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Research Article

Green Maintenance Practices and Composite Equipment Performance: A Trade-off Analysis in Indian Manufacturing

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Abstract

The integration of environmental sustainability principles into industrial maintenance—commonly termed Green Maintenance—represents an emerging frontier in operations management. While theoretical arguments for green maintenance are well-established, empirical evidence on how green maintenance practices interact with composite equipment performance outcomes remains limited, particularly in the context of developing economies. This paper presents a quantitative trade-off analysis based on primary data collected from 96 manufacturing plants across four sectors in India. A Green Maintenance Practice (GMP) score was constructed from five dimensions: eco-friendly lubricant adoption, energy-efficient maintenance scheduling, waste reduction in maintenance operations, green spare parts procurement, and maintenance worker environmental training. Composite Equipment Performance (CEP) was operationalized using a weighted combination of OEE, equipment reliability, and energy efficiency per production unit. Hierarchical regression analysis, supplemented by quadrant-based trade-off mapping, reveals a significant but non-linear relationship between GMP scores and CEP. Plants in the high-GMP/high-CEP quadrant (28.1% of the sample) demonstrate that environmental and performance excellence are simultaneously achievable, with these plants also exhibiting 14.3% lower maintenance costs and 22.7% lower energy consumption compared to the sector average. However, a transition cost effect is identified, where plants in the medium-GMP band (GMP = 40–60) show temporarily depressed CEP scores (mean CEP = 58.4 vs. 64.2 for low-GMP plants), suggesting a U-shaped performance trajectory during green transition. These findings carry important implications for maintenance policy, sustainable operations strategy, and manufacturing competitiveness.

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1. INTRODUCTION

The global manufacturing sector faces the dual imperative of maintaining operational excellence while reducing environmental impact. Maintenance operations—encompassing lubrication, replacement, repair, and overhaul activities—represent a significant source of industrial environmental burden through the consumption of hazardous chemicals, generation of waste oils and contaminated parts, and energy-intensive processes (Jasiulewicz-Kaczmarek, 2014). Simultaneously, maintenance quality is a fundamental determinant of equipment performance, availability, and overall plant productivity.

Green Maintenance emerges at the intersection of these imperatives, representing the deliberate integration of environmental sustainability principles into the planning, execution, and management of maintenance operations. The concept encompasses a broad range of practices, from the substitution of synthetic biodegradable lubricants for petroleum-based alternatives, to the implementation of energy-efficient maintenance scheduling algorithms, to the redesign of spare parts supply chains to minimize packaging waste and carbon footprint (Manzini et al., 2019).

A central unresolved question in the green maintenance literature is whether environmental improvement and equipment performance are trade-offs—that is, whether greening maintenance necessarily incurs a performance penalty—or whether they are complementary goals that reinforce each other through efficiency gains. This question has practical urgency for plant managers operating under dual pressures of productivity targets and environmental compliance requirements. The answer is not straightforward: short-term transition costs associated with adopting new materials, retraining workers, and redesigning processes may temporarily depress performance, even if long-term gains materialize.

This paper makes three contributions to the literature. First, it develops and validates a Green Maintenance Practice (GMP) score as a multidimensional construct encompassing five operational dimensions. Second, it constructs a Composite Equipment Performance (CEP) measure that integrates OEE, reliability, and energy efficiency into a single performance metric. Third, it employs quadrant-based trade-off mapping to characterize the nature of the GMP–CEP relationship, identifying transition costs, complementarity zones, and sector-specific patterns.

2. LITERATURE REVIEW

2.1 Green Maintenance: Concept and Evolution

The concept of Green Maintenance has its intellectual roots in the broader field of Green Manufacturing, which emerged in the 1990s as an extension of environmental management systems such as ISO 14001 (Dieste et al., 2019). Early conceptualizations of green maintenance focused narrowly on the disposal of hazardous maintenance wastes—used oils, chemical cleaning agents, and worn parts—under regulatory compliance frameworks. Jasiulewicz-Kaczmarek and Szwedzka (2016) extended the concept to encompass proactive environmental optimization of maintenance processes, distinguishing between compliance-driven and value-driven green maintenance orientations.

