Minería y Geología / v 42 /2026/ e002 ISSN 1993 8012

REVIEW ARTICLE

Tangible and Intangible Quality Costs in the Metallurgical Industry: A Systematic Review with a Focus on Production Processess

Costos de calidad tangibles e intangibles en la industria metalúrgica: revisión sistemática con enfoque en procesos productivos

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Abstract

Quality cost analysis allows for the examination of economic losses associated with deviations in production processes. However, the scientific literature has limitations regarding the conceptual and methodological integration of tangible and intangible costs, particularly in industrial sectors characterized by high technical complexity. The objective of this study is to systematically analyze published research on quality cost management and the methods proposed for its measurement. A systematic literature review was conducted following the PRISMA protocol. The search was performed in the Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar databases for the period 1998–2024. The analyzed corpus consisted of 84 scientific studies. The results identified research trends, application sectors, conceptual approaches for classifying quality costs, and methodological procedures used to estimate intangible costs. The analysis revealed methodological heterogeneity and limited incorporation of variables associated with risk, uncertainty, and operational complexity. These results highlight persistent gaps in the measurement of intangible costs and point to the need for analytical approaches that integrate these dimensions into quality management systems in industrial settings.

Keywords: quality costs, tangible and intangible costs, metallurgical industry, systematic review, PRISMA methodology

Resumen

El análisis de los costos de calidad permite examinar pérdidas económicas asociadas a desviaciones en los procesos productivos. Sin embargo, la literatura científica presenta limitaciones en la integración conceptual y metodológica de los costos tangibles e intangibles, especialmente en sectores industriales caracterizados por elevada complejidad técnica. El presente estudio tiene como objetivo analizar de manera sistemática la investigación publicada sobre la gestión de los costos de calidad y los métodos propuestos para su medición. Se desarrolló una revisión sistemática de la literatura siguiendo el protocolo PRISMA. La búsqueda se realizó en las bases de datos Scopus, Web of Science, ScienceDirect, SpringerLink y Google Scholar para el período 1998–2024. El corpus analizado estuvo conformado por 84 estudios científicos. Los resultados permitieron identificar tendencias de investigación, sectores de aplicación, enfoques conceptuales para la clasificación de los costos de calidad y procedimientos metodológicos utilizados para estimar costos intangibles. El análisis evidenció heterogeneidad metodológica y una limitada incorporación de variables asociadas al riesgo, la incertidumbre y la complejidad operativa. Estos resultados muestran vacíos persistentes en la medición de los costos intangibles y señalan la necesidad de enfoques analíticos que integren estas dimensiones en los sistemas de gestión de calidad en entornos industriales.

Palabras clave: costos de calidad, costos tangibles e intangibles, industria metalúrgica, revisión sistemática, metodología PRISMA

1. INTRODUCTION

La The metallurgical and mining-metallurgical industry is characterized by production processes of high technical complexity, high material and energy intensity, and a strong dependence on the precise control of physical, chemical, and operational parameters. In these environments, quality deviations have a significant economic expression due to their impact on metallurgical yield, energy consumption, generation of reprocessing, scrap production, and operational stability of industrial facilities. Consequently, quality management transcends simple conformity of the final product and is directly linked to the overall efficiency of the process, technological safety, and sustainability of the production system.

Quality failures can manifest at different stages of the metallurgical process, from raw material preparation to final forming and finishing operations. These deviations generate visible costs associated with reprocessing, material waste, unplanned stoppages, or contractual penalties, as well as less evident costs linked to the loss of operational stability, decreased process reliability, and deterioration of the organization's technical reputation. In this context, quality costs constitute an analytical category that integrates both registrable direct expenditures and intangible losses whose identification and quantification are complex (Azebaze & Takoudjou, 2021; Pérez-Mayedo *et al.*, 2025).

The study of quality costs progressively became consolidated within the management and industrial accounting literature based on the contributions of Juran and later developments in management accounting, which made it possible to relate process failures to avoidable economic losses (Gorbunova *et al.*, 2017; Rogošić, 2020). Over time, this field of research incorporated approaches from process engineering, operations management, and organizational control, which favored the integration of cost analysis with production performance evaluation in complex industrial systems (Mahmood & Kureshi, 2015).

In recent years, the literature has broadened its attention toward intangible or hidden quality costs, associated with organizational, human, and operational factors that are not directly reflected in accounting records. Research conducted in complex industrial contexts has identified losses linked to the turnover of specialized personnel, loss of operational knowledge, deterioration of the organizational climate, and recurrence of failures not detected at critical stages of the process (Brotons & Sansalvador, 2015; Abu *et al.*, 2018; Li *et al.*, 2018). These dimensions acquire special importance in the metallurgical industry, where the stability of technical knowledge and process reliability directly influence product quality and production system efficiency.

Various studies have proposed methodologies to address the estimation of these costs by integrating tools such as activity-based costing, statistical models, multi-criteria approaches, and fuzzy logic techniques (Mastrapa & Sánchez, 2017; Glogovac *et al.*, 2019). However, despite these advances, limitations persist in the integrated understanding of tangible and intangible costs in industrial environments characterized by high technical complexity. A significant portion of the literature continues to focus on measuring visible costs associated with internal and external failures, while hidden costs related to organizational factors, operational risks, or process instability receive fragmented methodological treatment.

This situation reveals the existence of a gap in the scientific literature, particularly in resource-intensive industrial sectors with high operational variability, such as the metallurgical industry. In these contexts, the interaction between technical, economic, and organizational variables significantly conditions productive performance and the sustainability of quality management systems.

Within this framework, the present study aims to systematically analyze the scientific production related to the management of tangible and intangible quality costs, with emphasis on their application in complex industrial contexts. The scientific contribution of this work lies in the critical systematization of the conceptual and methodological approaches used for the analysis of quality costs, as well as in the identification of persistent gaps in the measurement of intangible costs and in the integration of risk management approaches in industrial systems of high technical complexity.

2. METHODS

The present research was structured as a systematic review of the scientific literature, with the purpose of analyzing the state of knowledge on the management of quality costs, both tangible and intangible, with emphasis on their application in complex industrial environments of high material and energy intensity, such as metallurgical and mining metallurgical processes. To guarantee methodological rigor, transparency, and reproducibility of the study, the guidelines established by the PRISMA method (Preferred Reporting Items for Systematic Reviews and Meta Analyses) were adopted, which guided the stages of identification, selection, evaluation, and synthesis of scientific information.

