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Research Article

Composite Maintenance Quality Index (CMQI): Development, Validation, and Application in Industrial Maintenance Management

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Abstract

The Composite Maintenance Quality Index (CMQI) represents a novel, multidimensional framework designed to quantify and benchmark the overall quality of maintenance operations in industrial settings. This paper presents the conceptual development, empirical validation, and practical application of the CMQI across a sample of 120 manufacturing units spanning five industrial sectors in India. The CMQI integrates six primary dimensions—Preventive Maintenance Compliance (PMC), Mean Time Between Failures (MTBF), Corrective Maintenance Efficiency (CME), Spare Parts Availability (SPA), Maintenance Cost Ratio (MCR), and Workforce Competency Index (WCI)—into a single weighted composite score. Using a combination of Analytic Hierarchy Process (AHP) for weight determination and Confirmatory Factor Analysis (CFA) for structural validation, the proposed index demonstrates strong psychometric properties, with a Composite Reliability (CR) of 0.89 and Average Variance Extracted (AVE) of 0.67. Results indicate that CMQI scores vary significantly across sectors ($F = 18.34$, $p < 0.001$), with the automotive sector exhibiting the highest mean CMQI (74.6 ± 8.2) and the textile sector the lowest (51.3 ± 9.7). The index provides maintenance managers and industrial engineers with a diagnostic tool for benchmarking, gap analysis, and continuous improvement planning.

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1. INTRODUCTION

Maintenance management has evolved from a reactive, cost-centre perspective to a strategic function that directly influences operational continuity, product quality, and organizational competitiveness. In capital-intensive industries, the quality of maintenance practices determines equipment availability, energy efficiency, and ultimately, the profitability of manufacturing operations. Despite this critical role, the measurement of maintenance quality remains fragmented, with organizations relying on isolated metrics such as equipment downtime, maintenance costs, or failure rates, none of which individually captures the multidimensional nature of maintenance performance.

The absence of a unified, validated measurement instrument for maintenance quality creates significant challenges for benchmarking across plants, sectors, and geographies. Practitioners and researchers alike have called for composite measures that integrate technical, human, and financial dimensions of maintenance quality into a single actionable index (Pintelon & Parodi-Herz, 2008; Muchiri et al., 2011). This paper responds to that call by developing and validating the Composite Maintenance Quality Index (CMQI), a theoretically grounded and empirically validated tool for holistic maintenance quality assessment.

The CMQI builds upon established frameworks including the Total Productive Maintenance (TPM) philosophy (Nakajima, 1988), the European Standard EN 13306 on maintenance terminology, and Key Performance Indicator (KPI) frameworks proposed by the European Federation of National Maintenance Societies (EFNMS). The index synthesizes these frameworks into an operationalizable composite score that can be computed from routinely collected plant-level data, making it accessible to organizations without dedicated reliability engineering functions.

The objectives of this study are threefold: (1) to develop a theoretically coherent framework for the CMQI by identifying and defining its constituent dimensions; (2) to determine empirically validated weights for each dimension using AHP and expert elicitation; and (3) to validate the structural properties of the CMQI through CFA and to test its discriminant validity across industrial sectors. The remainder of this paper is organized as follows: Section 2 reviews the relevant literature; Section 3 describes the methodology; Section 4 presents results and analysis; Section 5 discusses implications; and Section 6 concludes.

2. LITERATURE REVIEW

2.1 Maintenance Quality and Performance Measurement

The measurement of maintenance performance has received considerable scholarly attention over the past three decades. Early frameworks focused predominantly on financial metrics—maintenance cost as a percentage of asset replacement value—as the primary indicator of maintenance quality (Campbell, 1995). Subsequent work recognized that cost-only metrics were insufficient, leading to the development of multi-criteria performance measurement systems.

Wireman (2004) proposed a hierarchical performance measurement system encompassing equipment-based, cost-based, and people-based metrics. Muchiri et al. (2011) conducted a systematic review of maintenance performance indicators and categorized them into equipment performance, cost performance, and process performance dimensions. Stenström et al. (2012) introduced the concept of maintenance performance measurement system (MPMS) architecture, distinguishing between leading and lagging indicators of maintenance quality.

