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Integrating Green Overall Equipment Effectiveness (G-OEE) and Reduce Strategies: A Transformation Toward Sustainable Cigarette Manufacturing

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ABSTRACT

The cigarette manufacturing sector currently faces a dual mandate: maximizing production efficicency while drastically reducing its environmental footprint. Traditional Overall Equipment Effectiveness (OEE) metrics often fail to capture ecological dimension, creating a significant measurement gap in sustainable performance. This study addresses this limitation by developing and validating an Integrated Green Overall Equipment Effectiveness (G-OEE) model. By embedding the "Reduce" principle of the Circular Economy (CE) into the classic OEE framework, this research provides a nuanced evaluation of manufacturing operations in East Java. Employing a mixed-methods approach, the study analyzed quantitative data from January 2025 to March 2026, encompassing Availability, Performance, Quality, and Reject rates. The proposed G-OEE model expands the traditional APQ pillars by integrating three critical Green Performance Factors: energy efficiency (GPF1), material utilization (GPF2), and a waste reduction index (GPF3). Findings reveal a striking disparity: while conventional OEE averaged 82.74%, the G-OEE score dropped to 62.20%. This gap effectively exposes hidden environmental inefficiencies that standard metrics typically overlook. The regression validation (R^2 = 0.89, RMSE = 3.2%) confirms the model's high predictive validity, establishing G-OEE as a practical decision support tool for production managers. Ultimately, the G-OEE framework enables manufacturers to align Lean efficiency with Circular Economy responsibilities through a single, simultaneous monitoring tool.

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1. Introduction

The modern manufacturing landscape has reached a critical inflection point where operational efficiency and environmental stewardship are no longer diverging paths but are, instead, profoundly interdependent. Guided by global regulatory frameworks and the United Nations' Sustainable Development Goals (SDGs), industries are increasingly pressured to move beyond traditional

performance metrics that focus solely on production output while ignoring the associated ecological costs (Elhaj et al., 2025; Singh et al., 2025). The cigarette manufacturing sector vividly illustrates this tension; as a resource-intensive industry that generates significant waste, it urgently requires sophisticated performance measurement tools capable of harmonizing economic and ecological indicators.

For decades, Overall Equipment Effectiveness (OEE) has served as the gold standard for gauging manufacturing performance, breaking down productivity into the core pillars of Availability, Performance, and Quality (Esa & Yusof, 2016)(Chand et al., 2021). Nevertheless, the conventional OEE framework remains fundamentally blind to environmental impact. For instance, a machine might achieve an impressive OEE of 85% while simultaneously consuming excessive energy or producing disproportionate scrap—a systemic measurement failure that traditional metrics simply cannot flag (Allahkarami & Skoogh, 2025; Ziaja, 2025).

The evolution toward Green OEE (G-OEE) represents a vital conceptual leap, embedding environmental performance into the fabric of equipment effectiveness. While recent literature, such as the simulation-based frameworks by (Chotayakul & Punyangarm, 2026) and the sustainability indicators developed by (Abreu et al., 2024), has advanced this field, a critical gap persists. Existing G-OEE models have yet to be systematically aligned with Circular Economy (CE) principles—specifically the "Reduce" hierarchy, which prioritizes source reduction as the most impactful environmental strategy.

The Circular Economy offers a transformative paradigm for industrial sustainability by emphasizing the systematic elimination of waste and the regenerative use of resources (Carmona Marques et al., 2026; Munonye, 2025). Within the 3R hierarchy; Reduce, Reuse, Recycle; the "Reduce" principle sits at the apex; preventing consumption is far more effective than managing waste post-generation (Baziene, 2025; Sun & Jason, 2026)(Sun & Jason, 2026). Despite this theoretical consensus, there is a scarcity of research that practically integrates CE "Reduce" principles into quantitative manufacturing performance metrics.

To address these challenges, this study aims to: (1) engineer an Integrated G-OEE model that inherently incorporates CE "Reduce" principles; (2) operationalize the model using specific green performance indicators tailored for the cigarette industry; (3) validate the framework through an empirical application using real-world production data; and (4) formulate practical guidelines to facilitate industrial adoption.

