International
Journal of Lean
Six Sigma

Quality cost deployment (QCD): a Lean-Inspired methodology for systematic reduction of total quality costs

Massimo Bertolini and Davide Castellano
*"Enzo Ferrari" Department of Engineering,
Università degli Studi di Modena e Reggio Emilia, Modena, Italy*

Received 11 September 2025
Revised 31 October 2025
Accepted 27 January 2026

Abstract

Purpose – This paper aims to tackle a key challenge in Lean Six Sigma (LSS): the rigorous financial justification and prioritisation of improvement projects. It introduces Quality Cost Deployment (QCD), a novel methodology to enhance the LSS toolkit by systematically linking Cost of Quality (CoQ) data to specific operational root causes. QCD provides a structured, financially-driven framework to evaluate and select initiatives, ensuring resources target projects with the highest strategic return.

Design/methodology/approach – The paper proposes a structured, five-step methodology that deploys five interconnected matrices to systematically map quality-related financial losses to their operational root causes, quantifies the financial impact of each cause and enables data-driven project selection. The methodology's practical application and effectiveness are validated through an empirical case study within an electronics manufacturing firm.

Findings – The case study validates QCD's effectiveness for strategic project selection. It uncovered significant financial losses by tracing them to origins like inadequate training, which contributed to a €51,000 annual loss. The analysis justified an improvement portfolio with a €35,000 investment, projected to deliver a three-year Net Present Value of €160,202, demonstrating a substantial return.

Originality/value – This paper contributes a new framework to the LSS toolkit. It addresses the gap between strategic CoQ analysis and operational deployment. QCD provides a structured, matrix-driven methodology to systematically link financial losses to their operational root causes. This operationalises CoQ insights, offering managers a financially robust tool to strategically select improvement projects and allocate resources to initiatives with the highest return.

Keywords Cost of Quality, Lean, Quality Management, Cost management, Manufacturing, Six Sigma

Paper type Research paper

1. Introduction

The contemporary global business paradigm is characterised by an unrelenting and dualistic pressure: an ever-increasing demand for superior product and service quality, coupled with an intense and unyielding requirement for rigorous cost control and heightened operational efficiency. These forces, driven by fierce global competition, sophisticated customer expectations and the hyper-transparency of the digital age, are no longer independent

---

International Journal of Lean Six Sigma
Vol. 17 No. 8, 2026
pp. 133-160
Emerald Publishing Limited
2040-4166
DOI 10.1108/IJLSS-09-2025-0252

objectives but are inextricably linked pillars fundamental to achieving and sustaining competitive advantage (Wang *et al.*, 2024; Roth *et al.*, 2020; Kumar *et al.*, 2018). In the modern “experience economy”, where a single negative review or service failure can have widespread reputational impact, the definition of quality has expanded beyond mere product specifications to encompass the entire customer journey. Conversely, suboptimal quality, even when seemingly minor, can lead to significant and cascading negative consequences. These extend far beyond the immediate and visible economic drains from internal failures – such as industrial scrap, rework, service redelivery and data correction – and external failures like warranty claims, product recalls, service level agreement penalties and customer churn (Sharma *et al.*, 2007; De Ruyter *et al.*, 2002). Poor quality also insidiously erodes an organisation’s most valuable intangible assets, including customer trust, brand reputation and market standing, while also impacting employee morale as teams are perpetually engaged in ‘firefighting’ rather than value creation. Furthermore, it imposes significant and increasingly scrutinised ecological and societal burdens through the inefficient utilisation of resources and the generation of waste (Psarommatis *et al.*, 2023; Khesal *et al.*, 2019; Dadashnejad and Valmohammadi, 2018). In this demanding environment, the establishment and diligent execution of comprehensive quality management systems (QMSs), propelled by proactive, data-driven and financially astute quality improvement (QI) initiatives, have evolved from a desirable operational attribute to an indispensable strategic imperative for modern enterprises, whether they produce tangible goods or deliver intangible services (Zahraee, 2016).

For many decades, organisations across industries have widely adopted and refined a portfolio of established QI paradigms, with Lean and Six Sigma principles forming the foundation of modern continuous improvement. Building on the groundwork of total quality management, the Lean philosophy provides a systematic approach to identifying and eliminating non-value-adding activities (waste) through tools like value stream mapping (VSM) – from reducing patient waiting times in healthcare to streamlining code deployment in software development (Bahria *et al.*, 2019; Dadashnejad and Valmohammadi, 2018; Carmignani, 2017; Delisle and Freiberg, 2014). Six Sigma offers a potent, project-based methodology for variation reduction and the elimination of defects through the rigorous application of statistical methods and a structured improvement cycle (DMAIC – Define, Measure, Analyse, Improve, Control). Together, these methodologies form the basis of Lean Six Sigma (LSS), offering powerful conceptual frameworks and practical toolkits for elevating operational performance, enhancing customer value and systematically curtailing errors, thereby fostering a culture of continuous improvement (Psarommatis and Azamfirei, 2024; Abdelbar *et al.*, 2019; Yadav *et al.*, 2017; Habidin *et al.*, 2016).

A critical, complementary financial perspective for any LSS program is provided by the Cost of Quality (CoQ) model. Far from being a static accounting tool, the modern application of CoQ has evolved into a dynamic instrument for strategic management. Contemporary literature demonstrates that CoQ is deeply intertwined with a firm’s competitive strategy and organisational structure (Dimitrantzou *et al.*, 2024), and its effective use is a hallmark of mature QMSs (Barakat and Elassimi, 2025; Glogovac and Filipovic, 2018). Organisations with higher maturity levels leverage CoQ not as a passive scorecard, but as a strategic tool to shift focus from failure detection to proactive prevention, thereby optimising quality investments (Barakat and Elassimi, 2025). Advanced frameworks now use CoQ for sophisticated, scenario-based strategic decision-making in areas like inspection strategy, balancing appraisal costs against the risk of external failures (Muffato Reis *et al.*, 2025). Furthermore, the advent of Quality 4.0 has amplified the strategic potential of CoQ by integrating it with real-time data analytics, enabling more predictive and data-driven quality management (Alsadi *et al.*, 2025). The CoQ model's foundational structure categorises quality-related expenditures into four domains: Prevention, Appraisal, Internal Failure and External Failure costs (Montgomery, 2013; Rodin and Beruvides, 2012), providing a universal financial language to articulate the economic consequences of quality performance.

However, despite this strategic evolution, a persistent and significant operational gap remains within many LSS deployments. While high-level CoQ analysis can strategically inform management about the magnitude and category of quality losses (Dimitrantzou *et al.*, 2020), it often lacks a structured, repeatable methodology to systematically link these aggregated financial figures back to their specific operational root causes on the shop or office floor. This creates a disconnect between the strategic insights provided by CoQ dashboards and the on-the-ground deployment of targeted improvement projects. Existing strategic CoQ models, such as those for optimising supply chains (Alglawe *et al.*, 2020) or inspection strategies (Muffato Reis *et al.*, 2025), are powerful for high-level decision-making but do not inherently provide a granular, step-by-step deployment mechanism to guide cross-functional teams from a resultant loss (e.g. high warranty costs) to its multiple causal losses (e.g. poor training, faulty component, incorrect design parameter) and then to a financially justified portfolio of solutions. This is the precise gap that structured cost deployment methodologies, originating from World Class Manufacturing, are designed to fill (Abisourour *et al.*, 2019; Carmignani, 2017). They provide the crucial link between the *what* (the financial loss) and the *why* (the root cause), enabling a truly proactive and economically rationalised approach to QI.

Similarly, while the LSS toolkit provides the methods to fix problems, it does not inherently prioritise those problems based on a holistic, enterprise-wide financial view of quality. The primary focus of a VSM analysis, while invaluable for streamlining operations, may not always extend to the comprehensive monetisation of all multifaceted quality-related losses across the four CoQ categories. Crucially, it does not inherently provide a structured framework for the subsequent strategic deployment of financially optimised improvement strategies, particularly within highly intricate, multi-stage environments where causal chains can be long and convoluted (Bertolini *et al.*, 2022; Wang *et al.*, 2021). Likewise, Six Sigma projects are often initiated based on identified operational problems, but these initiatives are not always predicated upon a holistically deployed, enterprise-wide financial quantification of the complete causal network of all quality costs (Rodin and Beruvides, 2012). This can lead to a portfolio of well-executed but suboptimal improvement projects, resulting in localised optimisations that may not represent the most effective use of limited organisational resources from a total financial perspective.

In stark contrast, various structured "cost deployment" frameworks, originating from the principles of World Class Manufacturing, have proven exceptionally effective in their respective domains by providing exactly this kind of structured, financially-driven approach. Manufacturing Cost Deployment (MCD), as originally conceptualised by Yamashina and Kubo (2002), presents a disciplined, matrix-driven system designed to comprehensively identify, quantify and strategically reduce all sources of manufacturing-related costs. This is achieved by tracing observed resultant losses back to their specific causal origins. The methodology's power lies in its sequential application of analytical matrices (A–E) that create a logical funnel, guiding a cross-functional team from a broad, qualitative mapping of losses to a focused, quantitative and financially-justified selection of improvement projects (Abisourour *et al.*, 2019). The inherent logic of this deployment philosophy has been successfully adapted to other areas, such as Energy Cost Deployment, Project Time Deployment and Design Cost Deployment (Bertolini *et al.*, 2024, 2022; Braglia *et al.*, 2020). These methodologies share foundational strengths: a systematic, step-by-step structure; a clear distinction between resultant symptoms and causal root problems; rigorous quantification in a unifying dimension; and a data-driven process for prioritising actions based on financial return (Carmignani, 2017; Habidin *et al.*, 2016; Chiarini and Vagnoni, 2015).