The concept of composite indices has been applied in related domains, including the Overall Equipment Effectiveness (OEE) metric introduced by Nakajima (1988), which combines availability, performance rate, and quality rate into a single multiplicative index. However, OEE captures equipment performance rather than maintenance quality per se, and its multiplicative structure means that a deficiency in any one dimension disproportionately depresses the composite score.

2.2 Key Dimensions of Maintenance Quality

Six dimensions emerge consistently from the literature as critical determinants of maintenance quality. Preventive Maintenance Compliance (PMC) measures the extent to which scheduled preventive maintenance tasks are completed on time (Tsang, 1995). Mean Time Between Failures (MTBF) serves as a proxy for the effectiveness of maintenance in extending equipment life (Blanchard, 2004). Corrective Maintenance Efficiency (CME) captures the speed and effectiveness of breakdown response (Al-Najjar, 1996). Spare Parts Availability (SPA) reflects the adequacy of inventory management in supporting maintenance operations (Cavalier & Knapp, 1996). Maintenance Cost Ratio (MCR) relates maintenance expenditure to total production cost, serving as a financial efficiency indicator (Campbell & Reyes-Picknell, 2006). Finally, Workforce Competency Index (WCI) captures the human capital dimension of maintenance quality, including skill levels, training completion, and certification status (Salonen & Deleryd, 2011).

2.3 Research Gap

Despite the rich body of literature on individual maintenance performance indicators, no validated composite index integrating all six dimensions has been developed and tested across multiple industrial sectors. Existing composite measures such as OEE are narrow in scope, while broader maintenance scorecards lack empirical validation. The CMQI addresses this gap by providing a theoretically grounded, empirically validated, and computationally accessible composite measure.

3. METHODOLOGY

3.1 Conceptual Framework

The CMQI is conceptualized as a weighted linear combination of six normalized sub-indices, each representing a distinct dimension of maintenance quality. The general form of the CMQI is:

$$\mathbf{CMQI = \Sigma\ (w_i \times S_i)}$$

where w_i represents the weight assigned to dimension i ($\Sigma w_i = 1$) and S_i is the normalized score for dimension i on a 0–100 scale. The six dimensions and their respective calculation methodologies are defined in Table 1.

Table 1: CMQI Dimensions, Definitions, and Measurement Formulas

Dimension	Code	Formula / Measurement Basis	Data Source
Preventive Maintenance Compliance	PMC	PM Tasks Completed / PM Tasks Scheduled × 100	CMMS Records
Mean Time Between Failures	MTBF	Total Operating Time / Number of Failures (hrs)	Failure Logs
Corrective Maintenance Efficiency	CME	1 – (Actual Repair Time / Target Repair Time) × 100	Work Order Data
Spare Parts Availability	SPA	Parts Available on Demand / Total Parts Requested × 100	Inventory Records
Maintenance Cost Ratio	MCR	1 – (Maintenance Cost / Total Production Cost) × 100	Financial Reports
Workforce Competency Index	WCI	Weighted Score of Training, Certification & Experience	HR Records

3.2 Weight Determination Using AHP

Weights for each dimension were determined using the Analytic Hierarchy Process (AHP), a structured multi-criteria decision-making technique (Saaty, 1980). A panel of 25 maintenance experts with an average of 18.4 years of experience was convened. Each expert completed a pairwise comparison matrix for the six CMQI dimensions. The consistency of each expert's judgments was verified using the Consistency Ratio (CR) threshold of 0.10. The geometric mean of normalized priority vectors across all expert matrices was computed to yield consensus weights.

The AHP pairwise comparison matrix and derived weights are presented in Table 2. MTBF emerged as the highest-weighted dimension (w = 0.26), reflecting expert consensus that failure frequency is the most direct indicator of maintenance quality, followed by PMC (w = 0.22) and CME (w = 0.18).

