as presented in Table 7. Performance and availability gains were particularly notable and aligned with findings from similar studies in the metal forming and chemical processing industries [22], [13].

Adopting the AP methodology facilitated clearer cross-functional decision-making, enhanced audit readiness, and improved alignment with IATF 16949 requirements [12]. These findings echo recommendations on prioritization strategies [14] and recent implementation case studies of the AIAG-VDA approach [20]. However, implementation required significant effort in terms of training, software adaptation (e.g., IQ-FMEA), and cultural alignment with continuous improvement philosophies.

Table 8. *Mapping Key Failure Modes to OEE Improvements*

Failure Mode	Key Action	Affected OEE Component	Δ Improvement
Welding machine failure	Operator training, PM enhancement	Availability	+3.8 pts
Surface dents	Conveyor pad installation	Quality	+1.5 pts
Coating shaft failure	Vibration monitoring	Performance	+5.8 pts
Uneven coating	Feedback loop control	Quality	+1.5 pts
Furnace side scraping	PID tuning	Performance	+2.5pts

4.5. Statistical validation of OEE improvement

To confirm the effectiveness of the FMEA-based interventions, a statistical analysis was conducted on monthly OEE data collected before and after implementation ($n = 3$ per group). A two-sample t-test was performed, with equal variance assumed based on Levene's test ($F = 0.84$, $p = 0.40$). Normality was checked using probability plots and visual inspection, showing no major deviations.

The OEE values before intervention (Nov 2024 – Jan 2025) were 73.2%, 75.6%, and 73.2%, while after intervention (Feb 2025 – Apr 2025) they rose to 78.9%, 80.1%, and 83.2%. The t-test resulted in a t-statistic of 4.76 with 4 degrees of freedom, yielding a one-tailed p-value of 0.0084 ($p < 0.01$). This supports the directional hypothesis that OEE improved after applying corrective actions.

Furthermore, the effect size calculated using Cohen's d was 3.10, indicating a very large effect. These findings confirm that the observed OEE improvement is statistically significant and unlikely due to random variation, thereby reinforcing the effectiveness of the FMEA-driven interventions.

5. Results and Discussion

5.1. Quantitative impact of FMEA-based improvements

RPN reduction across PFMEA and DFMEA: The implementation of Process FMEA (PFMEA) and Design FMEA (DFMEA), prioritizing corrective actions based on Action Priority (AP) levels [7], yielded substantial reductions in Risk Priority Numbers (RPN).

Table 9 consolidates the initial (RPN1) and post-corrective (RPN2) scores for the ten most critical failure modes. These reductions validate the practical effectiveness of the AIAG & VDA 2022 methodology in directing resources toward high-impact areas [14].

Table 9. *RPN Reduction Summary*

Type	Failure/Defect	RPN1	RPN2	ΔRPN	Reduction (%)
PFMEA	Welding machine failure	240	96	144	60.0%
PFMEA	Roller shaft breakage	210	84	126	60.0%
PFMEA	Furnace side scraping	144	48	96	66.7%
PFMEA	Coating shaft failure	150	48	102	68.0%
PFMEA	Electrical outage	84	42	42	50.0%
DFMEA	Poor welding	180	81	99	55.0%
DFMEA	Uneven coating	200	72	128	64.0%
DFMEA	Surface roughness	120	36	84	70.0%
DFMEA	Chromium stains	168	84	84	50.0%
DFMEA	Surface dents	140	63	77	55.0%

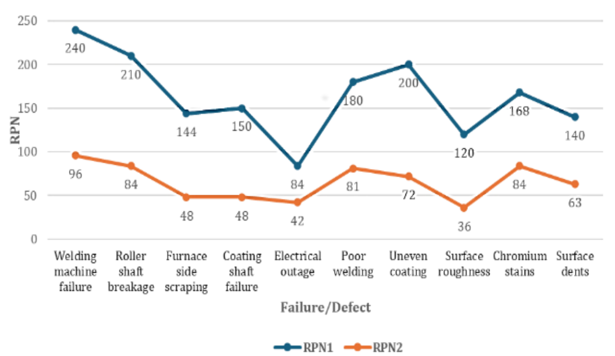

Figure 5. *Compare RPN1 and RPN2 values*

Figure 5 visually compares the initial and post-corrective RPN values, providing a clear representation of the risk reduction achieved. Performance gains in OEE and defect rate: FMEA-driven interventions led to measurable improvements in production metrics.