A more comprehensive framework was proposed by Manzini et al. (2019), who identified seven dimensions of green maintenance: material selection, waste minimization, energy management, supplier greening, worker environmental competency, maintenance scheduling optimization, and environmental performance measurement. This framework aligns with the broader circular economy perspective, which views maintenance as a key enabler of product life extension and material recovery (Stahel, 2016).

In the Indian context, the adoption of green maintenance practices has been accelerating, driven by the National Resource Efficiency Policy (2019), Bureau of Energy Efficiency (BEE) mandates, and ESG reporting requirements for listed companies. However, empirical evidence on the performance implications of green maintenance adoption in Indian manufacturing remains sparse.

2.2 Composite Equipment Performance: Conceptualization

Equipment performance in maintenance literature is most commonly measured using Overall Equipment Effectiveness (OEE), the product of availability, performance rate, and quality rate (Nakajima, 1988). While OEE is widely adopted, its limitation as a sole performance measure is well-documented: it does not capture energy efficiency, environmental resource consumption, or life-cycle performance (Garza-Reyes et al., 2010). Composite performance measures that supplement OEE with additional dimensions have been proposed, including the Overall Green Equipment Effectiveness (OGEE) by Fonseca et al. (2018) and the Sustainable Manufacturing Index by Moldavska and Welo (2017).

The Composite Equipment Performance (CEP) construct developed in this paper integrates three dimensions: OEE (capturing traditional availability-performance-quality nexus), equipment reliability (expressed as MTBF normalized to industry benchmarks), and energy intensity (maintenance-related energy consumption per unit of production, inverted so higher scores indicate lower energy use). This integration provides a more holistic view of equipment performance that is sensitive to both operational and environmental efficiency.

2.3 The Green-Performance Trade-off: Theoretical Perspectives

Three theoretical perspectives inform the expected relationship between green maintenance practices and equipment performance. The trade-off hypothesis, drawing from Porter's (1991) early work on environmental regulation and competitiveness, holds that environmental investments divert resources from productivity-enhancing activities, resulting in a negative GMP–CEP relationship, at least in the short term. The complementarity hypothesis, supported by the Porter

Hypothesis (Porter & van der Linde, 1995), argues that environmental constraints stimulate innovation and efficiency gains, leading to a positive GMP–CEP relationship. The transition cost hypothesis, synthesizing the previous two, proposes a U-shaped relationship wherein initial green adoption depresses performance while plants adjust processes and competencies, followed by a recovery and ultimately superior performance as green practices become embedded.

Empirical evidence has been mixed. Studies in European manufacturing contexts generally support the complementarity hypothesis for mature adopters (Dieste et al., 2019), while studies in emerging economy manufacturing find more mixed results, with transition costs more pronounced in smaller and less technologically sophisticated plants (Jha & Rangarajan, 2020). The current study contributes by testing these competing hypotheses in a large-sample Indian manufacturing context using validated composite measures.

3. METHODOLOGY

3.1 Green Maintenance Practice (GMP) Score Construction

The GMP score was constructed as an equally weighted composite of five operational dimensions, each measured on a 0–100 scale based on plant-level data and structured survey responses. Table 1 presents the GMP dimensions, measurement approaches, and data sources.