This brings the central problem into sharp focus. Despite the universal acceptance of the CoQ framework for reporting quality expenditures (Banasik and Beruvides, 2012; Dadfar and Brege, 2012) and the proven efficacy of cost deployment methodologies, a significant gap persists in both literature and practice. There is a conspicuous absence of a comparably structured, holistically integrated and systematically "deployed" methodology designed to proactively reduce the total CoQ across all four categories by methodically addressing root causal losses at their point of origin. While advanced paradigms like Quality Scorecards are valuable for monitoring performance (Roh *et al.*, 2022), they remain primarily diagnostic. A subsequent, equally rigorous and financially oriented deployment framework is the essential next step to translate diagnostic insights into tangible cost reductions.

This paper introduces Quality Cost Deployment (QCD) as a novel, Lean-inspired and systematically structured methodology designed to fill this critical gap and enhance the LSS toolkit. QCD provides a robust, matrix-based approach for the comprehensive identification, classification and tracing of all quality-related losses back to their specific causal origins within any operational system. It enables the rigorous quantification of their full financial impact and the strategic, data-driven deployment of targeted improvement actions designed to systematically reduce the total CoQ. By synergistically integrating the financial perspective of the CoQ framework with the causal-analytical rigour of cost deployment, QCD facilitates a proactive and economically sound approach to quality management. It creates a direct, auditable link from a high-level financial metric (e.g. warranty costs) to a specific, addressable root cause in a process (e.g. an inadequate training procedure). This moves decisively beyond reactive problem-solving towards an active, targeted and financially optimised strategy for company-wide QI. The structured nature of the QCD methodology, using a sequence of matrices (A–E), ensures clarity, repeatability and a transparent line of sight from problem identification to the implementation of financially justified improvement projects. This systematic approach is essential for navigating the inherent complexities of modern, dynamic operational systems and for ensuring that all QI efforts contribute demonstrably to the overall financial health and competitiveness of the organisation (Zhang *et al.*, 2025; Wang *et al.*, 2021; Roth *et al.*, 2020; Khesal *et al.*, 2019).

While QCD is conceptually inspired by the structured logic of cost deployment, particularly MCD, it represents a significant methodological innovation tailored for the unique complexities of quality costs. Its distinction arises from its fundamental re-engineering to navigate the four-pillar CoQ structure (Prevention, Appraisal, Internal and External Failure), which requires managing trade-offs between proactive investments and reactive failure costs. Crucially, QCD is also designed to map the complex, cross-category causal chains inherent in quality, tracing a single root cause, such as a design flaw, to its disparate financial impacts across increased appraisal, internal rework and external warranty claims simultaneously.

Furthermore, QCD is designed to be synergistic with, rather than a replacement for, other established strategic cost management frameworks. It can leverage the granular, activity-level data from Activity-Based Costing (ABC) systems to provide a more accurate financial quantification of losses in the C-Matrix (Khataie and Bulgak, 2013; Vetchagool *et al.*, 2021). Moreover, while Target Costing is a proactive, design-phase methodology for setting cost targets for new products (Sedevich-Fons, 2023), QCD serves as a complementary, operational-phase methodology for systematically reducing quality-related costs once a product or service is in production. It also shares the philosophical goal of Lean Accounting to make financial information more transparent and relevant to operational teams (Maskell *et al.*, 2011). However, whereas Lean Accounting often advocates for a systemic overhaul of a company's primary accounting systems (e.g. replacing standard costing with value stream costing), QCD is an analytical overlay that can be deployed alongside existing financial systems, offering a more flexible and less disruptive path to linking QI with financial results.

The remainder of this paper is structured as follows. Section 2 details the foundational principles of QCD, including system boundaries, operational decomposition from a quality perspective, and a comprehensive classification of quality losses. Section 3 provides an in-depth exposition of the five core analytical matrices (A-Matrix through E-Matrix) that drive the QCD process. Section 4 presents a practical case study illustrating the application of QCD in a real-world context, highlighting its operational steps and demonstrating its potential benefits. Section 5 offers managerial insights for decision-makers considering the adoption of QCD. Finally, Section 6 concludes the paper by summarising the key contributions of QCD, discussing the study's limitations, and outlining promising avenues for future research.

2. System boundaries, operational decomposition and classification of quality losses

The robust application of the QCD methodology commences with the precise delineation of its operational framework. This foundational stage is critical, as it ensures that subsequent analytical efforts are sharply focused, contextually relevant and ultimately yield actionable, impactful insights for QI. It involves three core activities: the establishment of clear system boundaries, a logical and practical decomposition of the operational entity from a quality management perspective, and the adoption of a comprehensive, consistently applied classification of quality-related losses. Neglecting this stage can lead to diffuse efforts, inaccurate analyses and ultimately, a failure to achieve the desired quality and cost objectives.

2.1 System boundaries: defining the scope of analysis

A foundational step in the QCD methodology is the precise definition of its operational framework through clear system boundaries. This critical activity circumscribes the scope of the analysis, ensuring it remains focused, manageable and targeted at improvements within the organisation's sphere of influence. Two primary boundaries must be established: spatial and temporal:

(1) *Spatial boundary:* This parameter defines the physical or procedural extent of the investigation. The selection is a strategic decision. A narrowly defined scope, such as a single problematic production line (e.g. "Assembly Line B for Product Model X") or a specific service process (e.g. "Inbound Customer Support Calls"), allows for a highly concentrated analysis, often leading to quicker, demonstrable improvements. This targeted approach is ideal for pilot projects or acute, well-localised problems. Conversely, a broader, system-wide boundary, encompassing an entire factory from receiving to shipping or a complete end-to-end service delivery process, provides a holistic view of quality performance. This facilitates the identification of systemic issues and interdepartmental loss transfers (e.g. poor data entry in one department causing rework in another). The choice should align with organisational objectives, available analytical resources and the perceived locus of major quality cost drivers.

(2) *Temporal boundary:* This parameter establishes the specific time-frame for data collection and analysis. Adherence to a consistent period is essential for accurate comparison, trend analysis and avoiding bias from short-term fluctuations, seasonal

variations or product lifecycle effects. The chosen period must be long enough to capture representative operational performance data. A common choice is a fiscal year, which aligns with financial reporting cycles and averages out monthly variations. However, shorter periods, such as a single quarter or six months, may be more appropriate for dynamic environments or initial pilot studies where rapid feedback is crucial. Regardless of the duration, all quality loss data – from internal scrap rates and rework hours to external warranty claims and customer complaint frequencies – must rigorously pertain to the same defined period. This requires careful management of time-lagged costs, ensuring that issues like warranty claims are consistently accounted for, whether by linking them to their production cohort or by analysing them based on the processing date within the boundary.

By defining these boundaries, the QCD methodology intentionally focuses the analysis on *controllable losses* – those quality-related costs and inefficiencies that can be directly influenced and mitigated through internal process improvements, managerial actions and resource allocation. External, non-controllable events, such as widespread supply chain disruptions or sudden regulatory changes, generally fall outside the direct intervention scope of a typical QCD project, although their significant impacts might be noted for broader strategic planning and risk management.

2.2 Operational decomposition: structuring for quality insight

To systematically unearth, catalogue and analyse the multifaceted quality losses that permeate an organisation, the operational entity (e.g. a factory or service system) is conceptually decomposed into logical, functionally distinct segments such as systems, operational areas or key process stages. This decomposition is a critical prerequisite for effective quality analysis because it is within these defined segments that quality is either generated, controlled or compromised. This structured decomposition essentially creates an operational "map" or blueprint of the organisation from a quality perspective. This map guides the QCD team in meticulously pinpointing the precise *locations* which may be the origin of causal losses (e.g. "Component Placement Stage") and where the symptoms of quality problems manifest (e.g. "Scrap at Final Test"). Such a granular approach is vital to avoid a specific or superficial loss identification process and is particularly critical for the effective and meaningful construction of the A-Matrix and B-Matrix, where quality losses must be unambiguously assigned to specific operational loci.

A practical, yet comprehensive, decomposition framework, adaptable to most operational contexts, would typically include the following key systems or areas:

- *Supplier and Incoming Material System:* Encompasses all interactions with external suppliers, from their selection and qualification to the receipt, inspection and handling of incoming materials or information. Poor quality frequently originates externally, and defects in supplied inputs can cascade through the system, causing significant internal and external failures. Understanding supplier process capability is crucial for prevention.
- *Production or Service Delivery System:* The core value-creation process where inputs are transformed into outputs. This is typically subdivided into distinct process stages, work centres or production/service lines for granular analysis. Most internal failures, such as scrap, rework, process deviations and quality-related downtime, are generated here. Controlling variability within this system is fundamental to overall quality performance.

- *In-Process Quality Control System:* Includes all planned inspection, testing and verification activities embedded within the operational process. These are appraisal activities designed to detect and contain non-conformances before they escalate to the next stage or to the customer. The cost-effectiveness of these controls is evaluated by balancing the cost of inspection against the cost of a defect escaping.
- *Finished Goods and Outgoing Quality System:* Represents the final internal checkpoint before a product or service is delivered to the customer. It involves final inspection, functional testing and verification against all specified requirements. Failures at this stage can lead to significant rework or, if missed, severe external failure costs, making it a critical control point for protecting the customer and brand reputation.
- *Customer and Post-Sales System:* Deals with the product or service once it is in the customer's hands. This system includes customer feedback mechanisms, warranty administration, product returns, service support and complaint resolution. It is where most external failure costs are realised and measured. Data from this system is vital for understanding field performance, perceived quality and long-term reliability, providing crucial feedback for future improvements.
- *QMS Support System:* The overarching system that supports all quality-related activities. It includes quality planning (e.g. FMEAs, control plans), employee training, documentation control, calibration, audits, and the corrective and preventive action system. Inefficiencies or deficiencies within the QMS itself are often the root cause of quality problems that manifest in other systems. The costs associated with maintaining this infrastructure are typically classified as prevention costs.

This decomposition framework must always be tailored to the specific operational structure, complexity and unique characteristics of the organisation under investigation. For example, a software development company would decompose its value stream into stages like "Requirements Gathering", "Design and Architecture", "Coding", "Testing" and "Deployment", demonstrating the framework's adaptability across different industries.