The bibliographic search was conducted between January and May 2025 in scientific databases of recognized academic impact, including Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. Combinations of keywords in English and Spanish were used, such as: cost of quality, quality cost management, intangible quality costs, tangible quality costs, quality economics, gestión de costos de calidad, and costos intangibles de la calidad. In order to capture studies relevant to the analysis of contemporary industrial processes, a time period between 1998 and 2024 was established as a temporal criterion.

The following inclusion criteria were defined for the composition of the analysis corpus: a) articles published in peer reviewed scientific journals; b) empirical, theoretical, or review research explicitly linked to quality cost management; c) full text available in Spanish or English; d) thematic relevance in relation to tangible and intangible quality costs in organizational and industrial contexts, including productive sectors characterized by complex technical processes, such as manufacturing, heavy industry, metallurgy, mining, or materials processing.

Complementarily, the following exclusion criteria were established: a) duplicate publications; b) documents not peer reviewed, such as academic theses, technical reports, or presentations at scientific events; c) studies focused on quality without explicit linkage to cost analysis; d) articles without access to the full text.

The selection process was carried out in three consecutive phases: identification, screening, and eligibility. In the identification phase, 286 potentially relevant articles were recorded (Figure 1). Subsequently, duplicates were removed and a first filter was applied by reviewing titles and abstracts, reducing the sample to 132 studies. Finally, after reading the full texts and systematically applying the inclusion and exclusion criteria, 84 articles were selected that formed the final analysis corpus.

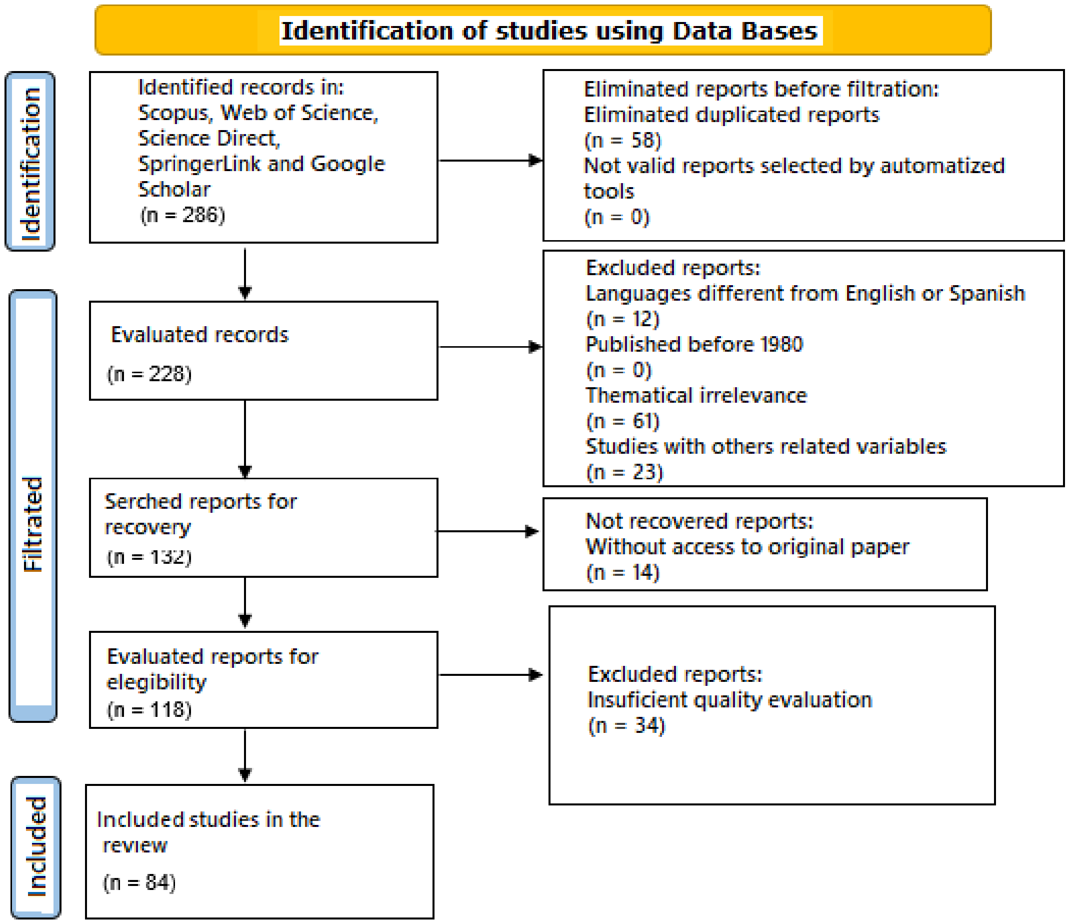

Figure 1. Flowchart of the article selection process.

Data extraction was carried out using a bibliographic analysis matrix that included variables such as: authorship, year of publication, country of origin, type of study, sector of application, type of costs analyzed (tangible/intangible), methodology employed, and main findings. For the qualitative analysis and categorization of the studies, a thematic content analysis approach was used, allowing the identification of patterns, predominant approaches, and emerging trends. Additionally, hierarchical clustering was implemented to group publications according to their co citation and thematic similarities. The bibliometric tools used for this analysis were Orange 3.26.0 and VOSviewer 1.6.16.

The methodological quality assessment of the included studies was performed using a set of analytical criteria that considered: (a) clarity in the formulation of the research problem; (b) coherence between objectives, methodological design, and results obtained; (c) consistency of the procedures for measuring or modeling quality costs; (d) validity of the analysis methods employed; and (e) relevance of the application context in relation to industrial production processes. Each study was independently examined by the authors and subsequently cross checked through academic discussion to ensure consistency in the classification and interpretation of the results.

3. RESULTS

A total of 84 relevant investigations related to quality cost management were examined. Of the total studies analyzed, 70% were developed in the last seven years, with a distribution showing a higher concentration of publications in the period between 2014 and 2018, followed by the interval 2018-2021, as illustrated in Figure 2. This temporal evolution reveals a sustained increase in academic and professional interest in the subject, particularly in industrial contexts where operational efficiency, process stability, and the reduction of productive losses acquire growing importance, as occurs in the metallurgical and mining metallurgical sectors.

