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Cost of Quality Models in Continuous Production Systems with Deteriorating Quality: A Review and Research Agenda

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Abstrak

Model Cost of Quality (CoQ) telah banyak diterapkan pada manufaktur diskrit, namun pengembangannya masih terbatas untuk sistem produksi kontinu yang rentan mengalami penurunan kualitas seiring waktu (time-dependent). Tinjauan literatur sistematis ini mengevaluasi penerapan lima model utama CoQ—PAF, ABC, Crosby, Opportunity Cost, dan Process Costing—pada sistem tersebut. Hasil analisis menunjukkan bahwa sebagian besar model masih mengasumsikan perilaku kegagalan yang bersifat statis, sehingga belum mampu merepresentasikan proses degradasi kualitas yang terjadi secara bertahap. Di antara model yang dikaji, pendekatan Opportunity Cost dinilai paling selaras dengan konsep kerugian dinamis, sementara Activity-Based Costing (ABC) dapat melengkapinya melalui pelacakan faktor pemicu biaya (cost drivers) terkait kualitas. Berdasarkan temuan tersebut, penelitian ini mengusulkan integrasi kedua pendekatan ke dalam kerangka CoQ dinamis berbasis waktu. Kerangka ini menggabungkan fungsi deteriorasi dan ambang batas kualitas, sehingga mampu merepresentasikan trade-off antara biaya pencegahan dan kerugian ekonomi akibat penurunan kualitas secara lebih akurat. Secara metodologis, tinjauan ini menyintesis 27 studi melalui analisis komparatif, sekaligus mengidentifikasi kesenjangan teoretis dan praktis dalam pemodelan CoQ untuk proses kontinu. Temuan ini memberikan landasan konseptual bagi pengembangan model CoQ yang lebih optimal pada industri kontinu, seperti produksi biogas, serta mendukung peningkatan efisiensi dan keberlanjutan industri.

Kata Kunci: *Biogas, Cost of Quality, Deteriorasi Kualitas, Pemodelan Dinamis, Produksi Kontinu*

Abstract

Cost of Quality (CoQ) models are well-established in discrete manufacturing but remain underdeveloped for continuous production systems experiencing time-dependent quality deterioration. This systematic literature review evaluates the applicability of five major CoQ models—PAF, ABC, Crosby, Opportunity Cost, and Process Costing—to such systems. The analysis reveals that most existing models assume static failure behavior and fail to capture gradual quality degradation. Among them, the Opportunity Cost model aligns best with dynamic loss concepts, while Activity-Based Costing can complement it by tracing quality-related cost drivers. The study proposes integrating these approaches into a time-dependent dynamic CoQ framework that incorporates deterioration functions and quality thresholds, better representing the trade-off between prevention costs and economic losses from quality decay. Methodologically, this review synthesizes 27 studies through comparative analysis, highlighting theoretical and practical gaps in CoQ modeling for continuous processes. The findings provide a conceptual foundation for developing optimized CoQ models in continuous industries such as biogas production, supporting efforts toward industrial efficiency and sustainability.

Keywords: *Biogas, Cost of Quality, Continuous Production, Dynamic Modeling, Quality Deterioration*

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1. Introduction

The concept of Cost of Quality (CoQ) has evolved into an important framework in modern quality management, enabling organizations to identify, evaluate, and optimize costs related to product and process performance (Daniela Gavriluc & Georgescu, 2023). CoQ generally falls into four main categories: prevention cost, appraisal cost, and failure cost (Spagnoli et al., 2024). Several studies have been conducted to develop the CoQ model over the past few years, but the majority of them have focused on the discrete production system, such as the electronic, mechanical, or semiconductor industries, where the quality failures can generally be identified and measured directly at the production unit level (Schiffauerova & Thomson, 2006a).

The majority of current CoQ models were initially created for batch-based production systems or those that permit process stoppages, including the Crosby model, the Prevention-Appraisal-Failure (PAF) model, and the Activity-Based Costing (ABC) method (Daniela Gavriluc & Georgescu, 2023). However, in many industrial environments, especially in continuous production systems, quality degradation often occurs in an insidious and halting manner over time-a phenomenon known as deterioration. This deterioration poses a significant challenge to conventional CoQ models, which are generally unable to capture the temporal dynamics and hidden costs that accompany it. Traditional CoQ measures tend to affect non-delayed and intangible cost components, making them difficult to implement in complex and dynamic systems (Martínez & Selles, 2015)

Continuous production systems, on the other hand, like those seen in wastewater treatment facilities, chemical industries, and biogas plants, are distinguished by their interconnected subprocesses, time-sensitive quality factors, and unbroken material flow (Okudaira, 2022). A single point in time cannot be blamed for quality decline in such systems; rather, it occurs gradually as a result of shifting operational or environmental circumstances. The requirement for a time-sensitive and dynamic CoQ model is thus highlighted by the fact that failure costs frequently emerge later and are challenging to link to the initial cause.