2.3 Classification of quality losses: the language of quality costs

A fundamental pillar of the QCD methodology is the adoption of a robust, clear, comprehensive and universally understood classification system for all quality-related losses. This classification is essential for enabling their subsequent consistent and credible quantification in monetary terms. The widely accepted CoQ model, as detailed by pioneers like Feigenbaum and Juran and extensively discussed in quality literature (Montgomery, 2013), provides an exceptionally suitable framework. It categorises all costs associated with achieving (or failing to achieve) product or service quality into four primary types, translating often abstract quality issues into the tangible financial impact of deviations from achieving perfect quality on the first attempt. The adoption of the CoQ framework provides a standardised lexicon for discussing quality matters in financial terms, making them more visible and understandable to management across different functions.

The four primary CoQ categories are:

(1) *Prevention Costs:* Proactive investments made to prevent defects and non conformances from occurring in the first place. These are often considered 'good' costs, as effective prevention (e.g. robust process design, comprehensive FMEAs, quality planning, fool-proofing or Poka-Yoke mechanisms, thorough training) can significantly reduce overall CoQ by minimising failure and appraisal costs.

(2) *Appraisal Costs:* Costs incurred to assess, measure and audit products, processes and services to ensure conformance to specified requirements. These involve activities like inspection, testing and calibration. While necessary to some extent, excessively high appraisal costs may indicate an over-reliance on detection rather than prevention, or inefficiencies in the appraisal processes themselves.

(3) *Internal Failure Costs:* Costs associated with defects and non-conformances found before the product or service is delivered to the external customer. These represent direct waste, inefficiency and lost opportunity within the organisation's own operations.

(4) *External Failure Costs:* Costs associated with defects and non-conformances found after the product or service has been delivered to the customer. These are typically the most damaging and expensive, directly impacting customer satisfaction, loyalty, brand reputation and potentially leading to significant financial liabilities.

This meticulous classification framework (see Table A1 in the online supplement) is indispensable for ensuring that the subsequent QCD matrices, particularly the C-Matrix dedicated to cost quantification, capture a comprehensive and accurate financial picture of all significant quality-related expenditures and losses. It provides the necessary granularity for the A-Matrix and subsequent analyses.

3. Quality cost deployment methodology

The QCD methodology, drawing structural parallels with MCD, is a systematic five-step process (Figure 1) where each step uses a dedicated matrix as its primary analytical tool. This structured progression provides a clear, repeatable pathway, guiding the analytical team from the initial, qualitative identification of diverse quality losses to the final, economically-rationalised selection of targeted improvement projects. A key analytical strength is the clear separation of causal losses from their origins, acknowledging that a single cause can lead to multiple resultant losses, and multiple distinct causal losses can originate from the same location.

A company in the electronics industry is used to exemplify the matrices of the QCD methodology in the following subsections. These illustrative examples (Tables 1–5) demonstrate the structure and logic of each matrix. The full application of these matrices using data from the formal case study is detailed in Section 4 and presented in the online supplementary tables (Tables A2–A6).

3.1 The A-Matrix: initial cartography of quality losses

The A-Matrix constitutes the inaugural and foundational step in the QCD process. It serves as an initial, high-level 'cartographic survey' or qualitative map of the existing quality loss

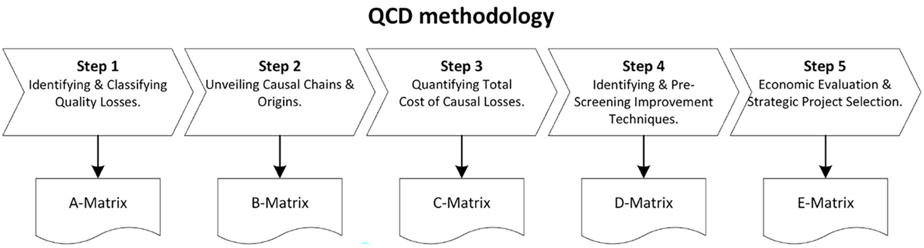

Figure 1. The Five Steps of the Quality Cost Deployment (QCD) Methodology (Conceptual Flow: A-Matrix → B-Matrix → C-Matrix → D-Matrix → E-Matrix)

Table 1. Illustrative A-Matrix for a control module assembly in an electronics company

Location (of manifestation)	Scrap (component damage) - IF	Rework (soldering defect) - IF	Cost of In-Process visual Inspection - AP	Warranty claim (module failure) - EF	Cost of supplier Qualification - PR	Excess inventory (buffer for defects) - IF	Downtime (machine jam) - IF
Supplier and incoming system							
component kitting area	▲		■		▲	■	
incoming Inspection - PSU	●	▲	▲ (high test time)			▲	■
raw PCB storage	■ (oxidation)						
Production process system							
SMT Line 1 - Paste Print	■ (smearing)	▲ (clean and rerun)	■				▲
SMT Line 1 - Pick and Place M/C A	● (misplacement)	▲ (manual correction)				▲	●
Manual Soldering Station #1	■	●	▲ (100% Visual)			●	■
automated conformal coating	▲ (uneven coat)	▲ (strip and recoat)	■				
In-Process quality control system							
automated optical inspection (AOI)			● (high cycle time)				
In-Circuit test (ICT) station	▲ (false fails)	▲ (retest)	● (fixture maint.)				▲
Finished goods and outgoing quality system							
functional test station	● (boot failure)	▲ (firmware reload)	■ (test records)			▲	
packaging and dispatch	■ (label error)	■ (repack)	■ (final check)				
Customer and post-sales system							
customer returns processing				● (high RMA volume)			
field service team				● (repeat visits)			
QMS support system							
training department					● (cost of outdated materials)		
calibration lab			▲ (overdue calibrations)				

Note(s): Legend: ● Very Significant; ▲ Significant; ■ Minor. CoQ categories: IF = Internal Failure, AP = Appraisal, EF = External Failure, PR = Prevention

Table 2. Illustrative B-Matrix for an electronics company – linkages

Causal loss description	Origin location (of causal loss)	Resultant: Rework (Solder Defect) at Station #1	Resultant: Scrap (module Failure - Solder origin) at functional test	Resultant: Warranty claim (module Failure - Solder origin) at customer	Resultant: Scrap (PSU DOA) at incoming inspection	Resultant: High false call rate at AOI station	Resultant: Scrap (component misplacement) at SMT M/C a
Inadequate soldering training	QMS/HR (training dept.)	X	X	X			
Poor PSU quality	Supplier X (incoming mat. System)		X	X	X		
Incorrect AOI test parameters	ICT (In-Process control)					X	
Outdated SMT feeder calibration	SMT M/C A (production)						X
Inadequate design review	Engineering dept.	X	X	X			
Poor component kitting	Supplier and incoming system						X

Table 3. Illustrative C-Matrix for an electronics company – cost quantification (annual costs in €) with intangible impact assessment

Causal loss description	Origin location (of causal loss)	Direct cost of causal loss (€)	Attributed rework cost (€)	Attributed scrap cost (€)	Attributed warranty cost (€)	Attributed appraisal cost (e.g. extra test) (€)	Total cost of causal loss (€)	Est. Intangible impact (H/M/L)
Poor PSU quality	Supplier X (incoming mat. System)	5,000	800	3,000	1,200	0	*10,000*	M
Inadequate soldering training	QMS/HR (training dept.)	3,000	20,000	7,500 (Incl. FTF scrap)	7,200*	0	*42,700*	H
Incorrect AOI test parameters	ICT (In-Process control)	1,000	0	2,250 (FTF scrap)	3,000	0	*6,250*	L
Outdated SMT feeder calibration	SMT M/C A (production)	500	0	12,000	0	0	*12,500*	L
Inadequate design review	Engineering dept.	2,000	5,000	1,500	4,800*	500	*13,800*	H
Poor component kitting	Supplier and incoming system	1,000	200	6,000	0	0	*7,200*	M
Total (all causal losses)		*12,500*	*26,000*	*32,250*	*16,200*	*500*	*87,450 (Grand Total COPQ)*	

***Note(s):** Shared warranty costs are allocated proportionally based on data from failure analysis. For instance, the total solder-related warranty cost of €12,000 is attributed 60% (€7,200) to Inadequate Soldering Training and 40% (€4,800) to Inadequate Design Review based on a Pareto analysis of field failure codes

Table 4. Illustrative D-Matrix for an electronics company – evaluating techniques for top causal losses

Causal loss description (COPQ)	Origin location	Proposed improvement technique	E	F	S	QPI	Shortlisted for E-Matrix?
Inadequate Soldering Training (€35,500)	QMS/HR (training dept.)	Technique B1: IPC-A-610 Soldering Certification Training	5	4	4	4.4	Yes
		Technique B2: Automated Optical Inspection (AOI) for Solder Joints	4	3	4	3.6	No (less direct)
		Technique B3: Purchase Advanced Soldering Stations	4	3	3	3.4	No
Poor PSU Quality (€10,000)	Supplier X (incoming mat. System)	Technique A1: Enhanced Supplier Audit and Joint QI Programme	4	3	4	3.6	Yes
		Technique A2: 100% Incoming PSU Burn-in Test	3	4	3	3.4	No (appraisal, not prevention)
Incorrect AOI Test Parameters (€6,250)	ICT (In-Process control)	Technique C1: AOI Vendor Optimisation and New Algorithms	5	4	3	4.2	Yes
		Technique C2: Internal Retraining on AOI Programming	4	4	3	3.8	Consider as supporting
Outdated SMT Feeder Calibration (€12,500)	SMT M/C A (production)	Technique D1: Implement Predictive Maintenance for Feeders	4	3	3	3.4	Yes
		Technique D2: Feeder Overhaul/ Replacement Programme	5	2	4	3.6	No (lower QPI for higher cost)

Note(s): Scores E, F, S are on a 1–5 scale. QPI is calculated using a weighted additive model: QPI = (0.4 × E) + (0.4 × F) + (0.2 × S). Higher QPI indicates a more preferred technique. The ‘Shortlisted’ column indicates selection for detailed economic analysis in the E-Matrix

Table 5. Illustrative E-Matrix for an electronics company (annual costs in €, eval. Period 3 yrs, discount rate 12%)