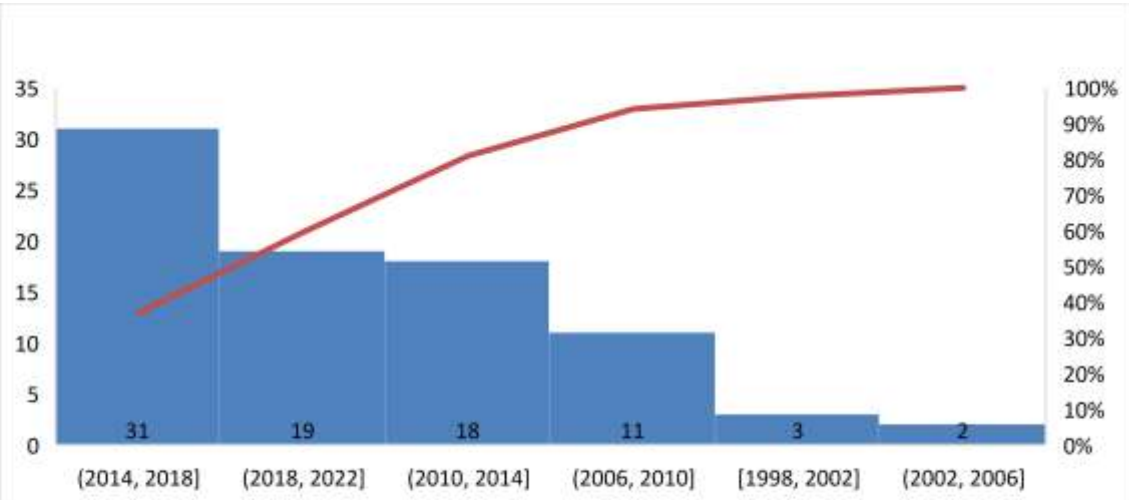

Figure 2. Pareto diagram of the investigations analyzed by year.

Regarding the sectors of application, it was identified that the production area concentrates the largest proportion of proposals linked to quality cost systems. This result is consistent with the nature of resource-intensive industrial processes, where quality deviations translate into reprocessing, scrap generation, unplanned stoppages, and yield losses, phenomena that are particularly frequent in metal transformation processes. Likewise, 55% of the reviewed investigations correspond to studies developed in Cuba, although the analysis covered works from a total of 20 countries, as shown in Figure 3.

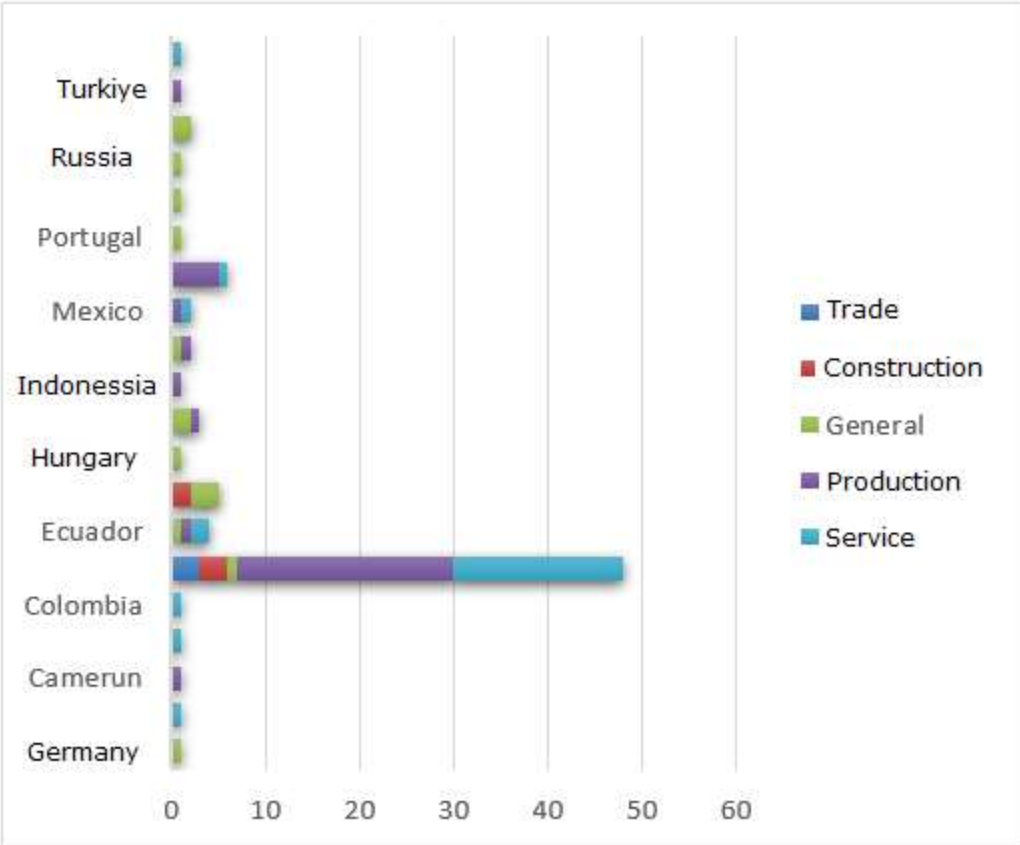

Figure 3. Number of investigations analyzed, by country and sector of application.

The high presence of Cuban investigations can be explained by the need to optimize organizational efficiency in a productive environment conditioned by economic constraints, limited resource availability, and a high dependence on the operational stability of industrial plants. In this context, quality cost management has become an analytical tool for identifying systemic inefficiencies and supporting decisions aimed at improving productive performance.

In particular, the years 2015 and 2019 concentrated the largest number of methodological proposals applied to the production and service sectors within the Cuban context, as observed in Figure 4, which coincides with a period of strengthening of quality control and management policies in transformation industries.

