The Impact of Quality Assurance, Quality Control, and Total Quality Management on Cost Efficiency and Rework Reduction in the Construction Projects

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ABSTRACT

Despite research on quality management, construction rework imposes substantial cost burdens on building projects. Previous studies have focused on conceptual frameworks without quantifying their real financial implications. Hence, this study examines how Quality Assurance (QA), Quality Control (QC), and Total Quality Management (TQM) interact to influence project economics, using 180 nonconformance reports from high-rise residential projects conducted between 2019 and 2024 to establish an empirical relationship between quality system maturity and the Cost Of Poor Quality (COPQ). Two analytical tools were developed: the Quality Cost Impact Metric (QCIM) and Quality Maturity Index 2.0 (QMI 2.0). These metrics quantify financial exposure through a prevention–appraisal–failure framework, providing construction managers with a decision-support approach grounded in actual project data. The results revealed distinct failure patterns across construction phases. Structural defects occurred infrequently, but generated severe financial consequences. In contrast, architectural works exhibited persistent, moderate-cost failures that gradually eroded profitability. Increasing the quality maturity was associated with nonlinear reductions in rework-related costs, with preventive strategies yielding greater cost reductions than reactive correction measures in the projects examined. These findings provide an empirically grounded framework for early-stage risk assessment and resource allocation in complex construction environments.

Keywords-quality management; TQM; QA/QC; COPQ; rework; cost efficiency

I. INTRODUCTION

Construction projects operate under conditions that differ significantly from those in manufacturing environments. A unique combination of site constraints, weather variability, subcontractor capabilities, and material characteristics shapes each project. This inherent lack of repeatability increases the risk of propagation errors, making quality management particularly challenging [1]. Although manufacturing benefits from controlled production lines and iterative process refinement, the construction industry must achieve specification compliance under continuously changing conditions.

The financial consequences of inadequate quality management are well-documented. The Cost Of Poor Quality (COPQ), which includes rework, schedule delays, corrective actions, and regulatory noncompliance, typically accounts for 5–15% of the total project costs. This proportion can exceed 25% [1, 2] in complex infrastructure developments. Although these values represent direct economic losses, they underestimate the full impact when indirect costs, such as damaged client relationships, diminished contractor reputation, and weakened competitive positioning, are taken into account.

Current industry practices place disproportionate emphasis on end-stage inspection rather than on preventive quality systems. However, this approach is economically inefficient and technically inadequate. The philosophy of Total Quality Management (TQM), together with structured QA/QC protocols, reframes quality as a process attribute rather than an outcome measure, thus improving predictability and reducing lifecycle costs [3, 4]. The transition from inspection- to prevention-based quality management represents a crucial shift in how construction organizations approach project delivery.

Although TQM theory encompasses three interconnected dimensions, Quality Planning (QP), Quality Assurance (QA), and Quality Control (QC), this study is deliberately scoped to QA and QC. The 180 NCRs analyzed document failures that occurred during project execution; they did not capture pre-construction planning decisions. QP, therefore, falls outside the evidentiary boundary of this dataset and is identified as a direction for future research.

A persistent gap in the construction quality literature is the absence of project-level empirical data linking quality system maturity to measurable financial outcomes. Existing frameworks remain largely conceptual. This study addresses that gap by introducing the Quality Cost Impact Metric (QCIM) and the Quality Maturity Index 2.0 (QMI 2.0), two instruments developed from actual NCR data to translate quality maturity assessments into quantifiable cost exposure estimates.

II. LITERATURE REVIEW

A. Total Quality Management in Construction Context

TQM originated in manufacturing but has become relevant in construction environments. The philosophy emphasizes continuous improvement, rigorous process control, strategic supplier integration, and active workforce engagement [3, 5]. TQM implementation directly addresses several significant industry weaknesses, including fragmented communication channels, inconsistent documentation practices, limited organizational learning, and a lack of standardization across projects.

Traditional project delivery models often fail to capture and transfer knowledge between subsequent projects, leading to the repetition of similar problems over time. As a result, quality problems are not systematically eliminated; instead, they reappear across different project contexts, undermining long-term performance improvement.