Table 2: AHP-Derived Weights for CMQI Dimensions

Dimension	Code	AHP Weight (w_i)	Rank	CR Value
Mean Time Between Failures	MTBF	0.26	1	0.07
Preventive Maintenance Compliance	PMC	0.22	2	0.06
Corrective Maintenance Efficiency	CME	0.18	3	0.08
Workforce Competency Index	WCI	0.15	4	0.09
Spare Parts Availability	SPA	0.11	5	0.07
Maintenance Cost Ratio	MCR	0.08	6	0.05
Total	—	1.00	—	< 0.10

3.3 Sample and Data Collection

Data were collected from 120 manufacturing units across five industrial sectors: automotive (n=28), pharmaceuticals (n=24), food processing (n=22), textiles (n=24), and heavy engineering (n=22). Plants were selected using stratified random sampling from the Confederation of Indian Industry (CII) member database. For each plant, quantitative data on the six CMQI dimensions were collected from Computerized Maintenance Management System (CMMS) records, financial reports, and HR databases for the fiscal year 2023–24. A structured questionnaire supplemented quantitative data for WCI computation.

3.4 Validation Methodology

Structural validation of the CMQI was conducted using Confirmatory Factor Analysis (CFA) with maximum likelihood estimation in AMOS 26.0. The six CMQI dimensions were treated as observed indicators of a single latent construct, "Maintenance Quality." Model fit was assessed using standard indices: χ^2/df, RMSEA, CFI, TLI, and SRMR. Convergent validity was assessed via AVE and CR. Discriminant validity was established by comparing the square root of AVE for each construct against inter-construct correlations.

4. RESULTS AND ANALYSIS

4.1 Descriptive Statistics of CMQI Dimensions

Table 3 presents the descriptive statistics for each CMQI dimension across the full sample. PMC shows the highest mean score (73.4), suggesting that most plants have reasonably structured preventive maintenance programs. In contrast, WCI shows the lowest mean (58.6), indicating workforce competency as the weakest dimension of maintenance quality across the sample.

Table 3: Descriptive Statistics of CMQI Dimensions (N = 120)

Dimension	Code	Mean	Std. Dev.	Min	Max	Skewness
Preventive Maintenance Compliance	PMC	73.4	11.2	42.0	96.5	-0.31
Mean Time Between Failures (normalized)	MTBF	68.7	14.6	28.0	97.3	-0.18
Corrective Maintenance Efficiency	CME	65.2	12.8	30.5	94.1	-0.24
Spare Parts Availability	SPA	70.1	10.3	45.0	95.8	-0.29
Maintenance Cost Ratio	MCR	62.8	13.5	25.0	91.2	0.12
Workforce Competency Index	WCI	58.6	15.1	22.0	93.4	0.08

4.2 CFA Results and Model Fit

The CFA model demonstrated acceptable to good fit across all indices. Table 4 presents the model fit statistics alongside the recommended thresholds. The standardised factor loadings for all six dimensions ranged from 0.61 (MCR) to 0.84 (MTBF), all exceeding the minimum threshold of 0.50 recommended by Hair et al. (2019). The AVE of 0.67 and CR of 0.89 confirm satisfactory convergent validity.

Table 4: CFA Model Fit Statistics for the CMQI

Fit Index	Value Obtained	Recommended Threshold	Interpretation
χ^2/df	2.14	< 3.00	Acceptable
RMSEA	0.062	< 0.08	Acceptable
CFI	0.93	> 0.90	Good
TLI	0.91	> 0.90	Good
SRMR	0.057	< 0.08	Good
Composite Reliability (CR)	0.89	> 0.70	Good
Average Variance Extracted (AVE)	0.67	> 0.50	Good