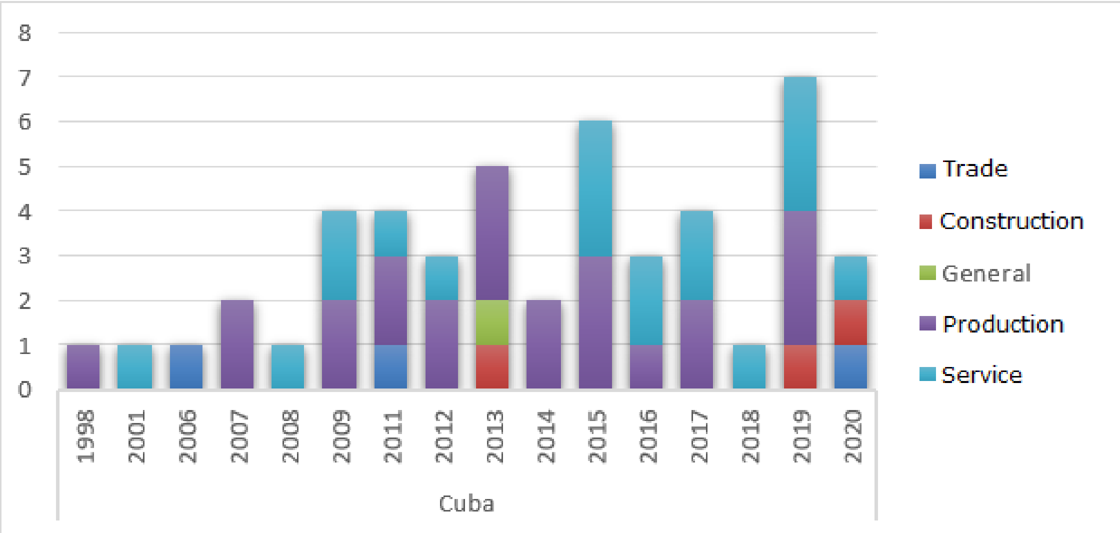

Figure 4. Number of Cuban investigations analyzed by year and sector of application.

Based on the analysis of the selected corpus, the review results were organized into four thematic axes: (1) the definition of tangible and intangible quality costs; (2) the relevance of their management for operational efficiency and industrial competitiveness; (3) the characterization of methodological procedures used in the design and implementation of quality cost systems; and (4) the examination of proposed methods for estimating intangible costs, with emphasis on the challenges associated with their measurement and the solutions addressed by the specialized literature.

3.1. Definition of tangible and intangible quality costs

The systematic review allowed establishing a structured conceptual basis for the analysis of quality costs, widely accepted in the specialized literature. Most theoretical approaches agree on their classification into four fundamental categories: prevention costs, appraisal costs, internal failure costs, and external failure costs (Arana *et al.*, 2017; Agrawal, 2020). This classification has proven useful for identifying, grouping, and controlling the economic resources allocated to ensuring compliance with quality requirements in complex production processes.

The concept of quality costs has been approached from different analytical perspectives. Some authors define them as the set of resources associated with quality planning, assurance, control, and improvement activities (Lavielle-Laugart, 2015; Gorbunova *et al.*, 2017). Other approaches link them directly to economic losses derived from non-conforming products or services, such as reprocessing, claims, or returns (Sailaja *et al.*, 2015; Macías *et al.*, 2019), categories that acquire significant expression in metallurgical processes due to the high sensitivity of products to dimensional, compositional, or microstructural deviations. A third theoretical line restricts their scope to expenses directly attributable to quality areas or departments (Rehacek, 2018; Ramírez-Romero *et al.*, 2019).

The literature consistently distinguishes between tangible and intangible quality costs. Tangible costs are characterized by their relative ease of identification and quantification, as well as their direct link to production operations and financial results. This category includes prevention costs, such as training of technical personnel, process standardization, and incorporation of control technologies; appraisal costs, associated with inspections, audits, and quality tests; and internal and external failure costs, related to reprocessing, warranties, returns, and loss of customers (Eraslan & Önal, 2021).

In contrast, intangible costs are defined as those whose measurement is complex due to their indirect or subjective nature. These costs are associated with loss of technical reputation, customer dissatisfaction, decreased loyalty, deterioration of institutional image, and reduction of business opportunities (Glogovac *et al.*, 2019; Azebaze & Takoudjou, 2021). In metallurgical environments, these effects can also manifest as loss of process reliability, decreased operational stability, and increased technological risk, with cumulative impacts on industrial performance in the medium and long term.

The distinction between tangible and intangible costs expands the understanding of quality costs as a multidimensional category that transcends the strictly accounting sphere. While tangible costs are reflected in verifiable financial records, intangible costs represent less visible structural consequences that are nevertheless decisive for the overall efficiency of the production system (Mahmood & Kureshi, 2015; Brotons & Sansalvador, 2015). Both components must be integrated into the design of quality management systems applicable to industries characterized by complex technical processes and high operational variability.

Together, quality costs include both investments aimed at preventing and evaluating the conformity of processes and products, as well as the losses associated with the existence, recurrence, or risk of non-conformity. Their analysis requires a conceptual approach that integrates visible and hidden economic dimensions, with the purpose of supporting continuous improvement processes consistent with the technical and operational demands of the metallurgical and mining-metallurgical industry (Rosiawan *et al.*, 2019; Rogošić, 2020).

3.2. Importance of quality cost management

Quality cost management makes it possible to identify, classify, and control the resources allocated to ensuring and improving the performance of production and service processes (Spagnoli *et al.*, 2024). In industrial environments characterized by continuous processes, high material intensity, and strict technical requirements, such as those of the metallurgical industry, this management acquires a significant operational dimension, directly affecting process stability, productive performance, and efficient use of resources.

Although some components of quality costs can be quantified with relative precision, Sousa and Nunes (2019) point out that actual figures often exceed recorded estimates due to the inherent limitations of traditional accounting systems. This discrepancy has driven the development of methodological approaches aimed at more accurately capturing the costs associated with quality deviations.

The categorization of costs into prevention, appraisal, internal failures, and external failures facilitates the analysis of operations and favors the adoption of corrective and preventive decisions. Berni *et al.* (2018) argue that having this information makes it possible to anticipate economic impacts derived from timely interventions, which helps maintain product conformity with technical specifications and optimize the use of available resources. In metallurgical processes, this classification is particularly useful for identifying losses associated with reprocessing, unplanned stoppages, scrap generation, and deviations in critical process parameters.

Several studies warn about the existence of intangible or indirect costs that are not explicitly reflected in accounting records. Azebaze and Takoudjou (2021) highlight that these hidden elements can progressively deteriorate financial margins and affect industrial competitiveness. For their estimation, methods have been developed that incorporate indirect indicators, such as specialized personnel turnover, customer loss, unproductive time, or operational instability – aspects that in metallurgical plants are also associated with the loss of technical experience and increased technological risk.