The advancement of dynamic CoQ models for continuous production systems is gaining significance in the realm of growing sectors like renewable energy, bioenergy, chemical manufacturing, and palm oil processing that have a sizable portion of Indonesia's GDP. A CoQ framework that can manage both time-varying quality results and ongoing quality degradation is desperately needed, as demonstrated by the biogas industry, especially those that use palm oil mill effluent (POME) to produce methane gas. Inadequate management of quality costs in these specific systems diminishes both technical and economic performance and poses a risk to long-term environmental sustainability (Yacob et al., 2005).

Table 1: Examples of Continuous Production Systems and Their Quality Degradation Characteristics

No	Industrial Process	Characteristic Similarities
1	Biogas production from palm oil waste, Palm Oil Mill Effluent (POME)	A continuous biological system demonstrating quality dynamics over time, wherein output quality is affected by substrate deterioration and the stability of the microbial environment.
2	Industrial Wastewater Treatment (Dürrenmatt & Gujer, 2012)	In continuous biological systems, the quality of output is affected by temporal factors and organic load.
3	The Cheese Industry (Jokovic et al., 2011)	Ongoing fermentation leads to the deterioration of texture and flavour over time.
4	Pulp and Paper Industry (Boguniewicz-Zabłocka & Kłosok-Bazan, 2020)	Ongoing chemical process resulting in pulp quality deterioration attributed to raw material variability
5	Alcoholic beverage industry (Feng et al., 2021)	The final product depends on temperature, time, and microorganisms.
6	Production of Antibiotics Enzymes in Biopharmaceuticals (Cruz-Casas et al., 2021)	The fermentation process is sensitive to time and contamination.
7	Pasteurized Milk Production (UHT/HTST) (Mejares et al., 2022)	The quality is contingent upon temperature and processing duration, with a potential for nutritional deterioration.

The examples in Table 1 illustrate that continuous production systems across diverse industries (from biogas generation and wastewater treatment to food, beverage, and pharmaceutical manufacturing) share a common challenge of quality deterioration over time. In these processes, output quality is not only determined by initial inputs but also by dynamic factors such as microbial stability, chemical reactions, fermentation stages, and processing duration. Such characteristics highlight the inadequacy of static CoQ models, as they fail to capture the temporal dimension of degradation and the interdependence between process conditions and quality outcomes. Therefore, understanding these industrial cases reinforces the need for a dynamic CoQ framework that explicitly incorporates deterioration functions and time-sensitive quality thresholds to better reflect real world production environments

This literature review aims to identify, evaluate, and critically analyze various existing CoQ models and assess their relevance in the scope of continuous production subject to quality deterioration. Five primary models are given particular consideration, including the PAF model, ABC model, Crosby model, Opportunity Cost model, and Process Costing model. The study elaborates on the advantages and limitations of each approach, and highlights the extent to which the models are appropriate for systems experiencing sustained deterioration. The study is ultimately expected to provide a theoretical basis for the development of dynamic time-based CoQ models customized for industries with continuous production flow and declining quality characteristics.

2. Methodology

This study adopts a systematic literature review (SLR) approach to examine the development, characteristics, and limitations of Cost of Quality (CoQ) models, with particular attention to their application in continuous production systems experiencing gradual quality deterioration. The review process was conducted in accordance with the PRISMA 2020 guidelines.

2.1. Review Design and Database

The literature search was conducted using Scopus and Emerald as the primary academic databases, as both provide comprehensive coverage of peer-reviewed journals in quality management, industrial engineering, and operations management. In addition, Google Scholar was used as a supplementary source for citation tracking to identify relevant studies that may not be indexed in the primary databases.

2.2. Study selection and screening process

The study selection process consisted of four main stages: identification, screening, eligibility assessment, and inclusion. The selection was conducted using the keywords “Cost of Quality” OR “Quality Cost”, applied consistently across all selected databases to retrieve studies explicitly addressing quality cost models and related frameworks. At the identification stage, a total of 9,265 records were retrieved from Scopus and Emerald after duplicate removal.

The screening stage was conducted using three sequential criteria. First, a publication year filter (2015–2025) was applied to focus the review on recent developments relevant to contemporary industrial and technological contexts (Screening 1). Second, the remaining records were screened based on publication type, retaining only peer-reviewed journal articles and excluding conference papers, books, and non-journal publications (Screening 2). Third, an accessibility filter was applied, whereby only open-access articles were retained to ensure full-text availability for detailed analysis (Screening 3).

Following the screening stage, the remaining articles were subjected to full-text assessment at the eligibility stage. Full texts were examined to confirm that the studies explicitly addressed Cost of Quality models, described the structure or logic of quality cost calculation, and discussed applications in industrial or service production systems, particularly in continuous production environments. Studies that merely mentioned Cost of Quality without methodological elaboration or addressed quality without explicit cost considerations were excluded. After the eligibility assessment, 27 articles met all inclusion criteria and were retained for the final synthesis. The overall selection process and the number of records retained at each stage are summarized in the flow diagram presented in Figure 1.