Project ID	Targeted causal loss (description)	Origin location (of causal loss)	Improvement technique	K_{Ch} (€/yr)	r	Gross saving (€/yr)	I_0 (€)	O (€/yr)	Net saving (€/yr)	NPV (€) @3yrs	PI	IRR (%)
P1	Inadequate soldering training	QMS/HR (training dept.)	IPC-A-610 Certification	35,500	0.80	28,400	10,000	1,000	27,400	55,826	6.58	> 100%
P2A	Poor PSU quality	Supplier X (incoming mat. System)	Joint QI programme with supplier alpha	10,000	0.60	6,000	5,000	500	5,500	8,210	2.64	≈ 45%
P3	Incorrect AOI test parameters	ICT (In-Process control)	AOI vendor optimisation	6,250	0.70	4,375	4,000	200	4,175	6,027	2.51	≈ 40%
P4	Outdated SMT feeder calibration	SMT M/C A (production)	Implement predictive maint.	12,500	0.75	9,375	7,000	800	8,575	13,594	2.94	≈ 55%
P5	Inadequate design review	Engineering dept.	Formal design review process	13,000	0.65	8,450	6,000	700	7,750	12,520	3.09	≈ 50%
P6	Poor component kitting	Supplier and incoming system	Enhanced supplier audits	7,200	0.70	5,040	3,000	400	4,640	8,145	3.71	≈ 65%

Note(s): K_{Ch} values from C-Matrix (Table 3). PVIFA (12%, 3yrs) ≈ 2.4018. For P1: PV Net Savings = €27,400 * 2.4018 = €65,810. NPV = €65,810 - €10,000 = €55,810 (slight rounding difference from table). PI = €65,810 / €10,000 = 6.58. IRR values are illustrative and would be calculated using financial software landscape as it manifests within the previously defined system boundaries. The primary objective of the A-Matrix is to systematically identify *where* within the decomposed organisation structure the various *types* of (resultant) quality losses are observed to occur. Concurrently, it aims to gain a preliminary, yet crucial, qualitative understanding of their relative significance or perceived severity from the perspective of experienced operational personnel, quality experts and process owners. This matrix, therefore, provides the first comprehensive, albeit primarily qualitative, overview of the organisation's current quality challenges and 'pain points', visually highlighting areas of concern.

The structure of the A-Matrix (Table 1) is designed to facilitate both clarity and comprehensiveness. The rows meticulously detail the specific locations of manifestation where resultant losses are observed (e.g. "Incoming Inspection - Bay 3", "SMT Line A - Pick and Place Machine"), while the columns systematically enumerate the specific types of resultant quality losses, consistently categorised according to the established CoQ framework (e.g. "Scrap - Wrong Component", "Rework - Solder Bridges"). The core activity involves the collaborative populating of its cells by a cross-functional QCD team, typically through brainstorming sessions, review of existing data like defect logs and QC reports, and leveraging the experiential knowledge of team members.

At the intersection of a location (row) and a loss type (column), the team makes an entry that represents a qualitative judgement of its impact. This initial reliance on qualitative assessment is a deliberate and pragmatic aspect of QCD that powerfully leverages the collective knowledge of the team. A commonly adopted and highly effective method for this assessment employs a visual, 'traffic-light' coding system: a red symbol (●) indicates a *very significant loss* that warrants immediate attention; a yellow symbol (▲) denotes a *significant loss* of notable concern; and a green symbol (■) represents a *minor loss* that is less critical but still present. A blank cell signifies that the specific loss is not observed or is considered negligible. This process visualises the distribution and concentration of quality losses across the organisation, fostering team consensus on the most pressing issues. The A-Matrix thus functions as an essential initial diagnostic tool, guiding prioritisation for deeper investigation (typically starting with the "red" cells) and forming a baseline qualitative snapshot against which future improvements can be compared.

Evidently, this initial reliance on qualitative assessment is susceptible to cognitive and social biases, such as group-think, availability bias or political influence, as is common in group decision-making. However, the A-Matrix is deliberately designed not as a final analytical instrument, but as a strategic focusing device. Its primary purpose is to efficiently leverage the team's collective experiential knowledge to prioritise the most critical areas for subsequent, rigorous, data-driven financial quantification in the C-Matrix. The qualitative 'red cells' act as hypotheses that are then validated or refuted by the quantitative analysis that follows, providing a built-in check against initial biases.

3.2 The B-Matrix: unveiling causal chains in quality losses

While the A-Matrix identifies *what* resultant quality losses are occurring and *where*, it does not reveal the underlying *why*. Many of these resultant losses are merely symptoms of deeper, often hidden, causal losses (i.e. root causes). The B-Matrix is the critical analytical instrument in the QCD methodology designed to meticulously trace, document and elucidate these complex cause-and-effect relationships. Sustainable QI can only be achieved by systematically addressing the true causal losses, rather than merely treating the symptoms.

The structure of the B-Matrix (Table 2) is designed to capture these relationships. Each row distinctly identifies a Causal Loss through two separate initial columns: its detailed description and its specific Origin Location. This allows for multiple distinct causal losses, even those from the same location, to be analysed independently. The subsequent columns represent the unique Resultant Losses, defined by their description and location of manifestation. A mark at the intersection signifies that the causal loss in the row directly contributes to the specific resultant loss in the column. This structure explicitly visualises how a single causal loss, originating from one point, can propagate through the system and lead to a variety of symptoms manifesting in different areas.

This linkage identification process is not arbitrary but is informed by a rigorous, multifaceted investigation. The team uses structured problem-solving techniques like the “5 Whys” and Fishbone diagrams to drill down to root causes. These qualitative findings are lent quantitative support through the rigorous analysis of available data, such as Pareto charts and correlation studies. Furthermore, direct process observation via Gemba walks and leveraging the collective expert opinion of the cross-functional team are used to hypothesise and validate the causal links. For example, a high scrap rate at a final test (a resultant loss) might be linked to several causal factors, such as “Out-of-spec Raw PCBs” from a supplier or an “Incorrect Solder Paste Stencil Design” from engineering. The B-Matrix differentiates these causes and maps their full impact.

Ultimately, the B-Matrix provides profound analytical insights by clearly distinguishing root causes from symptoms, which enables focused improvement efforts on fundamental issues at their point of origin. It also highlights high-leverage improvement opportunities, as addressing a single, potent causal loss can resolve multiple resultant losses across various locations. This facilitates a move away from reactive “firefighting” of symptoms towards the proactive elimination of underlying problems, enhancing a system-level understanding of how quality issues propagate.

It is important to acknowledge that the B-Matrix, in its two-dimensional format, represents a deliberate simplification of causality. Complex operational systems often exhibit non-linear relationships and feedback loops that a static matrix cannot fully capture. However, the B-Matrix is not intended to be a comprehensive system dynamics (SD) model. Its primary function is to serve as a pragmatic and actionable tool that creates a clear, traceable and understandable link between observed symptoms (resultant losses) and their primary root causes (causal losses). By focusing on the most significant “one-to-many” causal pathways, it effectively guides improvement efforts without the risk of “analysis paralysis” that a fully dynamic model might entail for a cross-functional project team.

3.3 The C-Matrix: monetising the impact of quality losses

Following the mapping of causal chains in the B-Matrix, the C-Matrix stage translates these operational issues into the explicit financial language of the business. This critical step quantifies, in precise monetary terms (e.g. €, $), the total Cost of Poor Quality (COPQ) associated with each identified causal loss. This comprehensive figure is achieved by summing the direct cost of the causal loss itself with the aggregated costs of all the resultant losses it triggers, as defined by the B-Matrix linkages. This process is essential for prioritising improvement efforts and constructing compelling business cases, as it answers the crucial question:

> *Q1*: ‘How much is this specific root problem, originating at this location, costing us annually?’

The C-Matrix (Table 3) is structured with each row representing a unique causal loss, identified by its description and origin location. Subsequent columns detail the components of its total cost: the immediate *Direct Cost* incurred at the point of the causal loss itself; the *Monetary Value of Associated Resultant Losses,* which are categorised by type (e.g.

Attributed Rework Cost, Attributed Scrap Cost, Attributed Warranty Cost); and finally, the *Total Cost Attributable to the C-Matrix*. This final sum represents the total annual financial burden imposed by that single root cause. It is the primary figure used for Pareto analysis and prioritisation, as it signifies the maximum potential annual saving if that causal loss were entirely eliminated.

Accurately quantifying these losses is governed by a principle of Traceability-Based Cost Attribution. This requires diligent data collection and a consistent, auditable costing methodology. A two-tiered approach is employed:

(1) Direct Attribution: Whenever possible, resultant loss costs are traced and allocated directly to a single, unambiguous root cause. For example, the cost of scrap material resulting from a specific machine's miscalibration is allocated entirely to the 'Improper Machine Calibration' causal loss. Data for this is typically sourced from production systems (MES, SCADA) and financial systems (ERP), which provide scrap quantities and standard material costs.

(2) Proportional Attribution for Shared Costs: Many resultant losses, particularly external failures like warranty claims, are often caused by multiple, interacting root causes. In these cases, the total cost of the resultant loss is partitioned among the contributing causal losses. This allocation is not arbitrary but is based on a data-driven, proportional analysis. For example, if warranty data analysis (e.g. Pareto of failure codes) indicates that 60% of field failures are due to solder joint fatigue (linked to "Inadequate Training") and 40% are due to component burnout (linked to "Ambiguous Specification"), the total annual warranty cost is allocated in that 60/40 proportion to the respective causal losses.

By default, shared resultant costs (e.g. warranty) are partitioned among contributing causal losses using data-driven proportional allocation (e.g. Pareto of failure codes). Full attribution to a single causal loss is allowed only when failure-code analysis and tear-down evidence conclusively indicate a single root cause (this decision and supporting evidence must be documented in the project record).

While the C-Matrix prioritises the quantification of tangible, measurable costs to maintain financial rigour, it also formally acknowledges the importance of intangible costs. A supplementary column, *Estimated Intangible Impact (H/M/L)*, is included. This allows the team to make a qualitative assessment of whether a causal loss has a high, medium or low impact on factors like brand reputation, customer trust or employee morale. This ensures that such critical, albeit difficult-to-quantify, factors are not excluded from the strategic discussion.