Authors such as González Reyes and Moreno Pino (2017), Glogovac *et al.* (2019), and Eraslan and Önal (2021) documented the economic consequences of non-quality in industries where errors cause reprocessing, returns, or contractual breaches, and introduced the concept of the "hidden factory" to describe activities that consume resources without generating value and often go unnoticed by management teams. In the metallurgical field, this concept is applicable to activities such as repeated process adjustments, redundant controls, or late correction of failures.

The meta-analysis conducted by Mahmood and Kureshi (2015), based on 57 studies published between 1975 and 2015, estimated that non-visible quality costs could range between 16.91% and 26.90% of revenue, with a mean of 21.91%. These results show the economic magnitude of intangible costs and highlight that their control represents an opportunity to improve financial performance, especially in industries with high operating costs.

The systematization and monitoring of quality costs have been associated with improvements in organizational performance. Research such as that of Arana *et al.* (2017) and Mastrapa and Sánchez (2017) shows that these practices contribute to loss reduction, improvement of operational indicators, and the creation of favorable conditions for moving towards continuous improvement schemes, compatible with the requirements of complex technical industries.

In this context, quality cost management provides an expanded view of the economic impact of operational deficiencies and facilitates the implementation of strategies aimed at the efficient use of resources. This practice reinforces decision-making processes and favors the configuration of industrial organizations with greater adaptive capacity in environments of high technical and economic demand.

3.3. Procedures for constructing quality cost systems: critical analysis

The methodological evolution identified in this review points toward models that integrate technological, analytical, and management tools to address both visible costs and those that are not explicitly recorded. The application of hybrid approaches, sectoral analysis, and a preventive orientation shape a landscape that favors the consolidation of more consistent quality systems adaptable to complex industrial contexts.

The most recent reviews, covering studies published between 2013 and 2021, show a wide diversity of methodologies applied to quality cost management. Among them, activity-based costing (ABC), models that integrate invisible costs, the use of fuzzy logic, statistical tools, and sustainability-oriented approaches stand out.

Mahmood and Kureshi (2015) point out that a significant proportion of quality costs escapes traditional metrics, justifying the need for tools capable of identifying and analyzing these hidden effects. Along these lines, Brotons and Sansalvador (2015) propose systems that incorporate variables that are difficult to quantify using fuzzy logic, improving the estimation of the economic impact of quality deficiencies in industrial processes.

Bécquer and Sánchez (2013) raise the need to structure cost systems based on processes and activities, following the principles of ABC costing, which allows for a more precise allocation of resources and an improvement in operational efficiency (Zambrano *et al.*, 2018). Díaz Martell and Vega (2015) confirmed the usefulness of this approach in sectors with high technical demand.

Other studies integrate statistical techniques with costing models. Abu *et al.* (2018) combined the Mahalanobis-Taguchi system with ABC costing to analyze remanufacturing processes, achieving better variable discrimination and a reduction in costs associated with quality deviations.

From a strategic perspective, González Reyes and Moreno Pino (2017) and Sedevich-Fons (2018) highlight the link between quality costs and management systems based on the ISO 9001 standard, favoring their use as instruments for continuous improvement. Arana *et al.* (2017) show that their systematic monitoring allows consolidating practices aligned with the PDCA cycle.

Other works, such as those of Rosiawan *et al.* (2019), Glogovac *et al.* (2019), and Spagnoli *et al.* (2024), develop models that prioritize interventions based on the relationship between quality costs and economic return, allowing efforts to be concentrated on processes with the greatest potential for financial impact.

Sectoral experiences also show favorable results. Studies applied in agri-food and processing industries show that systems adapted to the local productive context improve efficiency and traceability, and favor sustainability (Macías *et al.*, 2019; Ramírez-Romero *et al.*, 2019). In the environmental field, Mastrapa and Sánchez (2017) propose integrating quality costs with environmental costs, expanding the scope of business management.

Agrawal (2020) presents a conceptual framework that articulates Crosby's quality principles with structured tools such as ISM and MICMAC, allowing the identification of hierarchical relationships between management practices and their effects on costs, strengthening organizational planning.

The analysis of the methodological procedures employed reveals a marked heterogeneity in the available proposals. To identify the most recurrent variables, a linguistic corpus was created from the analyzed documents using the Sketch Engine tool, confirming the frequency of terms such as system, process, management, product, activity, control, prevention, appraisal, and improvement (Figure 5).

Figure 5. Variables associated with the quality cost systems analyzed.

However, a limited presence of variables such as intangible, hidden, risk, assurance, and variability were observed. This omission reduces the ability of models to adapt to complex industrial dynamics and limits their usefulness for scenario anticipation, sustainability, and integrated quality management.

Likewise, significant dispersion was identified in the classifications used to structure quality costs, making it difficult to compare studies and consolidate consistent theoretical frameworks. To mitigate this limitation, an approach that combines the inclusion of intangible costs with an emphasis on risk management is proposed (Figure 6).

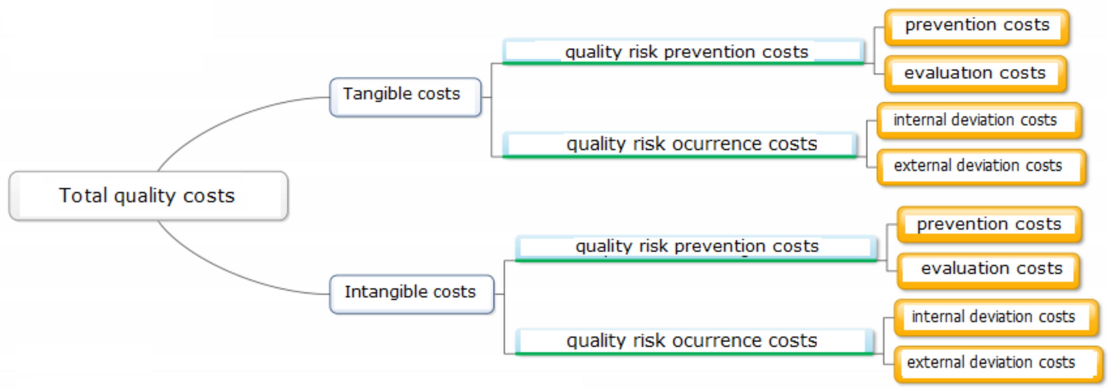

Figure 6. Conceptual map of total quality costs.