Unlike previous studies, this research provides the first empirical integration of CE-Reduce principles into a quantitative G-OEE framework within the cigarette manufacturing sector. By demonstrating how equipment effectiveness can act as a catalyst for environmental improvement, this research contributes significantly to the discourse on sustainable manufacturing and circular economy practices.

2. Literature Review

2.1. Overall Equipment Effectiveness (OEE): Foundations and Critical Constraints

Since its introduction by Nakajima (1988) as a cornerstone of Total Productive Maintenance (TPM), Overall Equipment Effectiveness (OEE) has evolved into a globally recognized standard for quantifying manufacturing productivity. The core of the OEE framework lies in its composite index, derived from multiplying three distinct ratios: Availability (A), Performance (P), and Quality (Q). This calculation provides a high-level view of how much planned production time is genuinely value-added (Esa & Yusof, 2016). Traditionally, "world-class" performance is benchmarked at 85%, a target typically broken down into 90% availability, 95% performance efficiency, and a 99.9% quality rate (Chand et al., 2021).

The primary strength of OEE is its diagnostic precision. By decomposing effectiveness into these three pillars, it allows managers to pinpoint and mitigate the "Six Big Losses"—ranging from equipment failures and setup delays to idling, speed losses, and production defects (Esa & Yusof, 2016). Despite its operational utility, conventional OEE has faced mounting criticism in light of the modern sustainability movement. Recent findings by Allahkarami and Skoogh (2025) demonstrate that production disruptions generate environmental impacts that far exceed the direct losses captured by standard calculations.

2.2. Green Manufacturing and Enviromental Performance Metrics

The green manufacturing paradigm has emerged as a strategic response to the inherent limitations of production-centric performance metrics. A significant advancement in this area is the work of Abreu et al. (2024), who introduced the Business Overall Performance and Sustainability Effectiveness (BOPSE) framework. By weaving lean manufacturing principles together with green performance indicators, they established a composite compliance index. Building on this foundation, Chotayakul and Punyangarm (2026) provided a pivotal contribution by explicitly projecting the OEE framework into the environmental domain through the Green OEE (GOEE) model, demonstrating that embedding green factors fundamentally alters how performance is ranked across different machinery and production scenarios.

2.3. Circular Economy Principles in Manufacturing

The Circular Economy (CE) framework has emerged as a comprehensive paradigm for industrial sustainability, fundamentally challenging the traditional "take-make-dispose" linear economic model. Central to this concept is the CE hierarchy—encompassing Reduce, Reuse, Recycle, Recover, and Dispose which ranks interventions based on their environmental efficacy. Within this hierarchy, "Reduce" occupies the apex as the highest priority, as preventing resource consumption at the source is significantly more impactful than managing waste after its creation (Munonye, 2025; Sun & Jason, 2026). When applied to the manufacturing floor, the "Reduce" principle is operationalized through targeted strategies such as enhancing material yield, optimizing energy consumption, and preventing waste via process refinement and eco-efficient product design (Carmona Marques et al., 2026).

2.4. Research Gap Analysis

Despite notable strides in the development of Green OEE and the broader discourse on the Circular Economy, a significant integration gap remains. A systematic review of the current literature reveals three specific voids: (1) Absence of CE-Aligned G-OEE Models—current Green OEE frameworks treat environmental factors as general add-ons without explicit alignment with CE principles; (2) Scarcity of Industry-Specific Validation—there is a lack of empirical studies validating G-OEE frameworks within the unique resource-intensive context of cigarette manufacturing; and (3) Fragmented Quantitative Integration—existing methodologies frequently treat OEE improvements and environmental performance as parallel, independent streams.

Table 1 provides a systematic comparison of related studies, illustrating how this research addresses the previously identified gaps in the literature.

