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Establishing a conceptual framework for Construction Quality 4.0 (CONQ4.0)

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Abstract

Purpose – The construction industry continues to face persistent quality challenges despite advancements in quality management (QM) and the integration of modern-day technologies. This study aims to explore the concept of Quality 4.0 in the construction sector and proposes a conceptual framework that considers the industry's unique characteristics.

Design/methodology/approach – This research is based on a literature review of Quality 4.0, Industry 4.0 (I4.0) and QM in construction. A targeted review of existing frameworks with a focus on their technology, processes and people leads to the development of a conceptual framework for Construction Quality 4.0 (CONQ4.0).

Findings – The study finds that while I4.0 technologies have been increasingly applied to QM as well as the increasing popularity of Quality 4.0, a comprehensive framework for Quality 4.0 in construction is lacking. The proposed CONQ4.0 framework builds on the established QM practices (i.e quality control, quality assurance and total quality management) and integrates three key dimensions: technology, process and people. It is also supported by critical enablers such as data management, lean principles and capability development.

Practical implications – The framework provides a foundation for construction firms to enhance QM through digitalisation, process optimisation and workforce capability development. It also highlights the importance of subcontractors' engagement and stakeholder alignment to ensure consistent quality practices across projects.

Originality/value – By contextualising Quality 4.0 within construction, this study offers a structured framework that balances technological innovation with human and process-centric considerations. The findings provide valuable insights for construction professionals and researchers aiming to enhance quality performance in the I4.0 era.

Keywords Construction, Quality 4.0, Framework, Industry 4.0, Lean construction

Paper type Conceptual paper

1. Introduction

Quality is important to human livelihood and the nation's development, and humanity's pursuit of quality remains constant. Especially in construction, quality products are of utmost important. Despite the research development in quality management (QM), widespread International Organization for Standardization (ISO) 9001 adoption among construction firms and more recently the advancements in the modern-day technologies, which are gradually introduced in construction, the construction industry's quality performance remains concerning. The poor-quality issues are often made into the news headlines. For example, recent research by the Australian Housing and Urban Research Institute (Lekan *et al.*, 2022) has found that approximately 70% of households report experiencing building quality issues. This highlights that quality issues are a persistent challenge within the construction industry and eliminating them entirely is close to impossible. The cost impact is significant, and GIRI (2025) reminds us that the direct cost of avoidable error is about 5% of project value; however, if unmeasured and indirect costs are taken into account, the estimate is closer to 10–25% of project cost, or up to £25 billion each year in the UK.

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From the QM research perspective, Koskela *et al*. (2019) pointed out that the decline of the quality movement is visible. This is echoed by Zonnenshain and Kenett (2020), who also noted, in the last few years, the quality discipline went into stagnation – very few innovative models for quality are being proposed, and the interest in quality engineering has dropped since 2004 by 70% in Google searches. Moreover, Asif (2020) highlighted misalignments between traditional QM and technology development, including (1) the QM model lacks the ability to define and manage quality for fluid and impermanent customer requirements, (2) traditional QM models make management systems bulky and (3) the management of operations of a networked firm is different from the supplier management required in traditional QM models. The quality professionals also seem to agree with this, as is evident in a survey (Mann, 2018) by the Chartered Institute of Building, which revealed that over 75% of construction professionals believe the industry's current management of quality is inadequate.

On the bright side, with advancements in technology, many researchers are inspired to explore the potential of integrating Industry 4.0 (I4.0) technologies into QM to drive innovation in quality practices. However, much of this exploration has occurred outside the construction sector. This study seeks to address this gap by examining the concept of Quality 4.0 within the context of the construction industry and attempting to establish a framework for Construction Quality 4.0 (CONQ4.0). In achieving that, there are a few significances to be expected: First, as Zonnenshain and Kenett (2020) wrote, the Fourth Industrial Revolution is an opportunity for the quality movement to generate some new ideas after years of stagnation, and this is applicable in the construction industry. Secondly, it was concluded that most studies on Quality 4.0 have focused on the manufacturing sector (Saihi *et al*., 2023) and logistics and supply chain (Chiarini and Kumar, 2022) and overlooked other industries. Emblemsvåg (2020) provided insights into Quality 4.0 in the project-based industry and call more stakeholders working with QM to focus more on project-based industries in the future. Lastly, although I4.0 has been adopted in construction, a framework for CONQ4.0 is lacking. More broadly, a general Quality 4.0 implementation framework is also missing (Kushwaha and Talib, 2025), highlighting the need for an industry-specific framework. With these aforementioned questions and opportunities, this study aims to address:

(1) What is Quality 4.0 in construction?

(2) What does a Quality 4.0 framework for construction look like?

We foresee several key contributions from this study. First, it establishes a construction-specific framework for Quality 4.0. Academically, this work contributes to the growing body of knowledge on Quality 4.0 by contextualising its principles within the construction industry. The framework's core people-process-technology dimensions align with sociotechnical systems thinking, which emphasises that meaningful performance improvement arises from the balanced adoption of social and technical subsystems, rather than from technological advancement alone. Practically, the framework identifies core elements that construction professionals should consider when planning or implementing Quality 4.0 practices. These insights offer actionable guidance for improving QM through digitalisation and innovation, ultimately supporting industry-wide advancement in quality performance.