For the delimitation of quality cost subgroups, it is proposed to use the classification established in Specific Accounting Standard No. 12 of Resolution No. 935/2018 of the Ministry of Finance and Prices of Cuba, as a reference framework to harmonize accounting practice with quality management needs.

However, the identification of the activities generating these costs continues to represent a challenge, due to the absence of uniform criteria in the literature. Therefore, it is suggested that such identification respond to the particularities of each organization, considering its internal processes. As guidance, a categorization based on the value chain is proposed, which facilitates a coherent assignment of activities to each type of cost (Table 1).

Table 1. Categorization of quality cost-generating activities according to the value chain

Quality Cost Category	Value Chain Stages	Representative Activities
Prevention Costs	Procurement, R&D, Production, HR	- Personnel training and certification - Development of procedure manuals - Supplier evaluation - Preventive equipment maintenance - Implementation of quality management systems - Preventive internal audits - Product design with a quality focus
Appraisal Costs	Production, Quality assurance, Logistics	- Raw material inspection - Laboratory testing - Verification of compliance with technical specifications - Finished product evaluation - Calibration of measuring instruments - Document control - Cross-audits
Internal Failure Costs	Production, Operational management	- Reprocessing of defective products - Correction of administrative errors - Unplanned stoppages - Material waste - Idle time due to failures

		- Unplanned production line adjustments - Disposal of non-conforming products
External Failure Costs	External logistics, Customer service, After-sales	- Product returns - Warranty replacement - Customer compensations - Legal claims - On-site technical intervention - Reputational crisis management - Customer loss costs - Post-delivery rework due to non-conformity

Table 2. Analysis of gaps in methodological procedures for the construction of quality cost systems

Methodological Component	**Presence in models**	**Main Function**	**Identified gap**
Planification	43 %	Establish objectives and scope of the system	Reactive approach predominates; lack of strategic anticipation
Implantation	100 %	Deploy processes, roles and tools	–
Control	100 %	Monitoring performance and compliance with standards	Fragmented attention to feedback
Continuous improvement	40 %	Adjust processes based on control findings	Poor incorporation of feedback loops
Complete Cicle PDCA	29 %	Integrate planning, execution, verification and action	Low integration of phases; fragmented vision
Process approach	40 %	Optimize flows and activities linked to quality	Limited adoption of systemic perspectives
Risk Management	3 %	Identify and mitigate threats to quality	Emerging risks excluded from most models

Prospective Analysis	7 %	Projecting future scenarios and their impact on costs	Absence of simulation and forecasting tools
Intangible cost inclusion	6 %	Considering unrecorded losses (motivation, image, loyalty)	Insufficient quantification methodologies

This panorama reveals the existence of theoretical and methodological gaps in current proposals. Consequently, the need arises to develop comprehensive systems that articulate available approaches with a systemic vision incorporating risk management and the treatment of intangible costs, so that quality cost systems respond more coherently to the complexity conditions inherent in current industrial environments.

3.4. Measurement of intangible quality costs

The analysis of quality costs should not be limited to material or directly recordable magnitudes, because this restriction distorts the representation of actual process performance. In industrial contexts, and particularly in metallurgical environments with high technical and operational demands, dimensions associated with worker and customer dissatisfaction, demotivation, social consequences derived from workplace incidents, and the impact on institutional image may be excluded; their economic expression is indirect but cumulative.

A significant portion of the literature on the measurement of intangible or hidden quality costs consolidates from the contributions of Kotler in 1991 and, especially, Albright and Roth in 1992, who propose methods for their estimation, as reported in Sansalvador and Brotons (2017). Building on these contributions, various authors address the quantification of intangible costs from different perspectives, notably Brotons and Sansalvador (2015), Agrawal (2020), and Azebaze and Takoudjou (2021).

These authors agree that the measurement of intangible quality costs presents persistent methodological difficulties, although their identification is necessary due to their influence on organizational performance. Azebaze and Takoudjou (2021) argue that these costs present a double risk, due to their economic magnitude and their remaining outside formal accounting records, which limits managerial capacity for their management. In industrial plants, this condition is associated with losses that manifest as recurrent inefficiencies, operational instability, and progressive performance deterioration.

According to the reviewed literature, the most frequently reported intangible cost is linked to revenue loss derived from damage to the organization's image as a consequence of customer dissatisfaction with defective products or services. However, this category does not exhaust the spectrum of hidden costs, because it also includes effects on the work climate, loss of technical trust, and reduction of business opportunities, factors that indirectly affect competitiveness.

Brotons and Sansalvador (2015) point out that only a portion of the elements integrated into the cost of quality can be estimated with acceptable degrees of precision and objectivity. Consequently, the actual values of the cost of quality often differ from those calculated by organizations and tend to be higher. This observation coincides with Mahmood and Kureshi (2015), who warn that despite the potential magnitude of intangible costs, the available applied evidence remains limited, which reduces the transfer of results to industrial sectors of high technical complexity.

Based on the specific bibliometric review of the topic, it was identified that the main methodological approaches are grouped into three lines: qualitative assessment, the use of probabilistic mathematical models (such as Taguchi's loss function or Taylor series expansion), and the use of fuzzy logic. Figure 7 presents the three clusters derived from the keyword co-occurrence analysis, using the agglomeration method by strength of relationship, employing VOSviewer 1.6.16.

The first trend group, represented in green in the graph, is based on exploratory qualitative analysis, mainly through case studies aimed at identifying the nature and composition of hidden costs in organizations. This approach starts from the recognition of the dysfunctions that generate them, with the purpose of structuring management control models aimed at their reduction. Complementarily, this group frequently uses methods based on expert judgment, cause-effect diagrams, and multi-criteria decision techniques, notably the Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). Representative investigations of this line include those developed by Sailaja *et al.* (2015), Agrawal (2020), and Azebaze and Takoudjou (2021).