B. Cost of Poor Quality: Direct and Indirect Components

The theoretical foundations of COPQ trace back to Juran's work in the 1950s [6], and were later extended in [7], which positioned quality as a financially quantifiable management discipline rather than a technical compliance function. Despite these significant contributions, practical application of COPQ in construction remained largely absent until the 1990s, when increasing project complexity and tightening contractual obligations pushed contractors toward more structured cost accountability. This framework has been extended to high-rise and infrastructure contexts. Yet an important limitation remains. That is, published findings show aggregate rework percentages, leaving phase-level cost dynamics and their relationship to quality system maturity unexamined.

COPQ comprises direct and indirect costs arising from quality failures. The direct costs include corrective rework, removal of nonconforming work, demolition of defective components, and material replacement. The indirect costs include schedule delays, productivity losses, legal and contractual risks, insurance premiums, and reputational damage. It has been indicated that indirect costs often exceed direct rework expenditures [8]. In many high-rise residential cases, hidden costs have a "multiplier effect," in which a single structural error triggers a cascade of secondary financial liabilities.

The American Society for Quality reported that accumulated COPQ reduces business margins, increases administrative costs, and disrupts supply chain relationships [9]. Therefore, organizations that do not systematically track COPQ tend to underestimate their true financial exposure to quality-related problems. This measurement gap often results in a "reactive trap," which limits their ability to justify expenditure on preventive quality initiatives. By failing to quantify the long-term ROI of prevention, management continues to prioritize immediate cost savings over systemic quality maturity.

C. Rework Causation and Phase-Specific Vulnerability

Rework costs typically range from 4% to 12% of the total project value [8]. Furthermore, four primary causes of rework in construction projects have been identified: design deficiencies, coordination failures between disciplines, workforce skill gaps, and material-specification mismatches. However, these causes do not affect all construction stages equally; instead, susceptibility to rework varies nonlinearly across project phases.

Structural works are highly sensitive to dimensional tolerances and load-bearing requirements. Minor deviations in the structural elements can necessitate extensive corrective measures, resulting in disproportionately high rework costs. From a risk-management perspective, this implies that structural failures represent "low-probability, high-impact" events. In contrast, architectural finishing activities are strongly influenced by workmanship quality and material compatibility issues. Defects at this stage tend to occur more frequently but typically involve lower per-unit repair costs, leading to different quality-control requirements across the construction phases [4]. This inherent duality suggests that a "one-size-fits-all" QA strategy is flawed for high-rise residential developments.

D. Prevention-Appraisal-Failure Cost Modeling

Juran’s Prevention Appraisal Failure (PAF) model provides a theoretical framework for optimizing quality-related costs. The model shows that investments in preventive activities, such as design review procedures, material verification systems, and supplier qualification audits, lead to significant reductions in failure-related costs. Authors in [10] indicate that integrating digital methodologies, such as Building Information Modeling (BIM), can reduce technical defects by up to 73%, thereby lowering failure costs and optimizing the overall project budget [10]. The current study emphasizes that this relationship is nonlinear; hence, small increases in preventive spending can disproportionately reduce downstream losses that would otherwise jeopardize a project’s net profit margins.

Although the PAF framework is widely accepted in manufacturing, the empirical evidence supporting its application in construction remains limited. Most existing studies rely on conceptual arguments rather than granular project-level cost data, underscoring the need for data-driven validation in building construction. By analyzing 180 nonconformance reports from high-rise projects, this study addresses this scholarly void, moving beyond theoretical assumptions to quantify actual fiscal impacts.

Existing maturity frameworks assess organizational process sophistication but stop short of connecting maturity scores to project-level cost outcomes. Conventional COPQ approaches, conversely, report aggregate failure costs without refering to the quality system conditions that produced them. QMI 2.0 and QCIM were developed to fill this gap. QMI 2.0 scores quality system maturity across four empirically evaluated dimensions, while QCIM converts that maturity score into a normalized cost exposure indicator anchored directly to project NCR data. Neither existing maturity models nor standalone COPQ frameworks currently offer this combination.

TABLE I. COMPARISON OF QMI 2.0–QCIM WITH ESTABLISHED QUALITY MATURITY AND COPQ FRAMEWORKS

Framework	Focus	Cost linkage	Empirical validation
ISO 9001:2015	Process compliance	No explicit project-level cost linkage	Limited
CMMI / EFQM	Organizational capability	No financial mapping	Limited
Traditional COPQ (Juran, Crosby)	Failure cost estimation	Aggregate cost only	Moderate
Proposed QMI 2.0 – QCIM	Maturity, cost integration	Direct project-level linkage	Empirical NCR-based (n=180)

As shown in Table I, existing frameworks tend to address either maturity assessment or cost estimation separately. The QMI 2.0–QCIM framework proposed in this study brings these two dimensions together by grounding the cost exposure indicator directly in project-level nonconformance data, a combination that the reviewed literature does not currently offer.