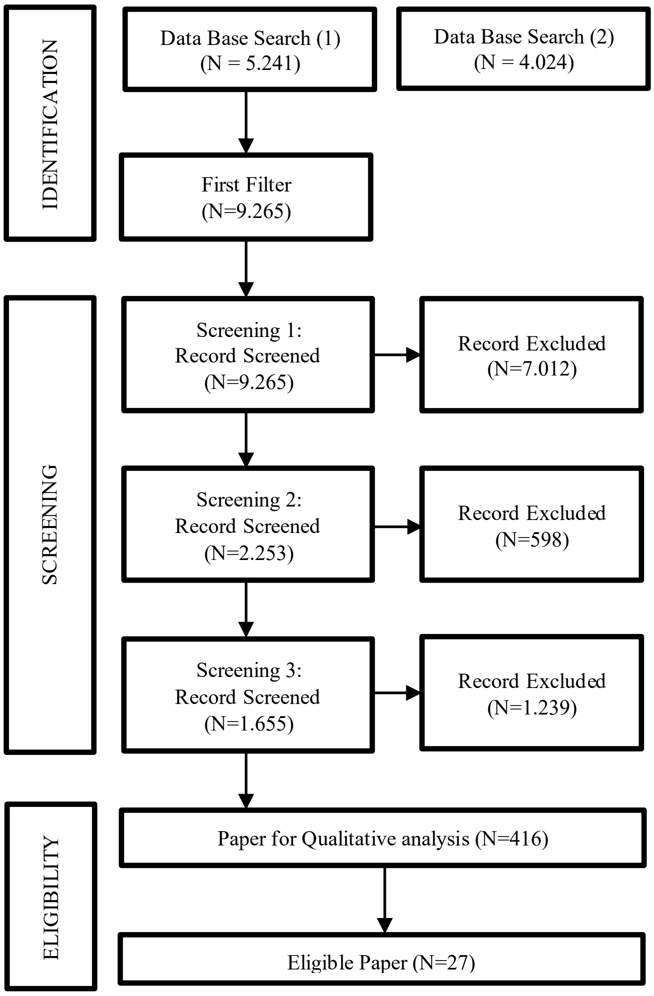

Figure 1: PRISMA Diagram

2.3. Inclusion and exclusion criteria

The inclusion criteria for this review comprised peer-reviewed journal articles that explicitly defined, developed, or applied Cost of Quality models; described the structure, costing logic, or analytical framework of CoQ; and reported applications in industrial or service contexts. Both conceptual and applied studies, including analytical modeling and case-based research, were considered. Articles were excluded if they only referenced Cost of Quality without substantive methodological discussion, focused on quality management without explicit cost modeling, or were descriptive or opinion-based without analytical contribution.

2.4. Data extraction and synthesis

The included studies were systematically analyzed and categorized based on two principal dimensions: the type of Cost of Quality model employed and the industry or application field in which the model was applied. This focused categorization enabled a comparative synthesis to identify dominant application patterns, sectoral coverage, and gaps in the implementation of CoQ models, particularly in continuous production environments experiencing gradual quality deterioration.

The synthesis provided the basis for identifying limitations in existing CoQ approaches and for formulating a research agenda toward the development of dynamic Cost of Quality models that explicitly incorporate time dependency, quality degradation, and associated economic losses.

3. Result and Discussion

3.1. Overview of Reviewed Studies

This section provides an overview of the reviewed literature on Cost of Quality (CoQ) models, serving as a foundation for the subsequent classification and comparative analysis. A total of the selected studies were systematically examined to capture the diversity of CoQ modeling approaches, application contexts, and methodological orientations within continuous and discrete production environments.

Table 2 summarizes the reviewed studies based on the type of CoQ model employed, the industrial or research context, and the main contribution of each study. The overview indicates that CoQ research has evolved from traditional accounting-based models toward more diverse analytical and decision-support approaches. Classical CoQ models, such as the Prevention–Appraisal–Failure (PAF) model, Activity-Based Costing (ABC), Crosby's quality cost model, Opportunity Cost, and Process Costing, remain widely referenced as foundational frameworks. These models are frequently applied in manufacturing, construction, and service sectors to structure and quantify quality-related costs.

At the same time, a substantial number of recent studies extend beyond the direct application of classical CoQ models. These studies introduce methodological enhancements, including fuzzy logic, multi-criteria decision-making techniques, data-driven analysis, and integration with maintenance, inspection, or risk management strategies. Such approaches aim to address practical limitations of conventional CoQ models, particularly under conditions of uncertainty, operational complexity, and increasing digitalization in industrial systems.

From an application perspective, the reviewed studies span a wide range of industrial contexts, including manufacturing systems, construction projects, healthcare services, and other process-oriented industries. However, most applications implicitly assume relatively stable process conditions or discrete production settings. Explicit consideration of continuous production characteristics, time-dependent quality deterioration, and dynamic interactions between process variables and quality costs remains limited across the literature.

Overall, the overview presented in Table 2 highlights both the breadth and the fragmentation of existing CoQ research. While numerous models and analytical approaches have been proposed, their applicability to continuous production systems with gradual quality deterioration is still not comprehensively addressed. This observation motivates the need for a more systematic classification of CoQ models and a deeper comparative analysis, which are discussed in the following subsection.