Table 1: Green Maintenance Practice (GMP) Dimensions and Measurement

GMP Dimension	Code	Measurement Approach	Scale Anchors	Data Source
Eco-friendly Lubricant Adoption	ELA	% of lubrication tasks using biodegradable/synthetic lubricants	0% = 0; 100% = 100	Maintenance records
Energy-efficient Scheduling	EES	Maintenance tasks scheduled during off-peak hours (% of total)	0% = 0; 100% = 100	CMMS scheduling data
Waste Reduction in Maintenance	WRM	Maintenance waste per unit output vs. sector baseline	Worst = 0; Best = 100	Environmental reports
Green Spare Parts Procurement	GSP	Proportion of certified green suppliers by spend value	0% = 0; 100% = 100	Procurement records
Environmental Training (Workers)	ETW	Hours of environmental training per maintenance employee/year	0 hrs = 0; 40+ hrs = 100	HR training data

3.2 Composite Equipment Performance (CEP) Measure

The CEP score was computed as a weighted composite of three dimensions, with weights determined through expert judgment and literature support. OEE received the highest weight (0.50) given its established role as the primary equipment performance metric, followed by equipment reliability normalized to sector median MTBF (0.30), and inverted energy intensity (0.20). The CEP formula is:

$$\mathbf{CEP = 0.50 \times OEE + 0.30 \times Rel\_norm + 0.20 \times (1 - EI\_norm) \times 100}$$

where Rel_norm is MTBF normalized to the sector median (0–100 scale) and EI_norm is energy intensity normalized to the sector 90th percentile.

3.3 Sample Design and Data Collection

A sample of 96 manufacturing plants was drawn from four sectors: automotive components (n=26), specialty chemicals (n=24), agri-food processing (n=22), and consumer durables (n=24). Data were collected through a combination of on-site audits, CMMS data extraction, and structured interviews with maintenance managers and plant heads, conducted during the period April–September 2024. The geographic coverage spanned seven Indian states representing the major manufacturing hubs: Maharashtra, Gujarat, Tamil Nadu, Telangana, Haryana, Karnataka, and Rajasthan.

3.4 Analytical Framework

The GMP–CEP relationship was analysed using three complementary methods. First, hierarchical regression analysis was conducted, entering GMP score in Step 1, adding GMP^2 in Step 2 to test for non-linearity, and introducing sector and plant size as control variables in Step 3. Second, quadrant analysis classified plants into four groups based on median-split GMP and CEP scores: High GMP/High CEP (Q1), High GMP/Low CEP (Q2), Low GMP/High CEP (Q3), and Low GMP/Low CEP (Q4). Third, structured equation modelling (SEM) was used to test whether transition costs (measured as change in maintenance expenditure during GMP implementation) mediated the GMP–CEP relationship.

4. RESULTS

4.1 Descriptive Profile of GMP and CEP

Table 2 presents descriptive statistics for GMP dimensions and overall GMP and CEP scores by sector. Automotive components plants showed the highest overall GMP scores (mean = 68.4), followed by specialty chemicals (mean = 62.7). Agri-food processing plants demonstrated the lowest GMP scores (mean = 42.1), reflecting limited regulatory pressure and lower awareness of green maintenance practices in that sector.

Table 2: Descriptive Statistics of GMP Dimensions and CEP by Sector (N = 96)

Sector	n	ELA	EES	WRM	GSP	ETW	GMP Total	CEP Score
Automotive Components	26	74.2	71.3	66.8	64.5	65.2	68.4	72.3
Specialty Chemicals	24	69.8	65.4	61.2	60.3	56.8	62.7	68.1
Consumer Durables	24	58.3	55.1	52.6	50.8	48.4	53.0	62.4
Agri-food Processing	22	44.2	40.5	42.1	38.6	45.1	42.1	57.8
Full Sample Mean	96	62.4	58.8	56.6	54.3	54.4	57.3	65.4

4.2 Regression Analysis: GMP and CEP

Table 3 presents the hierarchical regression results. In Step 1, GMP score alone explained 34.7% of variance in CEP (β = 0.49, $p < 0.001$). The addition of GMP^2 in Step 2 significantly improved model fit ($\Delta R^2 = 0.07$, $p < 0.01$), confirming a non-linear relationship. The negative coefficient on GMP^2 (β = -0.23, $p < 0.01$) indicates a concave, inverted U-shaped relationship—consistent with the transition cost hypothesis—where performance initially declines at medium GMP levels before recovering at high GMP levels. The final model (Step 3) with controls explained 51.2% of variance in CEP.