III. METHODOLOGY

The research design followed four consecutive stages. First, 180 nonconformance reports were gathered from five high-rise residential projects and individually verified against site audit logs, variation orders, and cost-control records to ensure that each NCR could be traced directly to a quantifiable financial outcome. Second, the confirmed NCRs were categorized by the affected work package, distinguishing between structural and architectural failures. Third, QMI 2.0 scores were assigned across all project stages through independent assessments conducted by two qualified QA/QC practitioners using identical evaluation criteria. Fourth, QCIM values were derived from the scored dataset and analyzed statistically to map cost behavior across construction phases and maturity levels.

1. Data acquisition and validation: Gathering and cross-referencing 180 unique nonconformance records against project audit logs to ensure data integrity.
2. Taxonomic classification: Categorizing failures by construction phase (specifically distinguishing between primary structural elements and secondary architectural finishing).
3. Index development: Developing and scoring a specialized QMI 2.0 to quantify organizational quality capabilities.
4. Statistical modeling: Conducting a granular analysis of cost patterns across maturity levels and work stages to identify nonlinear correlations.

A. *Data Source and Case Selection*

The NCRs were extracted from contractors' digital Quality Management Systems (QMSs), where nonconformance documentation is routinely archived as part of standard project quality-control procedures. A total of 180 NCRs were identified in the review of project quality documentation. After screening the records for completeness and the availability of the corresponding cost information, all eligible cases were included in the final dataset. Each NCR was subsequently cross-referenced with supporting documentation, including daily site logs, material inspection records, and procurement documentation, to confirm the occurrence of nonconformance and its associated financial impact.

The NCRs were categorized into two distinct construction phases based on the impacted work package: structural works (e.g., reinforcement installation, concrete quality, and dimensional tolerances) and architectural works (e.g., finishing quality, workmanship deficiencies, and material specification discrepancies). All rework cost values were standardized as a percentage of the corresponding project budget to ensure cross-project comparability and neutralize the effects of inflation or varying project scales.

Mechanical, Electrical, and Plumbing (MEP) systems were excluded from this study. Although MEP works constitute a significant portion of high-rise residential construction, the five examined projects did not maintain sufficiently consistent MEP nonconformance documentation to support reliable cross-project cost comparisons. Therefore, the findings presented in this paper pertain exclusively to structural and architectural work packages.

B. *Quality Maturity Index (QMI 2.0): Definition and Scoring*

A composite indicator, QMI 2.0, was developed to objectively quantify and benchmark organizational quality capacity. The index encompasses four critical dimensions: adherence to established QA/QC procedures, thoroughness and traceability of project documentation, workforce training and technical proficiency, and efficacy of inspection and testing protocols.

Each dimension was evaluated on a five-point ordinal scale (1 = extremely weak, 5 = very strong), utilizing standardized checklists cross-referenced against objective project evidence, including sanctioned procedures, document registers, training records, inspection reports, and the timeliness of Nonconformance Report (NCR) closure.

The evaluation was performed independently by two experienced QA/QC assessors utilizing identical criteria across all projects to eliminate subjective bias. The four-dimensional scores were averaged and subsequently normalized to a 0–1 scale to derive the final QMI value for each project stage.

The internal consistency of the QMI 2.0 framework was assessed using Cronbach’s alpha, yielding a coefficient of 0.84, indicating robust reliability. To ensure scoring consistency among assessors, interrater reliability was evaluated using the Intraclass Correlation Coefficient (ICC), which indicated high interobserver agreement (ICC > 0.80).

C. Construction of the Quality Cost Impact Metric (QCIM)

A normalized indicator, the QCIM, was defined to link quality maturity to financial exposure. QCIM represents the share of project costs attributable to quality failures adjusted by the observed maturity level of the quality system. It is expressed in:

$$\text{QCIM}=\frac{\text{Failure Cost}\times(1\text{-QMI})}{\text{Total Project Cost}} \tag{1}$$

The formulation of QCIM is grounded in the prevention–appraisal–failure cost model, which assumes that higher maturity reduces the likelihood of failures and the propagation of their downstream effects. In this study, the QCIM was treated as a comparative indicator rather than a predictive model. In addition, it was used to examine the relative exposure levels across the construction and maturity phases.