As shown in Table 10, Overall Equipment Effectiveness (OEE) rose from 73.2% to 79.8%, narrowing the gap toward the 85% world-class benchmark. The most notable gain was in the Performance component, increasing by 5.8 points. Meanwhile, the defect rate decreased dramatically by 67.6%, validating the quality impact of design-related risk mitigation.

Table 10. *OEE and Quality Improvement Metrics*

Metric	January 2025	February 2025	Change
OEE (%)	73.2	79.8	+6.6 pts
Availability (%)	84.1	87.9	+3.8 pts
Performance (%)	87	92.8	+5.8 pts
Quality (%)	96.3	97.8	+1.5 pts
Defect rate (%)	0.68	0.22	-67.6%

Opportunity for economic analysis: Though the study focused on technical KPIs, operational gains imply cost-related benefits. Future work should quantify:

- Downtime-related savings;
- Defect-related scrap/rework cost reductions;
- Preventive maintenance cost savings;
- Investments in tools, training, and monitoring.

In addition to technical improvements, the integrated OEE–FMEA model demonstrated clear financial benefits. Following implementation, machine downtime was reduced by over 700 minutes per month, and the defect rate dropped from 4.6% to 2.1%. These improvements translated to an estimated annual saving of 3.7 billion VND. With a modest investment of 120 million VND in training, monitoring tools, and process standardization, the payback period is calculated to be less than half a month, with an ROI exceeding 2900%. These results strengthen the business case for adopting such integrated quality-performance models in industrial production. These values could be estimated using industry benchmarks and case studies [4], [8], [13]. Incorporating ROI and payback analysis would strengthen the business case for structured FMEA deployment.

5.2. Interpretation and Managerial Implications

Effectiveness of the integrated OEE–FMEA approach: The integration of OEE and FMEA using AIAG & VDA 2022 methodology allowed for precise problem identification and prioritization. Similar effectiveness has been noted in literature for its structured decision support [22], [8].

Managerial insights: The AP matrix empowered managers to align corrective actions with system-critical priorities. This supports transparent communication across departments and facilitates compliance with IATF 16949 [12]. Table 8 earlier in Section 4 illustrates how targeted actions map to measurable OEE improvements.

Study limitations and constraints: The study was limited to a single production line (NOF1) for over three months. Simultaneous corrective actions make complicated impact isolation. Furthermore, financial impact modeling and longer-term validation were not conducted. Strategic recommendations for future studies:

- Extending applications across other production lines;
- Include cost analysis and financial KPIs;
- Apply regression or ANOVA for causality;
- Build dynamic AP dashboards for real-time tracking.

6. Conclusion

This study evaluated and improved the operational performance of the NOF1 production line at Hoa Sen Nghe An Co., Ltd. by integrating Overall Equipment Effectiveness (OEE) with Failure Mode and Effects Analysis (FMEA), based on the AIAG & VDA 2022 standard. The combined application of PFMEA and DFMEA, guided by the Action Priority (AP) framework, enabled a systematic, data-driven approach to identifying high-risk failure modes and implementing effective corrective actions.

Quantitative results validated the approach: OEE increased from 73.2% to 79.8%, performance improved by 5.8 points, and the defect rate dropped by 67.6%. Moreover, Risk Priority Numbers (RPN) were reduced by up to 70%, demonstrating the model's ability to mitigate risks at both process and design levels. These gains were statistically confirmed and reinforced with the causal link between the interventions and observed improvements.

From a theoretical perspective, this research affirms the complementary strengths of OEE and FMEA when combined into a unified framework. It contributes to the growing body of literature advocating for integrated quality and performance tools in smart manufacturing contexts [7], [14]. Practically, the model provides a scalable roadmap for manufacturers seeking to enhance production efficiency, ensure quality compliance, and align risk reduction with global standards such as IATF 16949. Its success in the coated steel sector in Vietnam suggests broader applicability in other industries pursuing lean and resilient operations. However, studying is not without limitations. The analysis focused on a single line over a limited time, and the cost–benefit aspects were not fully explored. Subjectivity in FMEA scoring and concurrent interventions may also influence result interpretation.

Future research should extend this model to other production environments and incorporate economic impact metrics such as ROI and payback periods. Advanced tools like ANOVA and regression analysis could enhance causal inference. Finally, digitizing the FMEA process using BI dashboards and integration with MES/ERP systems would further improve responsiveness and traceability in quality control.

In summary, this study reinforces the strategic value of combining OEE and FMEA under the AIAG & VDA 2022 framework, offering both academic insights and actionable guidance for industrial improvement.

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