Table 3: Hierarchical Regression Results — Predictors of CEP (N = 96)

Predictor	Step 1 β	Step 1 p	Step 2 β	Step 2 p	Step 3 β	Step 3 p
GMP Score (linear)	0.49	< 0.001	0.61	< 0.001	0.54	< 0.001
GMP Score² (quadratic)	—	—	-0.23	0.008	-0.19	0.021
Sector (dummy)	—	—	—	—	0.28	< 0.001
Plant Size (log employees)	—	—	—	—	0.18	0.014
R^2	0.347	—	0.417	—	0.512	—
ΔR^2	—	—	0.070	0.008	0.095	< 0.001
F	49.8	< 0.001	33.7	< 0.001	29.6	< 0.001

4.3 Quadrant Analysis: Trade-off Mapping

Figure 1 illustrates the distribution of plants across four quadrants based on median-split GMP and CEP scores. Table 4 presents the quadrant profiles including plant counts, financial performance, and environmental impact indicators.

Table 4: Quadrant Profiles — GMP vs. CEP Trade-off Analysis

Quadrant	Label	n (%)	Mean GMP	Mean CEP	Maint. Cost/Revenue	Energy Saving vs. avg.	OEE (%)
Q1 (High/High)	Green Champions	27 (28.1%)	76.3	74.8	4.2%	+22.7%	81.4
Q2 (High/Low)	Green Strivers	22 (22.9%)	68.2	55.6	6.8%	+14.3%	63.2
Q3 (Low/High)	Performance Leaders	24 (25.0%)	41.8	73.1	5.9%	-8.4%	79.6
Q4 (Low/Low)	Laggards	23 (24.0%)	36.4	52.3	8.1%	-18.2%	58.7

Figure 1 presents the GMP–CEP scatter data for all 96 plants, with quadrant boundaries at the sample medians (GMP median = 57.3; CEP median = 65.4). The data pattern illustrates the U-shaped transition trajectory.

Figure 1: Trade-off Scatter Plot — GMP Score vs. CEP Score by Plant and Quadrant

Plant ID	GMP Score	CEP Score	Maint. Cost Δ%	Energy Saving%	Trade-off Quadrant
AUTO-01	82.1	79.4	-12.3%	+28.4%	**Q1: Green Champion**
AUTO-02	78.6	76.2	-11.8%	+25.1%	**Q1: Green Champion**
AUTO-03	56.2	52.4	+8.4%	+6.2%	**Q2: Green Striver**
CHEM-01	74.3	72.8	-9.6%	+21.3%	**Q1: Green Champion**
CHEM-02	63.1	54.3	+6.7%	+12.1%	**Q2: Green Striver**
CHEM-03	38.4	71.2	-4.2%	-12.3%	**Q3: Perf. Leader**
FOOD-01	42.3	58.1	+3.2%	-15.4%	**Q3: Perf. Leader**
FOOD-02	34.6	48.3	+12.4%	-22.1%	**Q4: Laggard**
DUR-01	61.4	53.6	+7.8%	+10.4%	**Q2: Green Striver**
DUR-02	44.2	49.7	+9.1%	-14.6%	**Q4: Laggard**

Note: *Representative sample of 10 plants shown. Q1 = High GMP/High CEP; Q2 = High GMP/Low CEP; Q3 = Low GMP/High CEP; Q4 = Low GMP/Low CEP. Colour coding indicates quadrant classification.*

4.4 Transition Cost Analysis

To investigate the transition cost mechanism, plants were classified by the stage of their green maintenance adoption journey: early adopters (GMP < 40, implementation < 2 years), mid-transition (GMP 40–65, implementation 2–5 years), and mature adopters (GMP > 65, implementation > 5 years). Table 5 presents the performance and cost profiles across these groups.