Table 2: Summary of Reviewed Studies on Cost of Quality (CoQ) Models

No	Author(s) & Year	CoQ Model Type	Industry / Research Context	Main Contribution
1	Kazemi et al. (2020)	CoQ-based decision support (Fuzzy)	Manufacturing (sewing machine industry)	Proposes a fuzzy-based decision support system to estimate CoQ under uncertainty.
2	Rogošić (2021)	Quality costing implementation (maturity-based)	Cross-industry organizations	Analyzes quality costing maturity based on reporting practices.
3	Velkoska & Tomov (2021)	Conceptual CoQ framework	General / cross-industry	Provides a conceptual discussion linking CoQ with Industry 4.0 and sustainability.
4	Alsada & Kumar (2022)	PAF	Manufacturing enterprises	Applies the PAF model to identify visible and hidden quality costs.
5	Sansalvador & Brotons (2023)	Dynamic CoQ (Fuzzy-based)	Industrial case study	Develops a dynamic fuzzy-based CoQ model integrating maturity concepts.
6	Gual et al. (2024)	CoQ improvement framework	Manufacturing processes	Introduces a Lean and risk-based framework to reduce total CoQ.
7	Tambunan (2022)	PAF-based Quality Cost Chain	Value chain analysis	Proposes a PAF-based quality cost chain for strategic cost management.
8	Herzog & Grabowska (2021)	Quality cost account system	Medical industry	Demonstrates quality cost accounting to support continuous improvement.
9	Kokot-Stępień (2021)	Quality cost account methodology	Enterprise QMS	Presents a methodological framework for implementing quality cost accounts.
10	Bris et al. (2022)	PAF	Manufacturing companies	Analyzes quality cost flows in manufacturing firms using PAF classification.
11	Pérez-Fernández et al. (2022)	Multi-criteria CoQ evaluation	Manufacturing / Lean	Applies ANP to evaluate CoQ factors in Lean manufacturing.
12	Yang et al. (2022)	CoQ-linked maintenance model	Manufacturing systems	Integrates preventive maintenance decisions with CoQ considerations.
13	Krebish & Berberoglu,2020)	Quality costing & management style	Manufacturing organizations	Examines the relationship between management style and CoQ practices.
14	Khadim et al. (2023)	Hidden CoQ	Construction industry	Identifies hidden quality costs in construction projects.
15	Thabet et al. (2024)	Fuzzy expert system for CoQ	Manufacturing	Develops a fuzzy expert system to support CoQ estimation.
16	Palanisamy & Palanichamy (2025)	CoQ optimization (DOE-based)	Construction projects	Uses DOE to optimize CoQ-related decisions in construction.
17	Reis et al. (2024)	Inspection strategy & CoQ	Smart manufacturing	Proposes data-driven inspection strategies to minimize CoQ.
18	Teplická & Hurná (2021)	PAF	SMEs manufacturing	Applies PAF model to analyze quality costs in SMEs.
19	Oliveira et al. (2020)	Quality cost measurement	Manufacturing	Evaluates quality cost structures to support managerial decisions.

No	Author(s) & Year	CoQ Model Type	Industry / Research Context	Main Contribution
20	Khazaeli et al. (2024)	CoQ-oriented performance evaluation	Industrial systems	Links CoQ indicators with operational performance metrics.
21	Spagnoli et al. (2024)	CoQ-related risk and safety cost	Industrial operations	Connects safety risk management with quality-related costs.
22	Rosiawan et al. (2019)	ABC	Manufacturing	Applies activity-based costing to measure quality-related costs.
23	Purwanggono & Valentinus (2019)	ABC	Manufacturing	Implements ABC to support quality cost analysis.
24	Shraim (2020)	Opportunity Cost of Quality	Manufacturing	Evaluates opportunity costs arising from quality deficiencies.
25	Ayach et al. (2018)	Crosby & Process Costing	Cement industry	Combines Crosby and process costing to assess quality costs.
26	Zahar et al. (2016)	Crosby	Medical services	Applies Crosby model to assess quality costs in healthcare.
27	Tang et al. (2004)	Process Cost Model	Construction projects	Demonstrates the suitability of process cost models over PAF in construction.

3.2. Classification of CoQ Models

Based on the synthesis of the reviewed studies summarized in Table 2, Cost of Quality (CoQ) models can be grouped into five main methodological categories. These models differ in terms of cost structure, allocation logic, and suitability for various production environments.

a. Prevention–Appraisal–Failure (PAF) Model

The PAF model is one of the most widely adopted frameworks for structuring quality-related costs. It categorizes quality costs into prevention costs, appraisal costs, internal failure costs, and external failure costs. Numerous studies apply this framework to evaluate and control quality costs in manufacturing and service industries due to its conceptual clarity and managerial interpretability (Teplická & Hurná 2021; Bris et al., 2022). The traditional PAF model was proposed by Juran in 1951. This model addresses the optimisation problem between the cost of quality and the quality of the produced product (Figure 2).