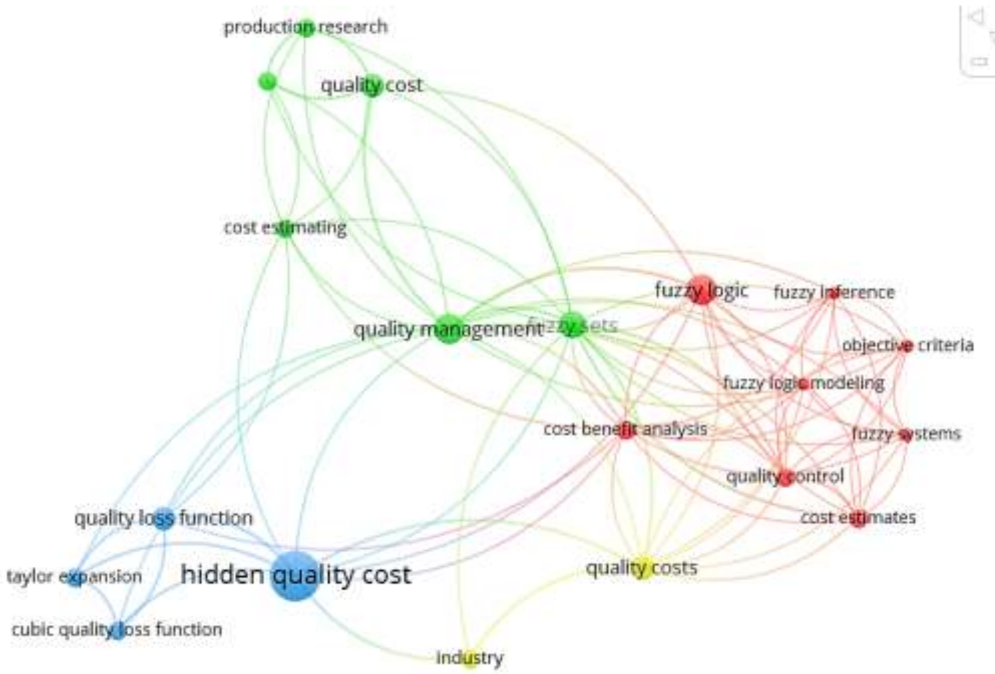

Figure 7. Clusters of keywords co-occurrence in research on intangible quality costs.

The second trend group, identified in blue, groups together investigations that combine probabilistic mathematical models with quality engineering tools to evaluate the loss associated with deviations from target values. In this cluster, approaches derived from Genichi Taguchi's loss function (1979), its extensions, and models based on Taylor series expansion predominate. Zhang *et al.* (2014) propose a controller for an asymmetric loss function, while Chiang *et al.* (2015) develop an optimization strategy for skewed normal distributions, applicable to quality improvement based on the symmetric or asymmetric behavior of the evaluated characteristics. Feng and Kapur (2006) address asymmetric quadratic loss functions and piecewise linear asymmetric functions to determine the optimal process mean and specification limits.

Along the same lines, Lazović and Mijatović (2012) consider scenarios with multiple significantly correlated quality characteristics, proposing a modification of the quadratic loss function for trivariate responses with exact feasible regions. Meanwhile, Li *et al.* (2018) extend the loss function using Taylor expansion up to the third order, employing cubic and quadratic functions to analyze quality loss and associated hidden costs. In the Cuban context, the contributions of González Reyes and Moreno Pino (2017) and León Leal (2018) stand out, applying Taguchi's loss function to quantify intangible costs in an organization in the drug distribution sector.

The third trend group, represented in red, is characterized by the use of fuzzy logic and the concept of possibility to address the imprecision and subjectivity inherent in the quantification processes of intangible quality costs. These approaches aim to incorporate qualitative information and expert judgments into the estimation of losses associated with quality deviations, using models that represent the uncertainty present in organizational processes. In this line, Brotons and Sansalvador (2015) integrate Crosby's quality management maturity grid with possibilistic regression techniques, allowing more precise weighting of the development stages of the quality system and estimating associated costs using fuzzy numbers. The estimates obtained and their short-term projections facilitate monitoring of the organizational situation and support the definition of corrective actions consistent with observed trends.

In later work, Sansalvador and Brotons (2017) develop a model for quantifying hidden quality costs based on the aggregation of subjective information using the Ordered Weighted Averaging (OWA) operator, with the aim of improving uncertainty treatment and result consistency, weighting expert opinions according to their confidence level and the organization's position on Crosby's quality management maturity grid.

The analysis of these proposals reveals recurring limitations. First, qualitative exploration, based on dysfunctions and their frequency estimated by expert judgment, provides inputs for designing control measures, although it has weaknesses in assigning comparable monetary values and determining their contribution to total quality costs. Second, Taguchi's loss function theory assumes that losses are generated for any deviation from the target value, under the assumption of loss symmetry, a premise that does not hold in many engineering processes, leading to more complex mathematical derivations. Furthermore, this approach privileges loss associated with customer satisfaction and reputation, with limitations in treating other intangible costs linked to quality. Third, possibility-based fuzzy logic incorporates uncertainty, but does not differentiate the indeterminacy inherent in human evaluation nor the coexistence of relative and absolute truths in the analysis of judgments.

Given these limitations, the incorporation of neutrosophic logic, as proposed by Pérez-Mayedo *et al.* (2025), emerges as a methodological alternative that expands the scope of measuring intangible quality costs. Its approach allows the explicit integration of uncertainty, indeterminacy, and inconsistency present in human judgments, favoring a more accurate analysis of quality-related phenomena by simultaneously considering the components of truth, falsehood, and indeterminacy.

From this perspective, neutrosophic logic helps strengthen organizations' analytical capacity to prioritize intangible risks, identify non-visible losses, and sustain continuous improvement processes in scenarios characterized by high complexity and uncertainty. The empirical evidence derived from its application in a steel plant shows that it is possible to translate qualitative risks, such as distrust in supplier relationships or deficiencies in communication flows, into quantifiable variables with direct utility for the management of intangible quality costs in complex industrial environments.

4. DISCUSSION

The results of this systematic review allow us to situate the analysis of quality costs within a field of research that has experienced significant expansion over recent decades. The recent literature shows a growing interest in understanding the economic impact of quality in organizational contexts characterized by high levels of operational complexity and by the interaction between technical, organizational, and strategic variables. In this sense, the review conducted by Psomas *et al.* (2022) shows that contemporary studies on quality costs have evolved from predominantly accounting approaches toward approaches that integrate operational, cultural, and organizational performance dimensions. This conceptual expansion reinforces the idea that quality costs should not be interpreted solely as financial records associated with control activities, but as an analytical system capable of reflecting the overall efficiency of production processes.