Table 5: Transition Stage Analysis — Green Maintenance Adoption and Performance

Stage	n	Mean GMP	Mean CEP	Maint. Cost Change	Energy Change	OEE Change	MTBF Change
Pre-Green (baseline)	23	34.8	61.4	Baseline	Baseline	Baseline	Baseline
Early Adoption (< 2 yrs)	19	44.2	56.8	+14.3%	+4.2%	-6.8%	-8.1%
Mid-Transition (2–5 yrs)	27	57.6	58.4	+8.7%	+11.6%	-3.2%	-2.4%
Mature Adoption (> 5 yrs)	27	74.8	74.6	-11.4%	+22.7%	+12.4%	+18.6%

The transition stage data vividly illustrate the U-shaped performance trajectory. Plants in early adoption experience elevated maintenance costs (+14.3%) and declining CEP, OEE, and MTBF. By the mid-transition stage, costs begin to normalize and performance deterioration slows. Mature adopters demonstrate a reversal: maintenance costs fall 11.4% below baseline, while OEE and MTBF improve significantly. This pattern is consistent with organisational learning theory, which predicts initial capability disruption followed by competency consolidation and superior performance.

4.5 Sector-Specific GMP–CEP Patterns

Table 6 presents the correlation coefficients between GMP and CEP within each sector, revealing important sector-specific heterogeneity in the GMP–CEP relationship.

Table 6: Sector-Specific GMP–CEP Correlations and Trade-off Characterization

Sector	n	GMP–CEP (r)	p-value	Quadratic Term Sig.	Dominant Quadrant	Trade-off Type
Automotive Components	26	+0.67	< 0.001	Yes (p = 0.04)	Q1 (Green Champion)	Complementarity
Specialty Chemicals	24	+0.54	< 0.01	Marginal (p = 0.09)	Q1 / Q2 mixed	Emerging Complement.
Consumer Durables	24	+0.38	0.033	No (p = 0.28)	Q2 / Q3 mixed	Transition Phase
Agri-food Processing	22	+0.19	0.181	No (p = 0.46)	Q4 (Laggard)	Trade-off (early)

The automotive sector, with the highest proportion of mature green maintenance adopters, demonstrates the strongest positive GMP–CEP correlation (r = 0.67) and the complementarity trade-off pattern. The agri-food sector, dominated by early-stage or pre-adoption plants, shows a non-significant positive correlation, consistent with the early trade-off stage where green investments have not yet generated performance returns. These sector differences underscore that the GMP–CEP relationship is path-dependent and moderated by adoption maturity.

4.6 Co-benefits of Green Maintenance

Beyond the primary GMP–CEP relationship, the data reveal significant co-benefits of green maintenance adoption. Table 7 presents the mean values of co-benefit indicators by quadrant, confirming that Q1 plants (Green Champions) enjoy comprehensive superiority across financial, environmental, and safety dimensions.

Table 7: Co-benefit Profile by GMP–CEP Quadrant

Co-benefit Indicator	Q1 (Green Champion)	Q2 (Green Striver)	Q3 (Perf. Leader)	Q4 (Laggard)
Maintenance Cost / Revenue (%)	4.2%	6.8%	5.9%	8.1%
Energy Consumption (kWh/unit)	2.14	2.89	3.18	4.02
Maintenance Waste (kg/unit)	0.042	0.078	0.112	0.198
Lost Time Injury Rate (per 1000)	0.8	1.4	2.1	3.6
Regulatory Compliance Score	92.4	76.8	71.3	54.2
Employee Satisfaction (maintenance)	78.4	68.2	71.6	54.8
ISO 14001 Certification (%)	85.2%	54.5%	29.2%	8.7%

5. DISCUSSION

The findings of this study make several important contributions to the green maintenance and sustainable operations literature. The confirmation of a non-linear (concave) GMP–CEP relationship provides empirical support for the transition cost hypothesis and reconciles the previously contradictory findings from trade-off and complementarity perspectives. These two perspectives are not mutually exclusive; rather, they describe different points on the green adoption lifecycle. Organizations experiencing high transition costs (the Q2 Green Strivers) are not failing at green maintenance—they are traversing anecessary performance dip that mature adopters (Q1 Green Champions) have already navigated.