The C-Matrix is a powerful tool because it enables a Pareto analysis (80 / 20 rule) of causal losses, highlighting financial priorities and focusing efforts on the "vital few" problems causing the most damage. It provides a quantitative business case for improvement by detailing the potential ROI for projects targeting specific causal losses. This translation of technical problems into universally understood financial impacts is crucial for gaining management support and buy-in. Furthermore, by creating a financial baseline, the C-Matrix serves as a mechanism to track the effectiveness of corrective actions post-implementation, demonstrating the actual savings achieved. Importantly, this quantitative step also serves as a critical validation mechanism, confirming or challenging the initial qualitative severity assessments made in the A-Matrix and thereby mitigating the risk of biases influencing the final project portfolio.

3.4 The D-Matrix: identifying and pre-screening improvement techniques

Once the most financially impactful causal quality losses have been identified and quantified via the C-Matrix, the D-Matrix serves as a structured platform for brainstorming and then systematically pre-screening potential improvement techniques or corrective actions. Its core purpose is to generate a viable set of alternative solutions for each key causal loss and then to evaluate these potential solutions against a balanced, multidimensional set of qualitative criteria. This pre-screening step is crucial for narrowing the field of potential solutions to a shortlist of the most promising ones, which will then undergo a more detailed economic analysis in the E-Matrix.

The D-Matrix (Table 4) typically lists the high-priority Causal Losses as its main rows, with each loss identified by its description and its COPQ to provide context. For each causal loss, a range of potential improvement techniques is considered. These techniques can span various categories, including the application of statistical tools like statistical process control (SPC) or DOE, the implementation of Lean methods such as Poka-Yoke or Standardized Work, the use of formal quality management methodologies like Six Sigma, or direct organisational and technical interventions. Organisational changes might involve targeted training programmes or supplier development initiatives, while technical solutions could include equipment upgrades, tooling redesigns or process automation.

For each pairing of a causal loss and a potential improvement technique, the QCD team evaluates the technique based on several criteria, typically on a scale from 1 to 5, where 5 is most favourable. Common evaluation criteria, as suggested by, e.g. Braglia *et al.* (2020), focus on three key dimensions. First is *Effectiveness (E)*, which is the anticipated ability of the technique to significantly reduce or entirely eliminate the targeted causal loss. Second is *Implementation Feasibility (F)*, which considers the ease or difficulty of implementation regarding technical complexity, required investment and resource availability. Third is *Sustainability (S)*, which assesses the likelihood that the achieved improvements can be maintained in the long term, considering factors like cultural fit and robustness. Optional criteria, such as speed of implementation or impact on employee morale, can also be included.

From these scores, a composite score, the Quality Priority Index (QPI), is calculated using a weighted additive model, a standard approach in multi-criteria decision analysis (MCDA) (El Korany *et al.*, 2025). This requires the QCD team to first assign weights to the criteria (w_E, w_F, w_S) reflecting their relative strategic importance, such that $w_E + w_F + w_S = 1$. For example, an organisation might place higher importance on Feasibility ($w_F = 0.4$) and Effectiveness ($w_E = 0.4$) than on long-term Sustainability ($w_S = 0.2$).

The QPI is then calculated for each technique:

$$\mathrm{QPI} = (w_E \times \mathrm{E}) + (w_F \times \mathrm{F}) + (w_S \times \mathrm{S}).$$

A higher QPI indicates a more desirable technique relative to the alternatives. This weighted additive model provides a more robust prioritisation than a simple multiplicative formula – such as the one adopted by, e.g. Braglia *et al.* (2020). In fact, it allows for unequal trade-offs and makes it more difficult for a high score in one criterion to compensate for a critically low score in another, such as Feasibility. The D-Matrix therefore facilitates a structured and strategically-aligned comparison, and typically, the technique(s) with the highest QPI for each causal loss are shortlisted for the more rigorous financial scrutiny of the E-Matrix. This ensures that analytical effort is focused only on the most viable solutions. The D-Matrix thus plays a critical role in encouraging a broad consideration of different solution types, systematically evaluating multiple alternatives, and narrowing the options before committing to a detailed economic analysis. This process is instrumental in building team consensus and aligning resources towards the most practical and impactful solutions.

3.5 The E-Matrix: economic evaluation and strategic project selection

The E-Matrix represents the crucial decision-making nucleus of the QCD process. It is here that the most promising improvement techniques, shortlisted from the D-Matrix based on their QPI scores, are subjected to a rigorous and detailed economic evaluation. The primary objective of the E-Matrix is to facilitate the selection of an optimal portfolio of QI projects – one that maximises the net financial benefit to the organisation while adhering to budgetary and strategic goals. This stage transforms the qualitative and semi-quantitative insights from earlier matrices into concrete, financially justifiable investment proposals, employing standard engineering economy principles to assess their viability and rank their attractiveness. Each row in the E-Matrix (Table 5) details a specific improvement project, capturing the critical financial, operational and evaluative parameters necessary for a sound investment decision.

A critical and transparent step in constructing the E-Matrix is the conversion of the qualitative Effectiveness (E) score from the D-Matrix into the quantitative, cardinal Effectiveness Factor (r). This is not an arbitrary conversion but a structured, consensus-based estimation process. The ordinal "E" score (1–5) serves as a qualitative anchor to guide the team in estimating the "r" value (0%–100%), which represents the percentage reduction of the targeted causal loss cost. The following heuristic scale is used as a guideline for this estimation:

- "E" Score of 5 (Very High Effectiveness): Suggests an estimated effectiveness factor (r) in the range of 70%–90%.
- "E" Score of 4 (High Effectiveness): Suggests an estimated r in the range of 50%–70%.
- "E" Score of 3 (Moderate Effectiveness): Suggests an estimated r in the range of 30%–50%.
- "E" Score of 1–2 (Low Effectiveness): Suggests an estimated r below 30%.

The final "r" value for each project is a specific point estimate within the suggested range, determined by the cross-functional team based on their expert knowledge, data from similar past initiatives or pilot studies. This process ensures the transformation from ordinal to cardinal data is both structured and defensible.

The foundation of the economic evaluation begins with the Targeted Causal Loss Cost (K_{Ch} in €/year), sourced directly from the C-Matrix. An anticipated Effectiveness Factor (r) is then realistically estimated to determine the percentage reduction in this cost achievable by the proposed technique. The product of these, the Expected Annual Gross Saving, quantifies the direct annual reduction in quality costs. To achieve this saving, a comprehensive, one-time Initial Investment Cost (I_0) is required. Furthermore, any new Ongoing Annual Operating Costs (O) needed to sustain the improvement are factored in. The difference between the gross saving and these ongoing costs yields the Net Annual Saving, which represents the project's recurring cash inflow.

These cash flows are then evaluated over a defined Project Evaluation Period (T in years), which should reflect the economic life of assets or the company's strategic planning horizon. Future cash flows are discounted to their present value using a company-specific Discount Rate (d in %) to account for the time value of money and investment risk. The primary criterion for assessing absolute economic benefit is the net present value (NPV), which represents the total discounted net benefit over the evaluation period:

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{(\text{Net Annual Saving})_t}{(1+d)^t} - \mathrm{I}_0.$$

A positive NPV indicates financial viability relative to the discount rate. While NPV is primary, other financial metrics provide a more complete picture. The Profitability Index (PI) is a relative measure useful for ranking independent projects under capital constraints. The Internal Rate of Return (IRR) represents the project's effective rate of return, while the Payback Period is a secondary indicator focusing on liquidity and risk by showing the time required to recoup the initial investment.

The Project Selection Process is a structured, multi-stage approach that integrates quantitative ranking with strategic qualitative oversight:

- *Initial Screening and Ranking:* After all financial metrics are calculated, an initial screening eliminates any projects with a negative NPV. Subsequently, the remaining viable projects are ranked based on their PI, which provides a data-driven starting point for portfolio construction, especially under capital constraints.
- *Strategic Tie-Breaking:* The quantitative ranking is then refined using the qualitative insights from the C-Matrix. In cases where two or more projects have similar financial rankings (e.g. comparable PI values), the project targeting a causal loss with a 'High' rated Estimated Intangible Impact is given strategic priority. This ensures that factors like brand reputation and customer loyalty are formally considered in the decision.
- *Qualitative Portfolio Adjustment:* Finally, the entire shortlisted portfolio of projects is subjected to a holistic review. This crucial step assesses the portfolio for interdependencies that are not captured in the individual project metrics. The QCD team must identify: • Synergies: Where one project might enhance the effectiveness of another. • Redundancies: Where two different projects partially address the same root cause, leading to an overestimation of combined benefits. Based on this review, the team can make final adjustments to the portfolio, ensuring the selected set of initiatives is not only financially sound on an individual basis but also strategically coherent and optimised as a whole.

To address the inherent imprecision of inputs and avoid the trap of false precision, the final and critical step of the E-Matrix process is a mandatory Sensitivity and Risk Analysis. The precise financial metrics (NPV, PI) calculated are not endpoints but are base-case scenarios that must be tested for robustness.

This analysis focuses on the key input variables that are based on estimation rather than hard data: primarily the Targeted Causal Loss Cost (K_{Ch}) from the C-Matrix and the estimated Effectiveness Factor (r). The QCD team should perform, at a minimum, a one-way sensitivity analysis by varying these key inputs within a plausible range (e.g. ±20%) or by defining pessimistic, expected and optimistic scenarios.

The results of this analysis are crucial for final project selection. A project that maintains a positive NPV and an attractive PI even under pessimistic assumptions is considered financially robust. Conversely, a project whose viability is highly sensitive to small changes in input estimates carries a higher risk. This step ensures that the final portfolio decision is based not on a misleading sense of precision, but on a sound understanding of each project's financial risk profile.