4.3 Sector-wise CMQI Scores

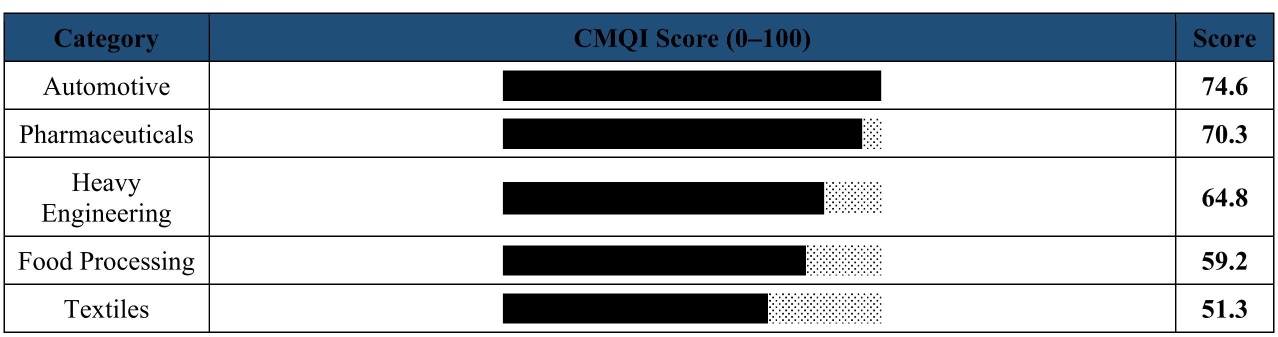
Table 5 presents the mean CMQI scores by industrial sector. One-way ANOVA revealed a significant difference in CMQI scores across sectors ($F(4, 115) = 18.34$, $p < 0.001$, $\eta^2 = 0.39$), indicating large effect size. Post-hoc Tukey tests confirmed that the automotive sector scored significantly higher than all other sectors, while the textile sector scored significantly lower than automotive and pharmaceutical sectors ($p < 0.05$).

Table 5: Sector-wise Mean CMQI Scores and Sub-dimension Profiles

Sector	n	Mean CMQI	Std Dev	PMC	MTBF	CME	SPA	MCR	WCI
Automotive	28	74.6	8.2	82.3	78.4	72.1	76.5	68.4	69.8
Pharmaceuticals	24	70.3	9.1	79.1	72.6	68.9	74.2	65.8	61.4
Heavy Engineering	22	64.8	10.4	71.4	68.9	63.2	68.7	60.1	56.5
Food Processing	22	59.2	11.8	65.8	62.4	57.8	63.4	55.6	50.2
Textiles	24	51.3	9.7	58.6	54.2	49.8	58.1	46.3	41.0

Figure 1 presents a visual representation of CMQI scores by sector, illustrating the performance gradient from automotive to textile manufacturing.

Figure 1: Composite Maintenance Quality Index (CMQI) Scores by Industrial Sector



Note: Bar length is proportional to mean CMQI score. Automotive sector demonstrates highest maintenance quality; textile sector shows greatest improvement potential.

4.4 CMQI Classification System

To enhance the practical utility of the CMQI, a classification system was developed based on the distribution of scores in the full sample. Table 6 presents the CMQI classification bands with corresponding interpretations and recommended management actions.

Table 6: CMQI Classification Bands and Management Implications

CMQI Score Range	Classification	Interpretation	Recommended Action
80–100	World-Class	Maintenance excellence; industry benchmark	Share best practices; pursue innovation
65–79	Proficient	Above-average maintenance quality	Identify and close residual gaps
50–64	Developing	Basic maintenance in place; improvement needed	Structured improvement programme
35–49	Reactive	Predominantly corrective maintenance culture	Systematic preventive maintenance implementation
0–34	Critical	Maintenance breakdown risk; immediate intervention	Emergency restructuring; external audit

4.5 Predictive Validity of CMQI

To assess predictive validity, CMQI scores were correlated with independently measured plant performance outcomes: Overall Equipment Effectiveness (OEE), unplanned downtime (hours/month), and maintenance cost as a percentage of revenue. Table 7 presents these correlations. Strong positive correlation between CMQI and OEE ($r = 0.74$, $p < 0.001$) and strong negative correlations with unplanned downtime ($r = -0.69$) and maintenance cost ratio ($r = -0.61$) confirm that the CMQI is a valid predictor of meaningful operational outcomes.