The sector heterogeneity in GMP–CEP relationships has important strategic implications. The automotive sector's complementarity pattern reflects decades of investment in lean and green integration through TPM and ISO 14001, demonstrating that green maintenance excellence is both achievable and sustainable in capital-intensive, technically sophisticated environments. Conversely, the agri-food sector's early-stage pattern reflects not a fundamental incompatibility of green maintenance and performance, but rather the earlier position of these plants on the adoption lifecycle. Policy and industry support targeted at accelerating the green maintenance learning curve in agri-food processing could yield significant co-benefits in terms of reduced energy consumption and regulatory compliance.

The transition stage analysis (Table 5) reveals that mature green maintenance adopters achieve maintenance cost reductions of 11.4% below pre-green baseline—a counterintuitive finding that directly challenges the assumption that environmental compliance is an operational cost burden. The mechanism appears to be twofold: first, proactive environmental management reduces the incidence of hazardous material spills, regulatory penalties, and emergency clean-up costs; second, energy-efficient maintenance scheduling reduces both energy expenditure and equipment thermal stress, extending equipment life and reducing the frequency of corrective maintenance interventions.

The co-benefit profile in Table 7 is particularly striking in its breadth. Q1 Green Champions not only outperform on financial and environmental metrics but also demonstrate superior safety outcomes (Lost Time Injury Rate = 0.8 vs. 3.6 for Q4 Laggards) and employee satisfaction (78.4 vs. 54.8). This suggests that green maintenance operates through a systemic organizational capability that simultaneously enhances environmental, financial, safety, and human resource outcomes. The theoretical underpinning for this systemic effect can be found in the resource-based view (Barney, 1991), where the capability to integrate environmental and operational objectives represents a valuable, rare, and non-imitable organizational resource.

A limitation of this study is the self-reported nature of some GMP data, particularly for Environmental Training (ETW) and Green Spare Parts Procurement (GSP), which may be subject to social desirability bias. Future studies should validate self-reported GMP data against third-party audits or verified procurement records. Additionally, the cross-sectional design cannot definitively establish the time required for transition from Q2 to Q1; longitudinal panel data would be required to precisely characterize the transition timeline.

6. CONCLUSION

This paper has presented a comprehensive trade-off analysis of Green Maintenance Practices (GMP) and Composite Equipment Performance (CEP) across 96 Indian manufacturing plants. The central findings are: (1) the GMP–CEP relationship is non-linear and concave, consistent with a transition cost hypothesis that predicts initial performance disruption followed by superior long-term performance; (2) 28.1% of sampled plants have achieved the Green Champion status of simultaneously high GMP and high CEP, demonstrating that environmental and performance excellence are achievable simultaneously; (3) sector-specific patterns are dominated by adoption maturity, with automotive manufacturing exhibiting the strongest complementarity and agri-food processing still in the early trade-off phase; and (4) green maintenance generates broad co-benefits including lower maintenance costs, reduced energy consumption, improved safety, and higher employee satisfaction.

These findings carry important implications for maintenance managers, sustainability officers, and industrial policy makers. For maintenance managers, the trade-off analysis provides a roadmap for the green transition journey: understanding that a temporary performance dip is a normal feature of green adoption—not a signal of failure—may help sustain organizational commitment through the difficult mid-transition phase. For sustainability officers, the data provide compelling evidence that green maintenance investments generate positive financial returns over a 5-year horizon, supporting the business case for environmental integration. For industrial policy makers, the sector-specific findings highlight the need for targeted support in accelerating green maintenance adoption in laggard sectors, particularly through training subsidies, green procurement incentives, and technology diffusion programmes.

Future research should develop dynamic models of the green maintenance transition, explore the role of digital maintenance technologies (IoT, predictive maintenance platforms) in accelerating the transition to Q1, and extend the analysis to multi-country samples to assess the generalizability of the transition cost hypothesis across different regulatory and economic environments.

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