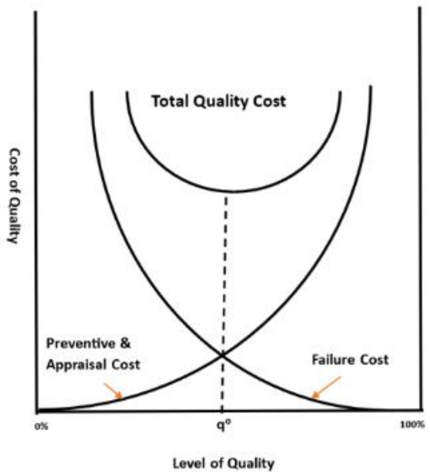

Figure 2: PAF Model
Source: (Rosiawan et al., 2019b)

Several authors represent the total cost of quality in the PAF framework as the sum of its four cost components. Following the formulation commonly adopted in the literature (Ganzorig & Bira,2023), the total quality cost can be expressed conceptually as:

$$COQ_{PAF} = C_{prev} + C_{app} + C_{fail(int)} + C_{fail(ext)} \quad (1)$$

where:

COQ_{PAF} : Total Cost of Quality
C_{prev} : Prevention Costs
C_{app} : Appraisal Costs
$C_{fail\,(int)}$: Internal Failure Costs
$C_{fail\,(ext)}$: External Failure Costs

b. Activity-Based Costing (ABC)

Activity-Based Costing (ABC) extends traditional quality cost measurement by allocating costs to the activities that generate them. This approach enhances cost accuracy by linking quality-related expenses to specific processes and cost drivers. ABC-based CoQ models have been applied to identify inefficiencies and support quality improvement in complex production environments (Rosiawan et al., 2019; Purwanggono & Valentinus, 2019).

In the Activity-Based Costing (ABC) approach, quality costs are allocated based on activities and their cost drivers. In general, the cost of an activity can be expressed as the product of the cost rate per unit of activity cici and the quantity of the activity driver (Hansen & Mowen, 2021):

$$C_A(A_i) = c_i \; x \; D_{A_i} \quad (2)$$

where

$C_A(A_i)$: activity cost for activity A_i
c_i : tariff per unit activity
D_{R_i} : quantity of activity drivers

Despite its analytical advantages, ABC-based CoQ models often require detailed activity data and stable process definitions, which can reduce their practicality in dynamic or continuously evolving production systems

c. Crosby's Cost of Quality Model

Crosby's Cost of Quality model emphasizes the principle of zero defects and distinguishes between the cost of conformance and the cost of nonconformance. This perspective frames quality improvement as an investment rather than a cost burden and has influenced managerial approaches to quality management across various sectors (Zahar et al., 2016; Ayach et al., 2018). In its basic representation, Crosby's model expresses total quality cost as:

$$CoQ = COC + CoNC \quad (3)$$

The procedures employed in the Crosby approach are as follows:

1. List all operations associated with quality, whether directly or indirectly.
2. Categorize activities into groupings of preventive actions (C_P), assessment or inspection activities (C_A), internal improvement activities (C_{IF}), and external failure activities (C_{EF}).
3. Categorize the expenses of each activity into Cost of Conformance and Cost of Non-Conformance according to the conditions set out by Ayach et al. (2018) given by Eq. (4)

$$CoQ = C_P + C_A$$
$$CoNQ = C_{IF} + C_{EF} \quad (4)$$

d. Opportunity Cost of Quality

The Opportunity Cost approach expands conventional CoQ analysis by incorporating indirect and hidden economic losses, such as lost sales, reduced customer loyalty, and unrealized production capacity. This perspective provides a broader estimation of the economic impact of quality problems beyond accounting-based measures (Shraim, 2020). Conceptually, the opportunity cost-based quality cost can be represented as:

$$COQ_{PAF} = C_{prev} + C_{app} + C_{fail} + C_{Opp} \quad (5)$$

where

COQ_{PAF} : total cost of quality
C_{prev} : prevention costs
C_{app} : appraisal costs
C_{fail} : failure costs
C_{Opp} : opportunity costs

Opportunity reflects the economic value of forgone opportunities due to quality deficiencies. Although relevant for capturing intangible losses, opportunity cost estimation often relies on assumptions and indirect measurement, which may introduce uncertainty in practical applications

e. Process Costing Model

The Process Costing Model (PCM) is a methodology for quality cost analysis that emphasizes the production process unit as the foundation for such a study. In contrast to conventional models that classify costs by function (such as PAF: prevention, appraisal, failure), PCM explicitly identifies and quantifies the cost of quality at each step along the value chain, encompassing both the costs associated with assuring conformity and those related to non-conformance. This approach integrates quality management principles with the process orientation advocated by the Total Quality Management (TQM) framework and ISO 9000 standards, particularly with process-based thinking and continuous improvement. Research models employing this framework include Tang et al., (2004).

The procedure for analyzing the cost of quality using the PCM approach is as follows:

1. Determine the particular processes for analysis, designating each process as P_i where $i = 1, 2, \ldots, n$
2. Determine the smallest activity within each process P_i and correlate each activity according to the input → activity → output sequence.
3. Ascertain the cost linked to each procedure and classify them into compliance costs (CoC) and non-compliance costs (CoNC).
4. Collect and calculate cost data for each activity in monetary units. The cost of an activity is based on the sum of its direct components (e.g., labour, materials, equipment) as demonstrated in the case studies by Tang et al. (2004)
5. Compute and evaluate the total costs associated with process quality. (Tang et al., 2004) given by Eq (6)

$$CoQ_{P_i} = \sum_{a_i \epsilon CoC} C(a_i) + \sum_{a_i \epsilon CoNC} C(a_i) \quad (6)$$

The total process quality cost per floor or work unit can be ascertained from the acquired totals and structures. This might offer suggestions for enhancements to activities with elevated CoNC levels. A visualization of quality improvement trends across the production cycle can also be generated.