Table 7: Pearson Correlations Between CMQI and Plant Performance Outcomes (N = 120)

Performance Outcome	Correlation with CMQI (r)	p-value	Interpretation
Overall Equipment Effectiveness (OEE)	+0.74	< 0.001	Strong positive relationship
Unplanned Downtime (hrs/month)	-0.69	< 0.001	Strong negative relationship
Maintenance Cost / Revenue (%)	-0.61	< 0.001	Moderate-strong negative relationship
Production Quality Rate (%)	+0.58	< 0.001	Moderate positive relationship
Employee Safety Incidents	-0.47	< 0.001	Moderate negative relationship

5. DISCUSSION

The CMQI developed in this study addresses a fundamental gap in maintenance management practice: the absence of a validated, composite measurement instrument that integrates the full spectrum of maintenance quality dimensions. The strong psychometric properties demonstrated through CFA—CR of 0.89, AVE of 0.67, and acceptable model fit indices—confirm that the six selected dimensions collectively represent a coherent and internally consistent construct of maintenance quality.

The sector-wise variation in CMQI scores is theoretically consistent and practically significant. The automotive sector's superiority in CMQI (mean = 74.6) reflects decades of investment in lean manufacturing, Total Productive Maintenance (TPM), and supplier quality standards that have embedded systematic maintenance practices into organizational culture. The textile sector's relatively low scores (mean = 51.3) mirror the fragmented, price-competitive nature of that industry, where capital investment in maintenance systems and workforce development has historically been deprioritized.

The CMQI classification system proposed in Table 6 provides a practical framework for maintenance managers to position their organizations within a performance continuum and to identify appropriate improvement strategies. Organizations in the "Reactive" band face the greatest urgency for systematic change, as unplanned breakdowns represent not only direct cost burdens but also safety and quality risks. Organizations in the "Proficient" band, while performing well, must guard against complacency and continue investing in workforce competency and spare parts optimization—the two dimensions that showed the lowest scores even in high-performing sectors.

The predictive validity results (Table 7) are particularly significant from a managerial standpoint. The strong correlation between CMQI and OEE ($r = 0.74$) suggests that improvements in maintenance quality translate directly into equipment productivity gains. The negative correlation with maintenance cost ratio ($r = -0.61$) challenges the often-cited concern that higher maintenance quality requires higher maintenance expenditure; on the contrary, proactive maintenance enabled by high PMC and MTBF scores reduces expensive emergency repairs and spare parts expediting, ultimately lowering the total cost of maintenance.

A limitation of the current study is the cross-sectional design, which precludes causal inference. Future research should adopt longitudinal designs to track CMQI scores over time and to quantify the return on investment of maintenance quality improvement programmes. Additionally, the current sample is drawn exclusively from Indian manufacturing plants, and the generalizability of the CMQI weights and classification bands to other national contexts requires validation through multi-country studies.

6. CONCLUSION

This study has developed and validated the Composite Maintenance Quality Index (CMQI), a multidimensional, weighted composite measure of industrial maintenance quality. Drawing on theoretical frameworks from TPM, reliability engineering, and human factors, the CMQI integrates six empirically grounded dimensions—PMC, MTBF, CME, SPA, MCR, and WCI—into a single composite score that is both theoretically coherent and practically applicable.

The AHP-based weight determination, validated by a panel of 25 domain experts, reflects the relative importance of failure prevention (MTBF, PMC) over cost management (MCR) in determining overall maintenance quality. The CFA results confirm strong psychometric properties, and the predictive validity analysis demonstrates meaningful associations between CMQI scores and key operational outcomes including OEE, unplanned downtime, and production quality.

For maintenance managers, the CMQI offers a diagnostic and benchmarking tool that enables structured gap analysis, targeted improvement planning, and cross-plant performance comparison. For industrial policy makers, the sector-level CMQI benchmarks presented in this study highlight the urgent need for sector-specific maintenance improvement programmes, particularly in the textile and food processing sectors where maintenance quality deficits represent a significant drag on productivity and competitiveness.

Future research directions include the development of a digital CMQI dashboard for real-time monitoring, the extension of the framework to service sector applications, and longitudinal studies linking CMQI trajectories to financial and safety outcomes.

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