To test the robustness of the indicator, alternative normalization bases such as phase-level budgets were evaluated, yielding consistent phase-level trends.

D. Statistical Treatment and Robustness Checks

Before the comparative analyses, the dataset was rigorously examined for distributional assumptions. The Shapiro–Wilk test was used to evaluate normality, whereas Levene’s test was employed to verify the homogeneity of variances between the structural and architectural categories. Given the inherent noise in construction cost data, these tests are essential for selecting the appropriate parametric or nonparametric modeling approaches.

Group disparities in rework cost behavior were assessed with a focus on practical significance, rather than solely on statistical significance. Cohen’s d was computed to measure the effect size, providing a standardized metric for the magnitude of cost variations. A post hoc power analysis conducted using G*Power verified a statistical power greater than 0.80, demonstrating that the NCR sample size of 180 was sufficient for the observed phase-level comparisons at a 95% confidence interval.

All calculations were performed using SPSS (version 26) and R-based statistical tools to ensure the transparency, consistency, and reproducibility of the results.

Statistical power and effect sizes were emphasized over p-values to ensure the practical relevance of the findings within the specialized domain of construction economics. Cohen’s d was computed for all comparisons of structural and architectural rework costs to quantify the magnitude of cost divergence, thereby facilitating a better understanding of "real-world" implications beyond mere statistical significance.

To further validate the findings, a post hoc power analysis using G*Power showed a statistical power greater than 0.80, confirming that the 180 NCR dataset was sufficient to detect significant differences between quality maturity and financial success. This threshold guarantees that the observed correlations are reliable and replicable despite the intrinsic variability typically encountered in high-rise project data. Finally, all data processing and modeling were performed using SPSS to maintain the highest level of computational rigor.

TABLE II. NONCONFORMANCE DISTRIBUTION AND CHARACTERISTICS

Construction phase	**NCRs (n = 180)**	**Primary root causes**
Structural works	42 (23.3%)e	Dimensional tolerances, reinforcement placement errors, and concrete quality deviations
Architectural works	138 (76.7%)	Finishing inconsistencies, workmanship deficiencies, and material specification mismatches
Total	180 (100%)	Design inadequacies, workforce competency gaps, and material inconsistencies

IV. RESULTS

A. Quantifying Quality Maturity Impact Through QCIM and QMI 2.0

Two interdependent metrics were developed to examine the relationship between quality maturity and financial performance. The QCIM represents the percentage of total project expenditure attributed to quality failures, weighted against the operational efficiency of the existing quality management system. This relationship can be mathematically defined as:

$$\text{QCIM} = (\text{Cf} \times (1 - \text{QMI}))\,/\,\text{Ct} \tag{2}$$

QMI 2.0 offers a standardized maturity score between 0 and 1 based on a multi-criteria empirical evaluation of four essential quality system dimensions: adherence to established QA/QC procedures, completeness of the documentation system, workforce training and competency enhancement, and the effectiveness of inspection protocols. The analysis conducted indicates that elevated QMI values signify the systemic maturity of quality management capabilities. Higher maturity levels were associated with reduced rework propagation at the source and lower QCIM values across the projects examined. By quantifying these management processes, QMI 2.0 converts audit-based assessments into normalized cost-exposure indicators, providing a basis for comparative evaluation of financial risk.

This paradigm represents a significant methodological improvement over existing quality evaluation approaches by directly linking previously siloed organizational capabilities to quantifiable financial performance metrics. Unlike traditional assessment models that treat quality as a compliance obligation, this framework positions quality maturity as the primary driver of cost efficiency. This provides project stakeholders with a transparent mechanism to visualize how investments in procedural rigor translate into tangible bottom-line savings.

B. Nonlinear Quality Cost Behavior Patterns

An examination of preventive, appraisal, failure, and total quality costs revealed a distinct nonlinear correlation. As investment in prevention increases, the cost of failure decreases at an accelerating rate rather than in a direct, linear fashion. In low-prevention environments, failure costs systematically dominate total quality expenses, triggering a "domino effect" in which early-stage structural discrepancies necessitate expensive downstream architectural adjustments.