4. Case study: application of quality cost deployment in an electronics manufacturing firm

To demonstrate its practical application, the five-step QCD methodology was implemented at "Alpha Components Ltd." (a fictional name for privacy), a medium-sized enterprise designing and assembling electronic control modules for industrial automation. The company faced a significant upward trend in warranty claims and escalating internal rework costs for its flagship "InduControl X1000" module, eroding profitability and customer satisfaction. Senior management selected the QCD framework to guide a strategic QI programme, valuing its structured, data-driven and financially-oriented approach to pinpointing and resolving root causal losses.

A cross-functional QCD team was formed, comprising members from production, quality assurance, design engineering, manufacturing engineering and procurement. The team's first task was to define the study's operational parameters. The *Spatial Boundary* was set to the entire dedicated assembly line for the "InduControl X1000" module, from component kitting through to final packaging. The *Temporal Boundary* was defined as the preceding 12-month period (1 July 2022 to 30 June 2023) to ensure a representative baseline of performance data, free from short-term anomalies.

The team began by populating the A-Matrix (Table A2 in the online supplement) to create a qualitative map of the quality loss landscape. By reviewing production records, scrap reports, warranty databases and interviewing line operators, they identified where different types of resultant losses were manifesting. The A-Matrix immediately highlighted several critical areas of concern, including high scrap rates due to SMD tombstoning and significant downtime at the SMT Pick-and-Place Machine #2; high rework caused by solder bridging at Manual Soldering Workstation #3; a high false-fail rate at the In-Circuit Test (ICT); and a high rate of modules failing boot-up at the Functional Test (FT) Rig. Furthermore, customer-facing systems showed a high volume of technical support calls regarding intermittent module resets and a high "No Fault Found" (NFF) rate during warranty repairs, indicating significant external failure costs and diagnostic challenges.

With these symptoms identified, the team constructed the B-Matrix (Table A3 in the online supplement) to uncover the underlying causal relationships. Through structured brainstorming, data analysis and direct process observation, several key causal chains were identified. For instance, the "Incorrect SMT Pick-and-Place Machine #2 Nozzle Selection/Maintenance Routine" was linked directly to scrap, rework and downtime manifesting at that same machine. A more complex chain revealed that "Inadequate Operator Training and Certification for Manual Soldering", originating in the Training Department, was the root cause of solder bridging rework at Manual Soldering WS #3 and a significant contributor to warranty returns due to solder joint fatigue. Similarly, an "Ambiguous Microcontroller Operating Temperature Specification" in design documents from the Engineering Department was traced as the cause for a lengthy incoming test protocol (Appraisal Cost), intermittent module resets (External Failure) and the high NFF rate at the warranty repair centre. This step was crucial in shifting the team's focus from merely treating symptoms to targeting the fundamental root causes of failure.

The third step was to quantify the annual financial impact of these causal losses by constructing the C-Matrix (Table A4 in the online supplement), translating the operational issues into the language of cost. This required extensive data collection from financial, production and quality systems, with all costs annualised and expressed in Euros (€). The findings were stark. The most financially damaging causal loss was 'Inadequate Manual Solder Training', contributing an estimated €51,000 annually to the COPQ, comprising €4,000 in ineffective training costs, €35,000 in rework costs and a proportionally allocated €12,000 in solder-related warranty claims (representing 60% of total warranty costs, based on field failure analysis). The team also rated this causal loss as having a "High" intangible impact due to its direct link to customer-facing field failures. The "Ambiguous Microcontroller Temperature Specification" was the second-largest contributor, costing

€50,500 annually in excess appraisal and warranty investigation costs. Other significant causal losses included the “Incorrect SMT Nozzle Maint.” (€33,500) and “Worn ICT Fixture Pins” (€21,000). This rigorous financial quantification provided a clear, data-driven basis for prioritising improvement efforts on the vital few problems causing the most significant financial damage.

Armed with this financial data, the team proceeded to the D-Matrix (Table A5 in the online supplement) to identify and pre-screen potential improvement techniques for the highest COPQ causal losses. For each causal loss, the team brainstormed a range of solutions and evaluated them using a QPI. The team adopted a weighted additive MCDA model for the QPI calculation, assigning weights of $w_E = 0.4$ (Effectiveness), $w_F = 0.4$ (Feasibility) and $w_S = 0.2$ (Sustainability) to reflect their strategic focus on effective and feasible solutions.

For the €51,000 “Inadequate Manual Solder Training” problem, implementing an official “IPC Solder Certification Programme” (QPI = 4.4) was shortlisted over purchasing an automated soldering machine (QPI = 3.6), due to its superior balance of effectiveness and implementation feasibility. For the €50,500 “Ambiguous µC Temp. Spec.” issue, instituting a “Formal Cross-Functional Design Review Process” (QPI = 4.4) was selected as the most robust systemic solution. This pre-screening process ensured that only the most promising and strategically aligned solutions were carried forward for detailed economic analysis, focusing the team’s resources effectively.

In the final step, the shortlisted improvements were subjected to a rigorous economic evaluation in the E-Matrix (Table A6 in the online supplement). The team first translated the qualitative Effectiveness (E) scores from the D-Matrix into quantitative effectiveness factors (r). Following the structured estimation guideline, for the “IPC Solder Certification Programme” (E = 5), the team estimated a high effectiveness factor of r = 70%. For the “Formal Design Review Process” (E = 5), a more conservative r = 60% was estimated due to the procedural nature of the change. The company had an annual QI budget of €50,000, and projects were evaluated over a 3-year period with a 10% discount rate. The team then calculated standard financial metrics such as NPV and PI for each potential project. The four primary projects under consideration were:

1. CS-PROJ-001: IPC Solder Certification Programme (Initial Investment I_0 = €18,000).
2. CS-PROJ-002: Formal Design Review Process (I_0 = €12,000).
3. CS-PROJ-003: SMT PM Revision + Auto Nozzle Inspection (I_0 = €20,000).
4. CS-PROJ-004: Enhanced ICT Fixture PM and Gold Pin Upgrade (I_0 = €5,000).

With a constrained budget, projects were ranked by PI for selection. The process started with CS-PROJ-004 (PI = 8.21), followed by CS-PROJ-002 (PI = 5.97) and finally CS-PROJ-001 (PI = 4.59). The cumulative initial investment for these three projects totalled €35,000, which was well within the €50,000 budget. The next project in rank, CS-PROJ-003, required a €20,000 investment, which exceeded the remaining €15,000 budget and was therefore deferred for future consideration.

The final selected portfolio (CS-PROJ-001, CS-PROJ-002 and CS-PROJ-004) represented an optimised investment of €35,000. This portfolio is projected to yield a combined 3-year NPV of €160,202, promising a significant return.

The team then performed a qualitative portfolio adjustment review and confirmed that the three selected projects (IPC Certification, Design Review and ICT Fixture PM) were largely independent, with no significant redundancies. In fact, they were deemed strategically complementary, addressing quality issues across training, design and equipment maintenance.

As a final step, the team conducted a sensitivity analysis on the three selected projects, varying the key cost and effectiveness estimates by ± 20%. The analysis confirmed that all three projects maintained a strongly positive NPV even under pessimistic assumptions, validating the robustness of the investment decision.

The comprehensive application of the QCD methodology provided "Alpha Components Ltd." with a clear, financially justified and strategically sound plan to address its most critical quality issues. Management appreciated the transparent linkage from observed problems to monetised root causes and the selection of an optimal portfolio of improvement projects that promised substantial operational and financial returns.

5. Managerial insights

The QCD methodology offers significant practical benefits for managers by directly addressing the critical LSS challenge of project selection and resource allocation. In environments with limited budgets and a finite number of Black Belts, managers must move beyond subjective criteria or responding to the "loudest voice". QCD provides a structured, front-end process to create a pipeline of financially vetted projects. This is achieved through the E-Matrix, which provides a robust and transparent framework for the economic evaluation of improvement initiatives using standard financial metrics like NPV and PI. By enabling LSS steering committees and Champions to make informed, data-driven decisions, QCD ensures that organisational effort is focused on a portfolio of projects that offers the greatest strategic return. Managers are advised to use the "Estimated Intangible Impact" rating from the C-Matrix as a crucial strategic overlay; a project with a slightly lower PI but a "High" intangible impact (e.g. on brand reputation or customer trust) may represent a superior strategic investment. The explicit consideration of both financial and qualitative factors ensures a balanced and comprehensive decision-making process.

A key advantage of QCD is its ability to empower LSS leaders with a holistic financial perspective on quality. While strategic applications of CoQ are increasingly prevalent (Dimitrantzou *et al.*, 2024; Muffato Reis *et al.*, 2025), reporting often remains at a level that, while strategically informative, can lack the granular traceability needed to pinpoint specific operational inefficiencies for LSS projects (Banasik and Beruvides, 2012). QCD, through its matrix-based approach, meticulously links observed quality problems (resultant losses) to their underlying root causes (causal losses) and quantifies their total financial impact. This detailed financial articulation, as visualised in the C-Matrix, provides the granular, monetised problem statement that is essential for a compelling project charter. It allows managers to understand precisely where quality-related costs originate and how they propagate through the operational system. This insight is crucial for moving beyond treating symptoms to addressing fundamental process deficiencies, a core principle of the deployment logic pioneered by Yamashina and Kubo (2002) and central to the LSS philosophy.

A crucial insight for managers is to treat the financial outputs of the E-Matrix not as certain forecasts but as robust base-case scenarios. The QCD methodology mandates a sensitivity analysis precisely to combat the risk of false precision. Managers should actively engage with the results of this analysis to understand how project viability (e.g. NPV) changes with variations in key assumptions, such as the initial cost of poor quality or the effectiveness of the proposed solution. This provides a clear view of a project's risk profile, enabling a final portfolio selection that is not only financially attractive but also resilient to real-world uncertainty.

The methodology also inherently fosters the cross-functional collaboration that is a hallmark of successful LSS deployments. The construction of the A-Matrix (mapping losses) and B-Matrix (identifying causes) requires structured input from diverse functional areas, such as operations, service delivery, IT, quality and customer-facing teams (Sharma *et al.*, 2007). This collaborative process, often facilitated by a Black Belt or Green Belt, breaks down functional silos and promotes a common language around quality problems and their financial consequences. When quality costs are no longer seen as merely a “QA problem” but as a shared organisational challenge with clear financial implications for everyone, buy-in for LSS initiatives increases significantly. This shared understanding and collective ownership, built during the QCD analysis, are vital for the successful implementation and sustainability of any QI program (Jayamaha *et al.*, 2014).