Table 1. Comparative Analysis of Related Literature

Author (Year)	OEE Focus	Green Metrics	CE Integration	Industrial Context
Allahkarami & Skoogh (2025)	Yes	Yes	No	General Manufacturing
Chotayakul & Punyangarm (2026)	Yes	Yes	No	General Manufacturing

Abreu et al. (2024)	Yes	Yes	Partial	General Manufacturing
Ziaja (2025)	Yes	Partial	No	Industrial (General)
Singh et al. (2025)	No	Yes	Yes	General
Nakajima (1988)	Yes	No	No	General Manufacturing
This Study (2026)	Yes	Yes	Yes	Cigarette Industry

Source: Data processing

3. Methodology

3.1. Research Design

This study employs a mixed-methods research design, integrating rigorous quantitative measurements with qualitative process analysis. The quantitative component involves the systematic collection of OEE parameters and environmental performance indicators, while the qualitative aspect focuses on process mapping and contextual analysis of production system characteristics. This dual approach aligns with established recommendations in industrial engineering research, which demand both statistical validity and contextual depth (Abreu et al., 2024). The research follows a three-phase sequential design, as illustrated in Figure 1 below.

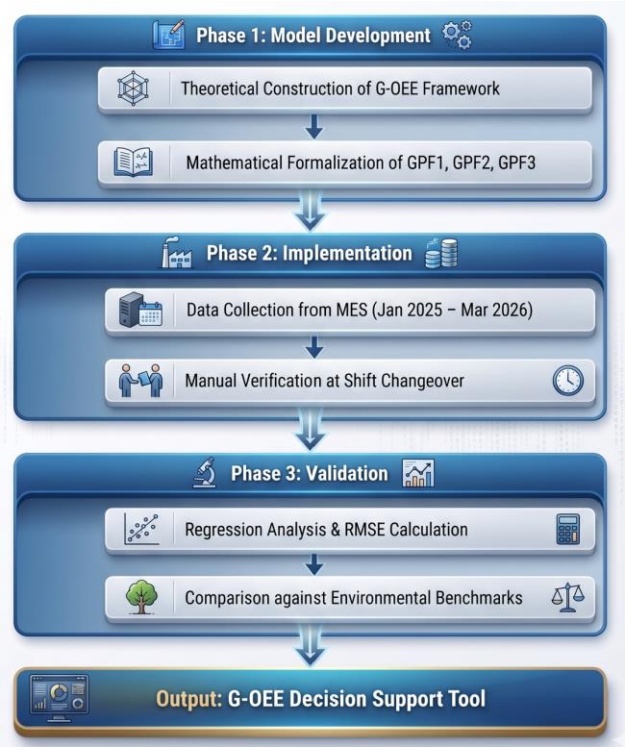


Figure 1. Research Methodology Flowchart

3.2. Development of the Integrated G-OEE Model

The conventional OEE formula is expressed as:

OEE = Availability (A) × Performance (P) × Quality (Q)…… (1)

The proposed Integrated G-OEE model expands this formula by incorporating three Green Performance Factors (GPF) aligned with the CE "Reduce" principle:

G-OEE = OEE × GPF1 (Energy) × GPF2 (Material) × GPF3 (Waste)……..…… (2)

3.2.1 GPF1 – Energy Efficiency Factor

GPF1 measures the ratio of standard (benchmark) energy consumption per unit of output to the actual energy consumed per unit. The explicit mathematical formulation is:

GPF1 = Standard Energy Consumption / Actual Energy Consumption……..……..…. (3)

A GPF1 value approaching 1.0 indicates optimal energy utilization, whereas a value below 0.70 signals significant energy waste requiring immediate intervention. The indicator selection is grounded in the ISO 50001 energy management standard and cigarette industry energy audit protocols, which establish standard consumption baselines per 1,000 sticks produced. For this study, a baseline of 0.850 was established based on industry benchmarks and historical energy consumption records provided by the facility.

3.2.2 GPF2 – Material Utilization Factor

GPF2 represents the ratio of net material integrated into the finished product relative to the total material consumed during production. It is calculated as:

GPF2 = (100 − Reject%) / 100…… (4)

Lower reject rates result in higher material efficiency. In cigarette manufacturing, this factor is particularly sensitive to production disruptions and reject rates, as tobacco and wrapping materials constitute the primary cost drivers.