From this perspective, the results identified in the present research coincide with the approach of Walston *et al.* (2025), who point out that the analysis of quality costs should simultaneously consider three interrelated dimensions: the direct costs associated with quality management, the costs derived from non-quality, and the hidden costs that remain outside traditional accounting systems. These authors argue that underestimation of hidden costs constitutes one of the main limitations in the economic evaluation of quality systems, since a significant proportion of organizational losses manifest through indirect effects related to the loss of operational efficiency, deterioration of customer satisfaction, or reduction of business opportunities. In this sense, the evidence analyzed in the present study confirms that intangible costs continue to receive limited methodological attention compared to tangible costs recorded in accounting systems.

Recent literature also highlights the strategic importance of quality costs in explaining organizational performance. Empirical research such as that developed by Alrjoub *et al.* (2023) demonstrates that quality costs can act as a mediating mechanism between management accounting systems and the financial performance of organizations. This finding suggests that systematic management of quality costs not only allows the identification of operational losses, but also helps strengthen organizations' capacity to improve their economic efficiency and competitiveness. Similar results are observed in sectoral studies analyzing the relationship between organizational culture and quality costs. Spagnoli *et al.* (2024), for example, identify a positive association between the maturity of the food safety culture and the reduction of costs derived from quality failures, indicating that organizational practices and management systems directly influence the magnitude of costs associated with quality.

Another relevant aspect identified in recent literature relates to the methodological evolution of quality cost analysis models. Traditionally, approaches focused on accounting classifications based on prevention, appraisal, and failure costs. However, recent studies propose integrating more sophisticated analytical tools to improve the explanatory capacity of these models. In this sense, Jagtap and Mahajan (2024) propose the use of simulation models to analyze the impact of quality costs on complex decision-making processes, such as contractor selection in public-private partnership projects. This type of approach allows evaluating alternative scenarios and more accurately estimating the economic consequences of quality-related decisions.

Likewise, the advancement of digital technologies and intelligent production systems has generated new opportunities for quality cost analysis. Reis et al. (2025) highlight that the incorporation of Industry 4.0 tools allows improving inspection strategies and optimizing quality cost management through the use of real-time data and advanced analytical models. These technological transformations open new possibilities for integrating quality cost analysis with digital monitoring systems, predictive analysis, and industrial process optimization, which is particularly relevant for sectors characterized by complex production processes, such as the metallurgical industry.

On the other hand, various empirical studies have analyzed the effectiveness of quality cost management models oriented toward prevention. Indra et al. (2025), based on empirical evidence obtained from the manufacturing sector in Indonesia, show that management systems that prioritize prevention activities tend to significantly reduce costs derived from internal and external failures. These results reinforce the widely recognized principle in the quality literature that investments in prevention generate economic benefits by reducing losses associated with errors in production processes.

However, despite the methodological and conceptual advances identified in recent literature, significant challenges remain for the comprehensive measurement of quality costs. Among these are the difficulties in quantifying intangible costs and integrating variables related to organizational behavior, knowledge management, and the uncertainty inherent in industrial processes. In this sense, Gavriluc and Georgescu (2023) point out that, although the literature on quality costs has experienced sustained growth, a significant portion of studies continues to focus on visible costs associated with quality failures, while hidden costs and organizational dimensions of quality receive more limited methodological attention. This situation restricts the capacity of management systems to reflect the real impact of operational deficiencies.

The comparative analysis of recent literature and the results obtained in this review indicates that the study of quality costs is moving toward more comprehensive approaches that incorporate economic, technological, and organizational dimensions into the analysis of productive performance. This conceptual evolution reinforces the need to develop analytical frameworks capable of integrating tangible and intangible costs within management systems oriented toward continuous improvement and sustainability of industrial performance. In the specific case of the metallurgical industry, characterized by high levels of technical and operational complexity, the incorporation of these approaches can help strengthen the capacity of organizations to identify hidden losses, optimize resource use, and improve the overall efficiency of production processes.

5. CONCLUSIONS

- The systematic review carried out confirms that the management of quality costs, both tangible and intangible, acquires particular relevance in industrial contexts characterized by complex production processes, high material intensity, and high technical requirements, as occurs in the metallurgical and mining-metallurgical industry. The analyzed literature shows a sustained increase in academic interest in the study of these costs, associated with the need to understand their impact on operational efficiency, economic performance, and the stability of production processes.
- The analysis of the methodological procedures used to construct quality cost systems reveals notable conceptual and operational heterogeneity. This dispersion limits comparability between studies and hinders the consolidation of integrated analytical frameworks. The limited incorporation of intangible costs and risk-related variables is a recurring limitation in existing models, particularly in industrial

environments where process variability and operational reliability condition overall performance.

- The examined literature shows that qualitative methods, probabilistic models, and fuzzy-logic-based approaches provide useful tools for approximating the measurement of intangible quality costs. However, these approaches have restrictions in comprehensively representing the uncertainty and indeterminacy present in organizational evaluation processes. In this context, neutrosophic logic expands the available analytical framework by allowing the simultaneous integration of truth, falsehood, and indeterminacy components in the analysis of intangible costs. The results obtained highlight the need to develop comprehensive quality cost management systems that articulate visible and hidden economic dimensions, preventive approaches, and analytical tools capable of addressing the complexity of contemporary industrial processes.
- Based on the gaps identified in the literature, future research could be oriented toward the development of integrated models that combine accounting analysis, risk management, and advanced modeling tools for estimating intangible costs. It is particularly relevant to explore the application of artificial intelligence techniques, predictive analysis, and neutrosophic logic to improve the capacity of quality management systems in the early identification of hidden losses and in the optimization of decisions in highly complex industrial environments.

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Additional Information

Conflict of Interest

The authors declare that they have no personal or commercial relationships that could lead to conflicts of interest.

Author Contributions

YPM: Conceptualization, investigation, methodology, original draft writing, and formal analysis. YVL: Conceptualization, investigation, methodology, review and editing of the original draft. NMAA: Methodology, review and editing of the original draft. All authors reviewed and approved the final version.

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Received: 02/02/2026
Accepted: 07/03/2026