Managers should also recognise the B-Matrix as a powerful, yet focused, analytical tool. Its strength lies in its ability to create a clear and actionable map of primary causal relationships, which is essential for guiding targeted LSS projects. However, its two-dimensional structure deliberately simplifies complex systemic interactions. Experienced managers and LSS leaders should therefore use the B-Matrix to identify and prioritise the most significant, direct causal chains while remaining mindful that secondary, non-linear effects or feedback loops may also be at play. The B-Matrix provides the starting point for intervention, not the final word on the system’s entire dynamic behaviour.

Beyond fostering collaboration, a key managerial insight is that QCD acts as an integrator, amplifying the value of existing management systems. For organisations with mature ABC systems, QCD provides a strategic deployment mechanism for the data generated. The granular activity-level cost data from ABC can be directly channelled into the C-Matrix, replacing estimates with precise financials and significantly enhancing the credibility of the project selection process (Hadid, 2019; Ihrig *et al.*, 2017). Similarly, QCD complements Target Costing; while the latter is a design-phase tool for setting cost targets, QCD provides the operational-phase framework to manage and reduce the inevitable “cost drift” that occurs post-launch, ensuring strategic profitability goals are maintained.

In addition, the QCD methodology provides a structured and repeatable approach for continuous improvement that complements the DMAIC cycle. Unlike specific problem-solving, QCD offers a systematic, step-by-step procedure that can be applied consistently across different operational areas and over successive improvement cycles (Thomas *et al.*, 2008). This repeatability ensures that the organisation builds a cumulative knowledge base on QI and can continuously refine its processes. The clear documentation within each matrix (A through E) also creates a detailed and auditable trail. This documentation is invaluable for LSS program management, allowing leaders to track progress, measure the financial effectiveness of implemented solutions post-project, and demonstrate the tangible return on investment of their QI efforts. This is particularly valuable in organisations aiming for certifications like ISO 9001 or pursuing broad operational excellence models.

Finally, by focusing on causal losses, QCD encourages the proactive, preventative approach to quality management that is at the heart of both Lean and Six Sigma. Instead of constantly firefighting the symptoms of poor quality (e.g. high scrap rates, service rework, customer complaints), managers can use QCD to identify, financially quantify and eliminate the root causes of these problems at their point of origin (Delisle and Freiberg, 2014). This strategic shift towards proactive prevention not only reduces internal and external failure costs but also minimises appraisal costs over the long term, leading to a more efficient and resilient operational system. The methodology’s emphasis on linking operational data to financial outcomes provides the concrete business case needed to justify investments in preventive actions – such as process redesign or Poka-Yoke solutions – which might otherwise be difficult to approve based on short-term cost considerations alone.

6. Conclusions, limitations and research perspectives

This paper has introduced QCD as a structured, matrix-driven methodology designed to enhance the LSS toolkit by systematically identifying, quantifying and reducing the total

CoQ. The five-step process, facilitated by the A through E matrices, guides organisations from a qualitative mapping of quality losses to the strategic selection of financially justified improvement projects targeting root causal losses. The primary contribution of QCD lies in its ability to bridge the critical gap between strategic-level CoQ analysis and the systematic, on-the-ground deployment of targeted LSS initiatives. It provides a transparent, data-driven and financially-oriented framework to strengthen the “Define” phase of DMAIC and to help LSS leaders make informed decisions on resource allocation to maximise the impact of their continuous improvement program.

Despite its contributions, this study has several limitations that provide fertile ground for future research. Firstly, the validation of the methodology is based on a single case study, which limits generalisability. Secondly, the methodology, particularly in the A-Matrix, relies on a consensus-based qualitative assessment that is inherently vulnerable to cognitive and social biases. These can include group-think, availability bias (where recent events are over-weighted) and political influence from dominant team members. Although the subsequent C-Matrix introduces a quantitative verification step, the analysis remains initially shaped by qualitative judgments, which can affect methodological robustness. Thirdly, the theoretical foundations of the study could be further reinforced. While QCD has been positioned relative to ABC and Target Costing, the project selection mechanism in the E-Matrix continues to use a traditional capital budgeting approach (NPV/PI). This approach does not formally account for the valuation of managerial flexibility under uncertainty – a central principle of more advanced financial valuation frameworks such as Real Options Analysis (ROA) (Ito *et al.*, 2024; Hernandez-Perdomo *et al.*, 2017). Moreover, although the methodology includes a qualitative assessment of project interdependencies, potential synergies and redundancies are not formally quantified within the financial model. Finally, the B-Matrix’s two-dimensional structure simplifies causal relationships and does not fully capture the non-linear, systemic interdependencies and feedback loops commonly observed in complex quality failures.

These limitations highlight several promising directions for future research. Multi-case studies across diverse industries are needed to strengthen the generalisability of findings. To enhance the reliability of the A-Matrix, future research could incorporate more structured expert elicitation methods – such as the Delphi method or the Nominal Group Technique – to reduce social and cognitive biases. Another potential improvement involves developing a hybrid A-Matrix process, where preliminary quantitative data are used to pre-weight critical areas before the qualitative team assessment.

Moreover, enriching the E-Matrix through the integration of ROA principles would enable the valuation of managerial flexibility in QI projects, offering a more dynamic and uncertainty-aware approach to project selection (Zare and Miller-Hooks, 2025). Future studies could also investigate embedding portfolio optimisation algorithms within the E-Matrix to formally model and optimise project interdependencies, moving beyond qualitative adjustments. In addition, to address the simplified treatment of causality, future work could explore integrating the QCD methodology with SD modelling – using QCD to identify and quantify primary losses, and SD to simulate feedback loops and long-term systemic behaviours.

To enhance methodological rigour and mitigate subjectivity, a further significant research opportunity lies in integrating advanced data analytics and Industry 4.0 technologies within the QCD methodology. Research into how Machine Learning algorithms, SPC data and predictive analytics can be embedded to validate causal links in the B-Matrix and support data-driven pre-screening in the D-Matrix could significantly augment the power of this LSS tool (Psarommatis *et al.*, 2022; Köksal *et al.*, 2011).

Furthermore, extending the methodology to incorporate broader sustainability considerations presents a pertinent future direction. This reflects the growing imperative for operational excellence frameworks to address environmental and social performance. Such an enhancement would involve explicitly integrating environmental costs (e.g. waste disposal, energy consumption associated with rework) and social costs (e.g. impact of product failures on customer safety) within the C-Matrix quantification. This would align the QCD methodology more closely with holistic, sustainable operational paradigms. Finally, a parallel research avenue could support wider adoption by practitioners through the development of specialised software tools to automate data collation, matrix construction and financial calculations, thereby lowering the barrier to implementation.

References

Abdelbar, K.M., Bouami, D. and Elfezazi, S. (2019), "New approach towards formulation of the overall equipment effectiveness", *Journal of Quality in Maintenance Engineering*, Vol. 25 No. 1, pp. 90-127.

Abisourour, J., Hachkar, M., Mounir, B. and Farchi, A. (2019), "Methodology for integrated management system improvement: combining costs deployment and value stream mapping", *International Journal of Production Research*, Vol. 58 No. 12, pp. 3667-3685.

Alglawe, A., Kuzgunkaya, O. and Schiffauerova, A. (2020), "Managing quality decisions in supply chain", *International Journal of Quality and Reliability Management*, Vol. 37 No. 1, pp. 34-52.

Alsadi, J., Alkhatib, F., Antony, J., Garza-Reyes, J.A., Tortorella, G. and Cudney, E.A. (2025), "A systematic literature review with bibliometric analysis of quality 4.0", *The TQM Journal*, Vol. 37 No. 5, pp. 1446-1470.

Bahria, N., Chelbi, A., Bouchriha, H. and Dridi, I.H. (2019), "Integrated production, statistical process control, and maintenance policy for unreliable manufacturing systems", *International Journal of Production Research*, Vol. 57 No. 8, pp. 2548-2570.

Banasik, M.A. and Beruvides, M.G. (2012), "A case study of the costs of quality: water utilities", "EMJ ", *Engineering Management Journal*, Vol. 24 No. 2, pp. 3-14.

Barakat, O. and Elassimi, T. (2025), "Unveiling the link between quality management maturity and cost of quality management in the moroccan agrifood sector: a qualitative study", *International Journal of Quality and Reliability Management, Article in Press*, Vol. 43 No. 1, doi: 10.1108/IJQRM-02-2025-0057.

Bertolini, M., Braglia, M., Marrazzini, L. and Neroni, M. (2022), "Project time deployment: a new lean tool for losses analysis in engineer-to-order production environments", *International Journal of Production Research*, Vol. 60 No. 10, pp. 3129-3146.

Bertolini, M., Leali, F., Mezzogori, D. and Di Paco, F. (2024), "A new lean tool for design management: design cost deployment", *Journal of Engineering Design*, Vol. 35 No. 2, pp. 217-240.

Braglia, M., Castellano, D., Gabbrielli, R. and Marrazzini, L. (2020), "Energy cost deployment (ECD): a novel lean approach to tackling energy losses", *Journal of Cleaner Production*, Vol. 246, p. 119056.

Carmignani, G. (2017), "Scrap value stream mapping (S-VSM): a new approach to improve the supply scrap management process", *International Journal of Production Research*, Vol. 55 No. 12, pp. 3559-3576.

Chiarini, A. and Vagnoni, E. (2015), "World-class manufacturing by fiat. Comparison with toyota production system from a strategic management, management accounting, operations management and performance measurement dimension", *International Journal of Production Research*, Vol. 53 No. 2, pp. 590-606.

Dadashnejad, A.-A. and Valmohammadi, C. (2018), "Investigating the effect of value stream mapping on operational losses: a case study", *Journal of Engineering, Design and Technology*, Vol. 16 No. 3, pp. 478-500.