The data indicate that total quality cost optimization is achieved when prevention and assessment efforts reach a maturity threshold sufficient to eliminate most failure modes. Beyond this point, the law of diminishing returns applies further investment in prevention yields diminishing returns. However, the present work's data reveal that most construction firms function well below this equilibrium point. This suggests considerable opportunities for cost reduction by strategically front-loading resources toward preventive quality measures rather than reactive correction.

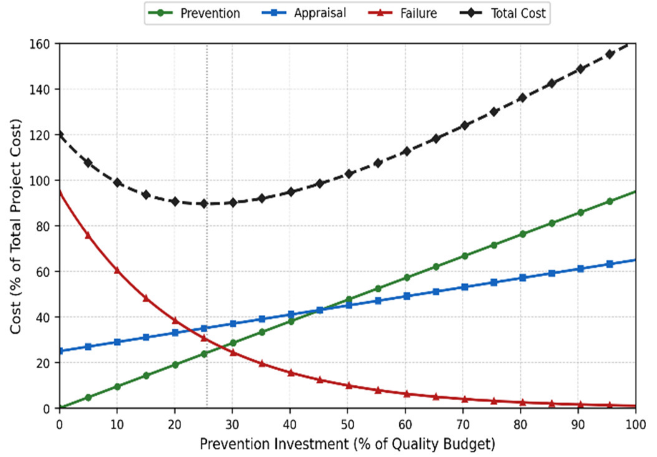

Fig. 1. The relationship between prevention/appraisal efforts and total quality costs.

Figure 1 illustrates how increased prevention and appraisal efforts substantially reduce overall failure-related costs, with the total cost curve exhibiting a characteristic minimum point that represents optimal resource allocation.

C. *Phase-Specific Rework Characteristics*

The structural and architectural construction phases exhibit inherently diverse patterns of quality failure, necessitating distinct management strategies. Structural studies exhibit "low-frequency and high-severity" profiles. Deficiencies in this phase, generally involving dimensional tolerance infringements, reinforcement positioning inaccuracies, and concrete quality discrepancies, arise relatively seldom (23.3% of total NCRs); however, they have exponential financial repercussions when they occur. The "irreversibility" of structural components necessitates extensive demolition and reconstruction for remediation, resulting in cascading schedule delays that often trigger liquidated damages.

Architectural projects, conversely, follow a high-volume, "death by a thousand cuts" pattern. These account for 76.7% of the recorded nonconformities and primarily involve discrepancies in finishing, deficiencies in craftsmanship quality, and inconsistencies in material specifications. Although individual occurrences incur negligible costs per incident, their aggregate frequency results in a significant "leakage" of the project's profit margin. This persistent management overhead requires a different level of supervision, focusing on labor-intensive craftsmanship rather than the rigid engineering controls required for structural integrity.

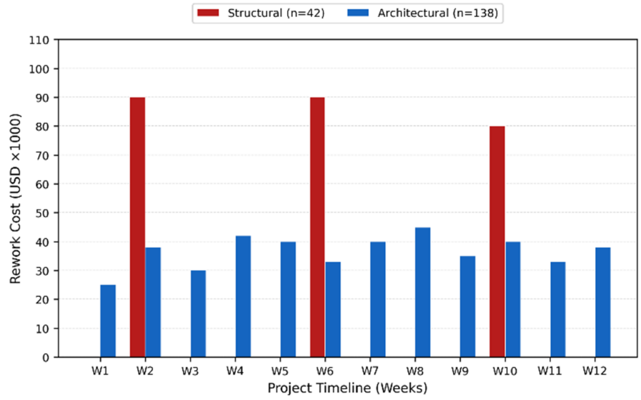

Fig. 2. Cost and frequency contrast between structural and architectural failures.

Figure 2 illustrates this contrast. Structural failures are infrequent, but financially severe. Architectural defects occur consistently and at moderate cost, accumulating throughout construction.

D. *Economic Impact Quantification*

The cost data derived from the 180 NCRs fall into two broad categories. Direct costs, specifically corrective rework labor, material waste, and equipment idle time, were fully traceable through site logs and variation orders, forming the quantitative backbone of this analysis. Structural NCRs, though limited to 23.3% of the total recorded nonconformances, generated disproportionately high direct costs in each instance, driven primarily by the demolition and reconstruction demands that structural remediation inevitably entails. Architectural NCRs, while individually inexpensive to resolve, accumulated across all five projects into a direct cost burden that proved financially significant in aggregate. Indirect costs, including schedule slippage, prolonged supervision, subcontractor disruption, and reputational consequences, fell outside the NCR dataset's traceable boundaries and could not be formally incorporated into the QCIM calculations. Quantifying these indirect dimensions remains an open research question and a natural extension of the framework introduced in this study.