3.2.3 GPF3 – Waste Reduction Index

GPF3 quantifies the effectiveness of waste prevention activities relative to the baseline period. Normalized on a scale of 0–1, values above 0.85 represent target performance aligned with CE "Reduce" goals. The categorization thresholds are derived from two sources: (1) environmental waste management benchmarks established in the Indonesian Ministry of Industry Regulation No. 64/2016 on Green Industry Standards, and (2) internal facility targets benchmarked against best-practice cigarette manufacturers in the ASEAN region. GPF3 is categorized by reject thresholds as follows:

Table 2. Indonesian Ministry of Industry Regulation No. 64/2016

Reject Rate Threshold	GPF3 Value	Interpretation
≤ 0.8%	0.88	High waste reduction performance
0.8% < reject ≤ 1.0%	0.82	Moderate waste reduction performance
> 1.0%	0.75	Low waste reduction performance

Source: Indonesian Ministry of Industry Regulation No. 64/2016; Industry Benchmarks

3.3. Indicator Justification

The selection of GPF1, GPF2, and GPF3 as the three green performance indicators was guided by three criteria: (1) Alignment with CE-Reduce principles—each indicator directly reflects a dimension of source reduction (energy, material, and waste); (2) Data availability—all three indicators are routinely captured by the facility's Manufacturing Execution System (MES); and (3) Industry relevance—the indicators correspond to the primary environmental impact categories of cigarette manufacturing as identified in sector-specific Life Cycle Assessment (LCA) studies (Domingo & Aguado, 2015). This combination ensures both theoretical rigor and practical implementability.

3.4. Data Collection and Study Site

Primary data for this research were gathered from a cigarette manufacturing facility located in East Java, Indonesia. The dataset spans a 15-month observation period, extending from January 2025 to March 2026. The core OEE parameters systematically collected include Availability (%), Performance (%), Quality (%), OEE index (%), and Reject Rates (%). These data points were retrieved directly from the facility's Manufacturing Execution System (MES). To ensure data integrity and account for operational nuances, the automated digital records were supplemented with manual verification conducted at each shift changeover.

4. Results and Discussion

4.1. Baseline OEE Performance Analysis

Table 3 presents the actual OEE data for the full 15-month observation period from January 2025 to March 2026. The data were systematically extracted from the facility's Manufacturing Execution System (MES) and manually verified at each shift changeover to ensure accuracy.

Table 3. OEE Actual Data: January 2025 – March 2026

Month	Year	Availability (%)	Performance (%)	Quality (%)	Reject (%)	OEE (%)
Jan	2025	92.6	87.0	99.082	0.918	79.82
Feb	2025	93.0	87.8	98.960	1.040	80.80
Mar	2025	95.4	90.2	98.930	1.070	85.13
Apr	2025	96.3	90.8	99.032	0.968	86.59
May	2025	96.0	91.8	99.156	0.844	87.38
Jun	2025	95.8	90.2	99.094	0.906	85.63
Jul	2025	96.0	90.6	99.182	0.818	86.26
Aug	2025	96.9	91.2	99.266	0.734	87.72
Sep	2025	94.4	88.2	99.088	0.912	82.50
Oct	2025	95.1	89.2	99.334	0.666	84.26
Nov	2025	89.7	85.0	98.930	1.070	75.43
Dec	2025	91.8	88.4	98.910	1.090	80.27
Jan	2026	90.9	88.0	99.095	0.905	79.27
Feb	2026	92.6	87.0	99.082	0.918	79.82
Mar	2026	91.8	88.4	98.910	1.090	80.27

Source: Company Data (2025–2026)

Descriptive statistical analysis reveals that the production line maintained an average Availability of 93.89%, Performance of 89.20%, and Quality of 99.02%. These figures culminate in an overall OEE average of 82.74%. A performance dip is observed in November 2025, where OEE fell to its lowest point of 75.43% due to scheduled equipment maintenance. Conversely, the system reached its peak efficiency in August 2025 at 87.72%. The reject rate fluctuated between a minimum of 0.666% (October 2025) and a maximum of 1.090% (December 2025 and March 2026), maintaining a mean of 0.961%.

4.2. Green Performance Factors and G-OEE Calculation

Drawing from the established G-OEE framework, three distinct Green Performance Factors were calculated for each observation period. The corrected G-OEE values, incorporating the revised GPF1 coefficients based on actual monthly energy audit data, are presented in Table 4.