Dadfar, H. and Brege, S. (2012), “Differentiation by improving quality of services at the last touch point: the case of Tehran pharmacies”, *International Journal of Quality and Service Sciences*, Vol. 4 No. 4, pp. 345-363.

De Ruyter, A.S., Cardew-Hall, M.J. and Hodgson, P.D. (2002), “Estimating quality costs in an automotive stamping plant through the use of simulation”, *International Journal of Production Research*, Vol. 40 No. 15, pp. 3835-3848.

Delisle, D.R. and Freiberg, V. (2014), “Everything is 5S: a simple yet powerful lean improvement approach applied in a preadmission testing center”, *Quality Management Journal*, Vol. 21 No. 4, pp. 10-22.

Dimitrantzou, C., Psomas, E. and Vouzas, F. (2020), “Future research avenues of cost of quality: a systematic literature review”, *The TQM Journal*, Vol. 32 No. 6, pp. 1599-1622.

Dimitrantzou, C., Psomas, E. and Vouzas, F. (2024), “The influence of competitive strategy and organizational structure on the cost of quality in food and beverage (F&B) companies”, *The TQM Journal*, Vol. 36 No. 8, pp. 2398-2417.

El Korany, T., Elbeltagi, E., Etman, E., Gaber, M. and Sanad, H. (2025), “Developing a comprehensive quality index for infrastructure projects”, *International Journal of Quality and Reliability Management*, Vol. 42 No. 10, doi: 10.1108/IJQRM-10-2023-0323.

Glogovac, M. and Filipovic, J. (2018), “Quality costs in practice and an analysis of the factors affecting quality cost management”, *Total Quality Management and Business Excellence*, Vol. 29 Nos 13-14, pp. 1521-1544.

Habidin, N.F., Salleh, M.I., Md Latip, N.-A., Azman, M.-N.-A. and Mohd Fuzi, N. (2016), “Lean six sigma performance improvement tool for automotive suppliers”, *Journal of Industrial and Production Engineering*, Vol. 33 No. 4, pp. 215-235.

Hadid, W. (2019), “Lean service, business strategy and ABC and their impact on firm performance”, *Production Planning and Control*, Vol. 30 No. 14, pp. 1203-1217.

Hernandez-Perdomo, E.A., Mun, J. and Rocco S, C.M. (2017), “Active management in state-owned energy companies: integrating a real options approach into multicriteria analysis to make companies sustainable”, *Applied Energy*, Vol. 195, pp. 487-502.

Ihrig, S., Ishizaka, A. and Mohnen, A. (2017), “Target setting for indirect processes: a new hybrid method for the continuous improvement management of indirect processes”, *Production Planning and Control*, Vol. 28 No. 3, pp. 220-231.

Ito, K., Tanaka, M. and Takashima, R. (2024), “Strategic investment in power generation and transmission under a feed-in premium scheme: a game theoretic real options analysis”, *Annals of Operations Research*, Vol. 343 No. 1, pp. 349-372.

Jayamaha, N.P., Wagner, J.P., Grigg, N.P., Campbell-Allen, N.M. and Harvie, W. (2014), “Testing a theoretical model underlying the ’Toyota Way’ - An empirical study involving a large global sample of toyota facilities”, *International Journal of Production Research*, Vol. 52 No. 14, pp. 4332-4350.

Khataie, A.H. and Bulgak, A.A. (2013), “A cost of quality decision support model for lean manufacturing: activity-based costing application”, *International Journal of Quality and Reliability Management*, Vol. 30 No. 7, pp. 751-764.

Khesal, T., Saghaei, A., Khalilzadeh, M., Rahiminezhad Galankashi, M. and Soltani, R. (2019), “Integrated cost, quality, risk and schedule control through earned value management (EVM)”, *Journal of Engineering, Design and Technology*, Vol. 17 No. 1, pp. 183-203.

Köksal, G., Batmaz, I. and Testik, M.C. (2011), “A review of data mining applications for quality improvement in manufacturing industry”, *Expert Systems with Applications*, Vol. 38 No. 10, pp. 13448-13467.

Kumar, P., Maiti, J. and Gunasekaran, A. (2018), “Impact of quality management systems on firm performance”, *International Journal of Quality and Reliability Management*, Vol. 35 No. 5, pp. 1034-1059.

Maskell, B.H., Baggaley, B., and Grasso, L. (2011), *Practical Lean Accounting: A Proven System for Measuring and Managing the Lean Enterprise*, 2nd ed. Productivity Press, Boca Raton, FL.

Montgomery, D.C. (2013), *Introduction to Statistical Quality Control*, 7th ed. John Wiley and Sons, Hoboken, NJ.

Muffato Reis, A., Verna, E., Costa, L., Sousa, S.D. and Galetto, M. (2025), "A scenario-based framework for strategic inspection decision-making in high-volume production environments", *International Journal of Quality and Reliability Management*, Vol. 42 No. 6, pp. 1822-1850.

Psarommatis, F. and Azamfirei, V. (2024), "Zero defect manufacturing: a complete guide for advanced and sustainable quality management", *Journal of Manufacturing Systems*, Vol. 77, pp. 764-779.

Psarommatis, F., Fraile, F. and Ameri, F. (2023), "Zero defect manufacturing ontology: a preliminary version based on standardized terms", *Computers in Industry*, Vol. 145, p. 103832.

Psarommatis, F., Sousa, J., Mendonça, J.P. and Kiritsis, D. (2022), "Zero-defect manufacturing the approach for higher manufacturing sustainability in the era of industry 4.0: a position paper", *International Journal of Production Research*, Vol. 60 No. 1, pp. 73-91.

Rodin, W.A. and Beruvides, M.G. (2012), "A cost of quality economic analysis of a six sigma program at a government contractor", "EMJ ", *Engineering Management Journal*, Vol. 24 No. 2, pp. 30-39.

Roh, H.Y., Ali, S., Song, H. and Shin, W.S. (2022), "Designing a quality scorecard (QSC) for system integration in the era of industry 4.0", *International Journal of Quality and Service Sciences*, Vol. 14 No. 2, pp. 157-179.

Roth, N., Deuse, J. and Biedermann, H. (2020), "A framework for system excellence assessment of production systems, based on lean thinking, business excellence, and factory physics", *International Journal of Production Research*, Vol. 58 No. 4, pp. 1074-1091.

Sedevich-Fons, L. (2023), "Quality and costs in health care: using target costing in support of bundled payment programs", *The TQM Journal*, Vol. 35 No. 6, pp. 1490-1513.

Sharma, R.K., Kumar, D. and Kumar, P. (2007), "Quality costing in process industries through QCAS: a practical case", *International Journal of Production Research*, Vol. 45 No. 15, pp. 3381-3403.

Thomas, A., Barton, R. and Byard, P. (2008), "Developing a six sigma maintenance model", *Journal of Quality in Maintenance Engineering*, Vol. 14 No. 3, pp. 262-271.

Vetchagool, W., Augustyn, M.M. and Tayles, M. (2021), "ISO 9000, activity based costing and organizational performance", *Total Quality Management and Business Excellence*, Vol. 32 Nos 3-4, pp. 265-288.

Wang, K., Yin, Y., Du, S. and Xi, L. (2021), "Variation management of key control characteristics in multistage machining processes considering quality cost equilibrium", *Journal of Manufacturing Systems*, Vol. 59, pp. 441-452.

Wang, Y., Liu, J., Zhou, L., Cong, L. and Sutherland, J.W. (2024), "Integrated operation planning and process adjustment for optimum cost with attention to manufacturing quality and waste", *Journal of Manufacturing Systems*, Vol. 73, pp. 241-255.

Yadav, O.P., Nepal, B.P., Rahaman, M.M. and Lal, V. (2017), "Lean implementation and organizational transformation: a literature review", "EMJ ", *Engineering Management Journal*, Vol. 29 No. 1, pp. 2-16.

Yamashina, H. and Kubo, T. (2002), "Manufacturing cost deployment", *International Journal of Production Research*, Vol. 40 No. 16, pp. 4077-4091.

Zahraee, S.M. (2016), "A survey on lean manufacturing implementation in a selected manufacturing industry in Iran", *International Journal of Lean Six Sigma*, Vol. 7 No. 2, pp. 136-148.

Zare, A. and Miller-Hooks, E. (2025), "A risk analysis approach to transportation infrastructure climate protection investment", *Transportation Research Part D: Transport and Environment*, Vol. 148, p. 104931.

Zhang, C., Li, X., Xu, H., Li, Z. and Zhao, X. (2025), “Does blockchain-enabled quality inspection work better in hybrid retailing?”, *Computers and Industrial Engineering*, Vol. 204, p. 111092.

Further reading

Abdul-Kader, W., Ganjavi, O. and Solaiman, A. (2010), “An integrated model for optimisation of production and quality costs”, *International Journal of Production Research*, Vol. 48 No. 24, pp. 7357-7370.

Ali, S.M., Hossen, M.A., Mahtab, Z., Kabir, G., Paul, S.K. and Adnan, Z.U.H. (2020), “Barriers to lean six sigma implementation in the supply chain: an ISM model”, *Computers and Industrial Engineering*, Vol. 149, p. 106843.

Castillo-Villar, K.K., Smith, N.R. and Simontoncy, J.L. (2012), “The impact of the cost of quality on serial supply-chain network design”, *International Journal of Production Research*, Vol. 50 No. 19, pp. 5544-5566.

Noshad, K. and Awasthi, A. (2015), “Supplier quality development: a review of literature and industry practices”, *International Journal of Production Research*, Vol. 53 No. 2, pp. 466-487.

Shin, W.S., Dahlgaard, J.J., Dahlgaard-Park, S.M. and Kim, M.G. (2018), “A quality scorecard for the era of industry 4.0”, *Total Quality Management and Business Excellence*, Vol. 29, Nos 9-10, pp. 959-976.

Supplementary material

The supplementary material for this article can be found online.

Corresponding author

Davide Castellano can be contacted at: davide.castellano@unimore.it