The empirical findings of this work support existing research while offering granularity into construction-specific cost dynamics. Rework accounted for 4–12% of the total project costs in the examined projects, a range that aligns with established international benchmarks. However, the obtained data further demonstrated that the associated cost burden is not uniformly distributed but fluctuates substantially across building phases. In addition, cost is directly proportional to the quality system's maturity.

Organizations that shifted from reactive "inspection-only" models to fully prevention-oriented quality systems achieved reductions in COPQ ranging from 30% to 50% [11]. This shift highlights a significant economic lever, particularly in large-scale projects, where marginal percentage gains translate into substantial absolute savings that can determine the overall feasibility of development.

Furthermore, technology-enabled coordination, specifically, the deployment of BIM-based clash detection, reduced coordination-related failures by up to 40% [3]. This finding refutes the perception of digital tools as mere overhead. Instead, it indicates that digital quality management infrastructure generates measurable returns on investment and should be reclassified as core strategic assets rather than optional technological add-ons. In the current high-inflation environment, such digital interventions are no longer a luxury but a fundamental necessity for project liquidity.

V. DISCUSSION

An examination of 180 nonconformances (synthesized in Table I) supports the need for dynamic QMSs tailored to specific construction phases. These findings challenge the "static" quality models traditionally applied in high-rise developments, affecting both project execution planning and the broader application of quality theory. By mapping the heterogeneous nature of quality failures, the analysis carried out suggests that a granular approach to QA is not merely an operational choice but a financial one.

Structural NCRs, which account for only 23.3% of recorded nonconformances, warrant disproportionate quality management attention due to their severe financial and technical consequences. The physical irreversibility of concrete placement and reinforcement installation implies that latent defects detected at later stages incur exponentially higher costs for each delay in discovery. For example, reinforcement alignment problems identified during pre-pour inspections require only modest adjustments, whereas comparable errors discovered after attaining the design strength may necessitate invasive demolition and structural retrofitting.

The analysis suggests that these fat-tail risks, low-frequency, high-impact events, generate significant financial exposure, despite their rarity. These findings have clear implications for quality resource allocation. Moreover, structural phases require redundant evaluation and front-loaded preventive measures, even though these measures may appear excessive when viewed from a historical frequency perspective. The magnitude of a potential failure outweighs the probability of its occurrence, justifying a "zero-tolerance" investment approach to structural integrity.

A. Architectural Paradox: High Frequency as a Profit Drain

Architectural construction accounts for 76.7% of quality failures, primarily due to finishing inconsistencies and workmanship defects. Although the costs of individual unit repairs are negligible, their persistent, repetitive occurrence results in a substantial aggregate cost due to COPQ. This indicates that preventive control methods, such as targeted worker skill development, greater specification clarity, and rapid feedback loops, are more effective than retrospective end-of-pipe inspection procedures.

The aggregate cost implications directly challenge the misconception that "moderate-impact" issues require only moderate management attention. High frequency converts marginal unit costs into significant overall losses, eroding net profitability and disrupting project timelines through accumulated "micro-delays." This study’s findings indicate that during the architectural phases, quality management must shift from reactive oversight to proactive prevention, emphasizing the standardization of craftsmanship rather than solely detecting flaws after they occur.

B. QCIM-QMI Framework Contribution

The established methodology illustrated that systematic prevention through worker training, supplier certification, and rigorous design reviews yield significant reductions in rework costs. The performed analysis identified a distinct nonlinear relationship: specific threshold effects emanate when incremental improvements in quality and maturity yield disproportionate cost-saving advantages.

The obtained data revealed a "maturity barrier." As the QMI approached 1.0, failure costs were systematically neutralized through early detection and robust process control. Organizations operating below a QMI of 0.6 incur significantly higher COPQ than those exceeding this threshold, indicating that fragmented or "checklist-only" quality systems yield minimal economic benefit. This underscores that effective quality management is an "all-or-nothing" commitment; it necessitates comprehensive, integrated methodologies rather than selective, superficial implementation.