Overall, this classification demonstrates that while the five CoQ models provide a solid theoretical foundation for quality cost analysis, their direct applicability to continuous production systems with gradual quality deterioration remains limited. This limitation motivates the comparative analysis between discrete and continuous production systems presented in the following subsection.

3.3. Comparative Analysis: Discrete vs Continuous Systems

A fundamental issue identified in the reviewed literature concerns the implicit assumption regarding the nature of the production system in which Cost of Quality (CoQ) models are applied. Most classical CoQ frameworks were originally developed and validated within discrete production systems, where products are manufactured in identifiable units, inspections are performed at specific checkpoints, and quality deviations can be directly associated with individual items or batches (Schiffauerova & Thomson, 2006; Teplická & Hurná, 2021)

In discrete manufacturing environments, quality costs are commonly structured around clearly observable prevention, appraisal, and failure activities. Defective units, rework, and scrap can be readily identified, allowing models such as the PAF framework and ABC-based approaches to be effectively implemented for cost classification and managerial decision support (Bris et al. ,(2022) Rosiawan et al. 2019). As a result, most empirical applications of CoQ models implicitly assume relatively stable process conditions and static relationships between quality activities and cost outcomes.

In contrast, continuous production systems operate under fundamentally different conditions. These systems are characterized by uninterrupted material flows, strong interdependencies among process stages, and quality attributes that evolve gradually over time rather than manifesting as discrete failures (Okudaira, 2022; Dürrenmatt & Gujer, 2012). Industries such as biogas production, wastewater treatment, chemical processing, and fermentation-based manufacturing exhibit progressive quality deterioration driven by process dynamics, raw material variability, and environmental conditions (Yacob et al., 2005; Feng et al., 2021).

Consistent with the gap identified in the Introduction, our analysis confirms that conventional CoQ models are ill-suited to capture the indirect and cumulative nature of failure costs in continuous systems. Unlike discrete manufacturing, where defects are directly observable, continuous systems exhibit failure through gradual efficiency losses and yield decline—a nuance that static models often overlook.

Furthermore, while discrete systems model deterioration through defect rates, continuous systems require a time-dependent representation of quality decay, which simultaneously impacts product quality, process stability, and economic performance. This dynamic is rarely integrated into existing CoQ frameworks.

Overall, this comparative analysis highlights that while classical CoQ models provide a strong theoretical foundation for quality cost analysis, their direct applicability to continuous production systems with gradual quality deterioration remains limited. These limitations underscore the need for adapted or hybrid CoQ frameworks that explicitly consider continuous process characteristics, time-dependent quality degradation, and indirect economic losses. To synthesize these differences and clarify the relative strengths and weaknesses of existing approaches, a comparative summary of the five main CoQ models is presented in Table 3.

Table 3: Comparative Characteristics of Cost of Quality (CoQ) Models

CoQ Model	Main Analytical Focus	Typical Application Context	Suitability for Continuous Systems	Ability to Capture Quality Deterioration	Key Limitations
PAF Model	Classification of quality-related costs (prevention, appraisal, failure)	Discrete manufacturing and service systems	Low	Implicit and static	Assumes stable processes and discrete failure events
Activity-Based Costing (ABC)	Activity-level allocation of quality costs	Complex manufacturing and logistics systems	Moderate	Indirect	High data requirements and limited real-time adaptability
Crosby's CoQ Model	Cost of conformance vs nonconformance	Manufacturing and service organizations	Low	Not explicitly addressed	Normative orientation with limited analytical depth
Opportunity Cost of Quality	Economic losses beyond explicit quality costs	Continuous and competitive production environments	High	Conceptually explicit	Relies on estimation and assumptions
Process Costing Model	Process-stage-based quality cost identification	Process industries and continuous manufacturing	Moderate–High	Partially addressed	Limited integration of time-dependent dynamics

The comparative analysis summarized in Table 3 highlights fundamental mismatches between conventional CoQ approaches and the requirements of continuous production systems. To synthesize these findings and visualize the pathway toward an adapted modeling framework, a conceptual framework is proposed in Figure 3

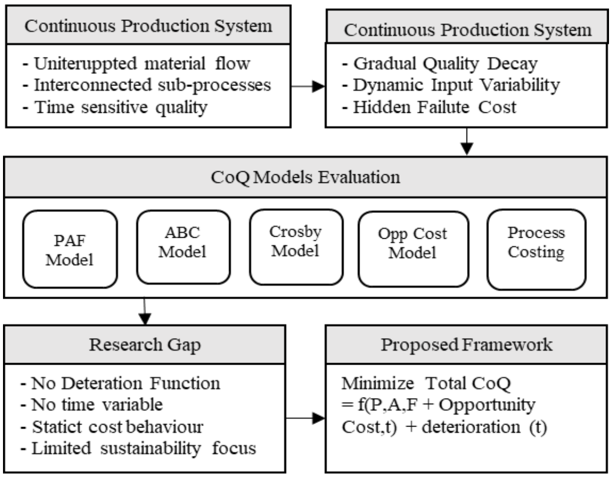

Figure 3: Conceptual Framework for Developing Dynamic Cost of Quality Models in Continuous Production System

3.4. Methodological Extensions and Analytical Approaches

To address the limitations identified in classical Cost of Quality (CoQ) models, a number of methodological extensions have been proposed in the literature. These methodological extensions aim to address limitations related to uncertainty, complexity, and dynamic behavior that are not adequately captured by traditional CoQ frameworks. The reviewed literature indicates that such approaches are increasingly used to enhance the explanatory and prescriptive power of CoQ analysis, particularly in complex and process-oriented production environments.