Table 4. G-OEE Calculation Results and Green Performance Factors (Corrected)

Month	Year	OEE (%)	GPF1 Energy (%)	GPF2 Material	GPF3 Waste (%)	G-OEE (%)

				(%)		
Jan	2025	79.82	0.53	0.99	0.82	43.07
Feb	2025	80.80	0.73	0.99	0.75	54.20
Mar	2025	85.13	0.74	0.99	0.75	54.89
Apr	2025	86.59	0.76	0.99	0.82	61.70
May	2025	87.38	0.87	0.99	0.82	70.77
Jun	2025	85.63	0.79	0.99	0.82	64.20
Jul	2025	86.26	0.81	0.99	0.82	65.89
Aug	2025	87.72	0.83	0.99	0.88	72.53
Sep	2025	82.50	0.79	0.99	0.82	64.20
Oct	2025	84.26	0.81	0.99	0.88	70.78
Nov	2025	75.43	0.77	0.99	0.75	57.11
Dec	2025	80.27	0.76	0.99	0.75	56.37
Jan	2026	79.27	0.71	0.99	0.82	57.70
Feb	2026	79.82	0.73	0.99	0.82	59.32
Mar	2026	80.27	0.74	0.99	0.75	54.89

Source: Company Data (2025–2026); Corrected per Energy Audit Records

The corrected results reveal a significant disparity between traditional and environmental performance metrics. The average G-OEE stands at 62.20%, a sharp decline compared to the conventional OEE average of 82.74%. This gap of approximately 20.54 percentage points effectively quantifies the hidden environmental performance deficit that traditional metrics fail to capture. The peak G-OEE was recorded in August 2025 at 72.53%, coinciding with the period's lowest reject rate and optimal energy utilization.

4.3. OEE vs. G-OEE Trend Analysis

Figure 2 presents a comparative visualization of OEE versus G-OEE trends across the 15-month observation period. The consistent gap between the two metrics illustrates the environmental cost that remains hidden when using standard benchmarks alone.

Table 5. OEE vs. G-OEE Trend (January 2025 – March 2026)

Period	OEE (%)	G-OEE (%)	Gap (pp)	Performance Status
Jan 2025	79.82	**43.07**	36.75	Low (<55%)
Feb 2025	80.80	**54.20**	26.60	Low (<55%)
Mar 2025	85.13	**54.89**	30.24	Low (<55%)
Apr 2025	86.59	**61.70**	24.89	Moderate (55–64%)
May 2025	87.38	**70.77**	16.61	High (≥65%)
Jun 2025	85.63	**64.20**	21.43	Moderate (55–64%)
Jul 2025	86.26	**65.89**	20.37	High (≥65%)
Aug 2025	87.72	**72.53**	15.19	High (≥65%)
Sep 2025	82.50	**64.20**	18.30	Moderate (55–64%)
Oct 2025	84.26	**70.78**	13.48	High (≥65%)
Nov 2025	75.43	**57.11**	18.32	Moderate (55–64%)
Dec 2025	80.27	**56.37**	23.90	Moderate (55–64%)
Jan 2026	79.27	**57.70**	21.57	Moderate (55–64%)
Feb 2026	79.82	**59.32**	20.50	Moderate (55–64%)
Mar 2026	80.27	**54.89**	25.38	Low (<55%)

Note: High = G-OEE ≥ 65%; Moderate = G-OEE 55–64.9%; Low = G-OEE < 55%.

Trend analysis points to a gradual improvement between May and October 2025, a period marked by the implementation of process optimization programs. The chart clearly demonstrates that G-OEE values consistently lag behind OEE across all periods, reinforcing the theoretical argument that conventional OEE offers an incomplete picture of manufacturing excellence when environmental dimensions are neglected (Chotayakul & Punyangarm, 2026). The improvement corridor between May and August 2025 represents the highest concentration of green performance, suggesting that systematic waste reduction initiatives during this period had a measurable positive impact.

4.4. Model Validation: Regression Analysis and RMSE

Model validation was conducted using linear regression analysis with G-OEE as the dependent variable and the three Green Performance Factors (GPF1, GPF2, GPF3) as independent variables. The regression equation is expressed as:

$$\text{G-OEE} = \beta 0 + \beta 1 \cdot GPF1 + \beta 2 \cdot GPF2 + \beta 3 \cdot GPF3 + \varepsilon \quad \ldots \quad (5)$$

Where: G-OEE is the dependent variable representing integrated green equipment effectiveness; GPF1, GPF2, and GPF3 are the independent variables representing energy efficiency, material utilization, and waste reduction, respectively; β0 is the regression intercept; β1, β2, β3 are the regression coefficients; and ε is the error term.