This approach enhances the construction management literature by bridging the gap between abstract quality theory and project-level financial outcomes. While previous studies have suggested theoretical correlations, the present study objectively corroborated them using granular construction-specific data, providing project managers with a standardized implementation mechanism to justify quality-related investments.

C. Implications for Industry Practices

The findings contest widely held beliefs regarding the economics of quality management. The data indicate that quality should not be viewed as a cost center to be minimized but as a strategic investment that yields verifiable results. Organizations that categorize quality spending as overhead neglect the leverage effect on overall project economics.

Prevention-first strategies are economically justifiable in construction settings. Each dollar invested in prevention, such as design review, material testing, and labor training, prevents several dollars in subsequent failure costs. This multiplicative relationship indicates that ideal quality, particularly in the prevention and appraisal categories, significantly surpasses current industry standards. In the high-stakes environment of high-rise construction, front-loading quality costs are not a luxury but a risk-mitigation requirement to maintain project liquidity.

The practical implication of these findings is straightforward. Projects operating below a QMI of 0.6 consistently recorded higher COPQ ratios, confirming that partial or checklist-only quality systems provide limited financial protection. For contractors, this translates into a clear reallocation priority: investment in workforce training, supplier qualification, and early-stage design review delivers measurably greater returns than equivalent spending on end-stage inspection. In high-rise residential construction, where a single structural failure can trigger costs that dwarf an entire prevention budget, and where architectural defects quietly erode margins across hundreds of individual work packages, treating quality management as a phase-specific financial strategy rather than a uniform compliance obligation is not a refinement; it is a requirement.

VI. CONCLUSION

This study confirmed that quality management serves as a strategic economic tool rather than a mere compliance burden. Through the analysis of 180 Nonconformance Reports (NCRs) and the application of Quality Cost Impact Metric-Quality Maturity Index 2.0 (QCIM-QMI 2.0), several findings with direct practical relevance were established.

Systemic quality integration for risk mitigation: Shifting quality management from a retrospective inspection task to an embedded process control function results in a quantifiable reduction in the Cost Of Poor Quality (COPQ). Organizations adopting a lifecycle-wide quality approach have demonstrably superior financial and technical outcomes.

Economic value of quality maturity: QCIM–QMI 2.0, provided a mathematically sound foundation for quantifying financial exposure linked to quality system deficiencies. By bridging the gap between organizational maturity and project-level outcomes, the proposed framework enabled evidence-based resource allocation and justified investments in quality-related training and technology.

The "maturity threshold" in prevention: Preventive measures consistently yield the highest return on investment. This study's findings highlight a nonlinear enhancement in financial performance once an organization crosses the 0.6 QMI threshold. Strategic investment in prevention effectively mitigates both high-severity structural risks and architectural flaws.

Phase-specific management strategies: Quality failure patterns differ significantly between structural and architectural phases. Structural work demands rigorous and redundant prevention owing to the catastrophic nature of failure. In contrast, architectural phases benefit from standardized craftsmanship and rapid feedback loops to mitigate profit erosion from frequent, moderate-impact defects.

In contemporary construction landscapes, where complexity is escalating and margins are tightening, the transition from reactive correction to proactive management is essential for economic viability. Firms that fail to optimize these quality-cost connections face an increasing competitive disadvantage. This study provides construction stakeholders with verified instruments to transform quality management from compliance-driven overheads to crucial strategic competence.

This study has several limitations that should be acknowledged. The 180 NCRs were drawn exclusively from five high-rise residential projects, and the findings therefore reflect a specific building typology and project context. Extending these conclusions to other construction sectors or procurement environments requires caution. Furthermore, indirect costs, such as schedule penalties, subcontractor disruption, and reputational consequences, fell outside the traceable boundaries of the NCR dataset. They were not incorporated into the QCIM calculations, meaning that the full financial impact of poor quality is likely higher than the figures reported in this work. The QMI 2.0 scoring also relied on assessor judgment; although interrater reliability was statistically confirmed, the index has not been tested against independent project datasets. These boundaries define a clear agenda for future research.

DECLARATION OF COMPETING INTERESTS

The author declares that there are no competing interests.

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Not applicable to this work.

DATA AVAILABILITY

The data supporting the findings of this study are available from the author upon reasonable request.

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