One prominent stream of research integrates fuzzy logic into CoQ modeling to handle imprecision and uncertainty in quality-related variables. Fuzzy-based CoQ models are commonly applied when quality attributes cannot be precisely measured or when expert judgment plays a significant role in cost estimation. Studies employing fuzzy logic demonstrate improved flexibility in representing qualitative assessments of prevention, appraisal, and failure costs, especially in environments characterized by variability and incomplete information (Kazemi et al., 2020; Sansalvador & Brotons, 2023; Thabet et al., 2024). However, most fuzzy CoQ applications remain static and are primarily designed for decision support rather than continuous monitoring of quality deterioration.

Another stream of studies applies multi-criteria decision-making (MCDM) techniques, such as the Analytic Hierarchy Process (AHP) and Analytic Network Process (ANP), to support the prioritization of quality improvement initiatives and the allocation of quality-related resources. These approaches enable the structured evaluation of multiple qualitative and quantitative criteria, including cost components, perceived impacts, and performance considerations. Applications of MCDM in Cost of Quality (CoQ) research have been reported mainly in manufacturing contexts, demonstrating their usefulness as decision-support tools for strategic quality management (Pérez-Fernández et al., 2022); Yang et al., 2022).

In addition, several studies discuss system-oriented perspectives on CoQ, particularly in relation to quality cost accounting frameworks and managerial control systems. These approaches emphasize the interrelationships between quality-related activities and cost outcomes, supporting informed decision-making at the organizational level (Herzog & Grabowska, 2021); (Kokot-Stępień, 2021). However, such models typically focus on static or comparative analyses and do not explicitly represent time-dependent quality dynamics or feedback-driven behavior.

More recently, several studies have explored the integration of CoQ concepts with digital technologies and data-driven approaches, reflecting the broader transition toward Industry 4.0. These works investigate the use of real-time monitoring, sensor data, and advanced analytics to support proactive quality cost management (Gual et al.,2024). While these approaches offer promising opportunities for dynamic quality cost assessment, their application in continuous production systems remains at an early stage and is largely exploratory.

Overall, the methodological extensions identified in the reviewed literature contribute valuable tools for enriching CoQ analysis under complex and uncertain conditions. However, most approaches are developed as add-ons to existing CoQ frameworks and do not fundamentally reformulate quality cost models to explicitly incorporate continuous process characteristics and gradual quality deterioration. This observation reinforces the need for integrated CoQ modeling approaches that combine dynamic system representation with comprehensive cost structures, which is further discussed in the subsequent sections.

3.5. Industrial Domain of CoQ Models

Building on the methodological extensions discussed in the previous section, it is equally important to examine where Cost of Quality (CoQ) models have been applied across different industrial contexts. An analysis of the 27 reviewed studies indicates that CoQ research is predominantly concentrated in discrete manufacturing sectors, where production processes, inspection points, and cost aggregation mechanisms are relatively well defined. In these industries, classical CoQ models—such as the PAF framework, Activity-Based Costing, and Crosby's model—are widely adopted to support quality improvement and cost control initiatives.

Beyond discrete manufacturing, CoQ applications are also reported in project-based and service-oriented industries, including construction, healthcare, and logistics. In project-based environments, process costing and ABC-based CoQ models are frequently employed to trace rework and inspection costs across activities or project stages. In service sectors, simplified PAF structures and Crosby-oriented approaches are commonly used to assess nonconformance costs and service inefficiencies. However, these applications typically emphasize descriptive or diagnostic analysis and rarely incorporate dynamic quality behavior.

More recent studies have begun to explore CoQ applications in continuous and process industries, such as chemical processing, energy systems, wastewater treatment, and biogas production. These industries are characterized by uninterrupted material flows and gradual quality variation, which challenge the assumptions underlying classical CoQ models. The reviewed literature shows that while existing frameworks are occasionally adapted for such contexts, explicit representation of time-dependent quality deterioration remains limited. Table 4 summarizes the main industrial domains of CoQ applications, the dominant modeling approaches used in each sector, and representative references, providing a structured overview of current practice and highlighting underexplored areas.

Table 4: Field of Application of CoQ Topics since 2020

No	Field of Application	Article
1.	General	
2.	Manufacture	Herzog & Grabowska (2021), Kokot-Stępień (2021), Bris et al. (2022), Pérez-Fernández et al. (2022), Yang et al. (2022), Gual et al. (2024)
3.	Construction	Krebish & Berberoglu (2020), Khadim et al. (2023), Thabet et al. (2024), Palanisamy & Palanichamy (2025)
4.	Automotive	Reis et. al. (2024)
5.	Small Medium Industry	Teplická & Hurná (2021)
6.	Food, Forestry and Agriculture	Oliveira et al. (2020), Khazaeli et al. (2024), Spagnoli et al. (2024)

3.6. Quality Appraisal

To enhance methodological rigor, a summarized quality appraisal of the reviewed studies was conducted using an adapted Critical Appraisal Skills Programme (CASP) framework. CASP was selected due to its flexibility and suitability for assessing methodological clarity in engineering and management-oriented review studies.