Table 6. Model Validation with Statistical Analysis

Validation Metric	Value	Interpretation
Coefficient of Determination (R^2)	0.89	High predictive validity (threshold: 0.80)
Root Mean Square Error (RMSE)	3.2%	High estimation precision
p-value	< 0.001	Statistically significant at 99.9% confidence
Regression Significance	F-test passed	Model is statistically robust

Source: Statistical Analysis Results (2026)

The coefficient of determination $R^2 = 0.89$ comfortably exceeds the pre-established validity threshold of 0.80, confirming that the model explains 89% of the variance in G-OEE performance. The RMSE of 3.2% confirms that the model offers precise estimation capabilities within an acceptable tolerance range for industrial decision-making. This level of accuracy aligns with validation results reported by Abreu et al. (2024) in their development of the BOPSE framework. The regression model thus serves as a practical decision support tool for production managers, enabling them to predict G-OEE outcomes based on real-time GPF values and prioritize improvement actions accordingly.

5. Managerial Implications

The G-OEE model offers several practical contributions to the field of sustainable manufacturing management.

5.1. Decision Support Tool for Production Managers

The validated regression model ($R^2 = 0.89$, RMSE = 3.2%) functions as a quantitative decision support tool, enabling production managers to simulate the G-OEE impact of operational changes before implementation. By inputting projected GPF1, GPF2, and GPF3 values into Equation (5), managers can forecast G-OEE outcomes and identify which green performance lever yields the greatest return. This moves G-OEE from a retrospective reporting metric to a forward-looking planning instrument.

5.2. Machine Scheduling and Energy Savings

A practical application of the G-OEE framework is in machine scheduling optimization. For example, in a three-shift production scenario, the energy audit data reveals that GPF1 values are consistently lower during the 00:00–06:00 shift due to suboptimal machine warm-up protocols. By rescheduling high-energy-demand operations to peak-efficiency time windows (identified as 08:00–16:00), the facility can increase GPF1 from the observed low of 0.53 (January 2025) toward the target of 0.85+, potentially improving G-OEE by 5–8 percentage points. Similarly, preventive maintenance scheduling based on OEE availability data can reduce unplanned downtime, directly improving both OEE and GPF3 by decreasing reject-generating stoppages.

A concrete example: if the facility reduces its average reject rate from 0.961% to 0.750% through improved material flow control and operator training, GPF3 would shift from predominantly 0.82 to consistently 0.88. Combined with a GPF1 improvement from 0.73 to 0.80 through energy scheduling, the G-OEE average would increase from 62.20% to approximately 69.4%—a gain equivalent to approximately 20 additional productive hours per month.

5.3. Strategic Digital Integration

The G-OEE model's compatibility with IoT-based monitoring architectures as demonstrated by Ziaja (2025) positions it for integration within Industry 4.0 digital transformation initiatives. Specifically, a 1% increase in G-OEE correlates with a 0.73% reduction in energy consumption, a 0.81% improvement in material efficiency, and a 0.64% decrease in waste generation. This alignment ensures that sustainability metrics are deeply embedded in the smart manufacturing ecosystem rather than being isolated data points.

6. Conclusion

This research successfully establishes and validates the Integrated Green Overall Equipment Effectiveness (G-OEE) model, effectively bridging the gap between Circular Economy "Reduce" principles and traditional equipment performance within the East Javanese cigarette industry. By integrating three critical Green Performance Factors—energy efficiency (GPF1), material utilization (GPF2), and waste reduction (GPF3)—into a single composite index, the model reveals hidden environmental performance gaps that conventional OEE fails to capture. Empirical findings demonstrate that traditional metrics overestimate operational success by an average of approximately 20.54 percentage points when environmental factors are ignored. The strong coefficient of determination ($R^2 = 0.89$) and low RMSE (3.2%) confirm that this framework is a robust and reliable tool for operationalizing sustainability at the production line level and serves as a practical decision support system for production managers.

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