The appraisal focused on key CASP criteria relevant to Cost of Quality (CoQ) research, including clarity of research objectives, transparency of model structure and assumptions, appropriateness of the applied methodology, relevance of the production context, and clarity of reported findings.

Overall, most studies demonstrated clear objectives and well-defined CoQ frameworks, particularly those applying classical models in discrete production and service settings. However, limited attention was given to time-dependent quality behavior and continuous process characteristics. This methodological gap was consistently observed across different CoQ models and analytical approaches, highlighting the need for more dynamic and system-oriented CoQ frameworks, as discussed in the following section.

3.7. Future Research Agenda

The synthesis of the reviewed literature reveals persistent gaps in Cost of Quality (CoQ) research when applied to continuous production systems. While classical CoQ models and their methodological extensions provide valuable insights into quality-related cost structures, most studies remain focused on discrete or relatively stable production environments. This limits their analytical relevance for systems characterized by uninterrupted flows and gradual quality variation.

A key gap identified across the reviewed studies is the limited incorporation of time-dependent quality deterioration within CoQ frameworks. The majority of existing models assume static process conditions and constant relationships between quality activities and costs. In continuous production systems, however, quality degradation often occurs progressively and affects cost performance cumulatively rather than through discrete failure events. As a result, traditional CoQ models struggle to represent the dynamic interaction between process behavior and quality-related economic losses. Future research should focus on developing dynamic and system-oriented Cost of Quality frameworks that explicitly account for quality deterioration and continuous process characteristics.

This limitation is particularly evident in process-based and energy-related industries, including biogas production systems. Biogas plants operate under continuous conditions where variability in feedstock quality, biological process dynamics, and operational control influence gas quality and yield over time (Cruz-Casas et al., 2021). In such systems, quality-related losses are more accurately reflected as efficiency reductions or opportunity losses rather than isolated defects. Figure 4 illustrates the typical biogas production process from Palm Oil Mill Effluent (POME), highlighting stages where gradual quality deterioration and associated cost implications may occur.

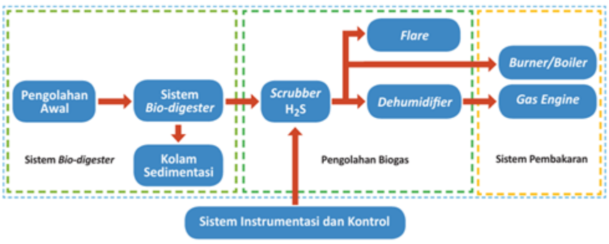

Figure 4: Processing of POME into Biogas
Source: Rahayu et al. (2015)

Continuous production contexts, such as biogas systems based on Palm Oil Mill Effluent (POME), provide a relevant illustrative setting for advancing such research. This model can be enhanced to address dynamic and continuous system challenges by alterations to its functional structure. The requisite alterations encompass:

1. Incorporate the time variable (t) as a factor in the cost function. In continuous processes, time serves as both a parameter and an independent variable influencing the pace of degradation, inspection expenses, and product quality decline;
2. Integrating the degradation function of raw material quality or processes into the calculation of failure costs and opportunity costs. This function may exhibit either exponential or linear characteristics over time, contingent upon the observed degradation behavior;
3. This model aims to minimize total quality expenses within a designated timeframe, encompassing preventative costs, assessment costs, internal and external failure costs, and opportunity costs associated with defective products or lost potential revenue.

4. Conclusion

This study presents a structured review of Cost of Quality (CoQ) models with an emphasis on their applicability to continuous production systems that experience gradual quality deterioration. By synthesizing 27 selected studies, the review maps the evolution of classical CoQ frameworks, their methodological extensions, and their application across different industrial contexts, providing an integrated overview of the current state of CoQ research.

This review synthesizes that classical CoQ models—though robust in discrete contexts—are inherently limited by their static assumptions when applied to continuous production. Their inability to model time-dependent quality deterioration represents a fundamental gap, particularly for industries like biogas production and wastewater treatment.

The analysis further shows that recent methodological extensions, including fuzzy logic, multi-criteria decision-making, simulation, and data-driven approaches, have improved flexibility in handling uncertainty and complex decision environments. However, these approaches are commonly applied as supplementary tools rather than as integrated frameworks capable of explicitly representing time-dependent quality deterioration and continuous process behavior.

An important contribution of this review lies in highlighting the distribution of CoQ research across industrial domains. Manufacturing and service sectors dominate the literature, whereas continuous and process-based industries—such as energy systems and biogas production—remain comparatively underrepresented. In continuous systems like biogas production from Palm Oil Mill Effluent (POME), quality-related losses tend to accumulate gradually and are often manifested as efficiency reductions or opportunity losses, underscoring the limitations of discrete-oriented CoQ models.

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