2. Methods

This study aims to present a conceptual framework of Quality 4.0 for the construction industry. The primary method is based on literature review. Figure 1 outlines the methodology. Despite Quality 4.0 being an emerging topic, there have been several review papers undertaken. To begin with, we conducted a keyword search using the terms "Quality 4.0" and "review" in the Scopus database, limiting the subject areas to "engineering" and "business and management". Additional filters were applied to restrict the document type to "articles" and "review papers", the source type to "journals" and the language to "English". Despite these criteria, the search

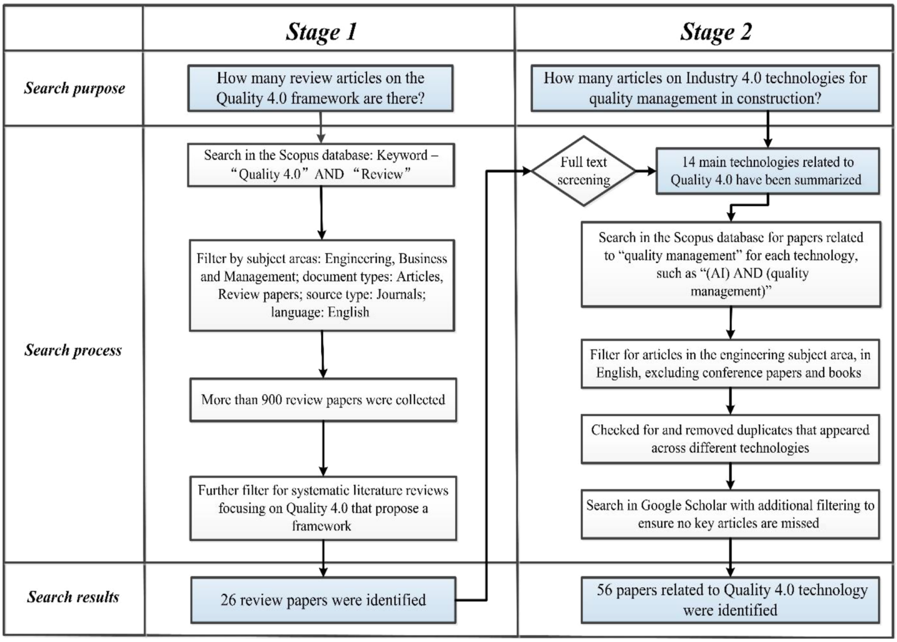

Figure 1. Methodological framework

still returned over 900 papers, the majority of which were found to be irrelevant to the specific scope of this study. After further filtering based on the nature of study – specifically those that adopted a systematic literature review (SLR) focus on Quality 4.0 and ideally proposed a framework as an outcome – we identified 26 review papers. We focus on review papers for two reasons: first, the review studies have already synthesised relevant research by themes and topics, offering useful insights, and secondly, while some systematic reviews, such as Alsadi *et al*. (2024) excluded review papers, we argue that these studies are valuable and should be included. These research outputs are valuable in providing definitions, conceptual frameworks and associated elements (see Table 1). It is interesting to note that several studies also provided background on the evolution of Quality 4.0, which prompts reflection on the progression from Quality 1.0 to Quality 3.0 in the construction context (see Section 4.2).

Considering the central role of technology in Quality 4.0 discussions, a similar approach was adopted to review the application of I4.0 technology in QM in the construction industry. In total, 14 main technologies related to Construction 4.0 were identified, including artificial intelligence (AI), the Internet of Things (IoT), building information modelling (BIM), digital twins, blockchain, cloud computing, augmented reality (AR), virtual reality (VR), cyber-physical systems (CPS), robotic systems, drones and aerial photography, computer vision, big data and 3D printing. Subsequently, literature related to "quality management" for each technology was searched, such as "(AI) AND (QM)". We filtered the results to only include articles, excluding conference papers and books. We also limited the subject area to engineering and the language to English. Next, we checked for and removed duplicates that appeared across different technologies. Finally, to ensure no key papers were missed, we supplemented our search with additional filtering in Google Scholar. The literature spanned from 2004 to 2025. This comprehensive approach yielded a final collection of 56 articles.

Table 1. A review of existing review papers on Quality 4.0

No	Authors	Period of study	No. of papers reviewed	Key focus	Technology related	Process related	People related	Framework development?
1	Sony *et al.* (2020)	Not specified	Not mentioned	Ingredients for the Quality 4.0 implementation	Handling big data prescriptive analytics algorithms	Quality of design, quality of conformance and quality control. Vertical, horizontal and end-to-end integration	Leadership for quality Training for quality Organisational culture Top management for quality	No
2	Dias *et al.* (2022)	2011–2021	203	Implications of technology for quality	Cybernetics (digitisation and automation) Connectivity and integration Data management Simulation and extended reality	Quality Management systems	Skill and competencies Training and education Supportive organisational culture	Yes Technology, QMS and people
3	Baran and Korkusuz Polat (2022)	Not specified	226	Relationship between Industry 4.0 and quality	IoT, cloud computing, AI, big data and 3D printing were the preferred Industry 4.0 technologies	Not discussed	Quality of people	No
4	Kumar *et al.* (2022)	Not specified	not mentioned	Address the knowledge gap and propose a framework	Physical layer Connectivity layer Digital layer	Vertical integration Horizontal integration End-to-end integration	Technology knowledge worker Non-technology Knowledge worker Support workers	Yes
5	Ho *et al.* (2022)	Not specified	200	Augmented reality-based manufacturing for Quality Control 4.0	Hardware and software of AR	Maintenance and assembly	Not mentioned	No

(*continued*)

Table 1. Continued

No	Authors	Period of study	No. of papers reviewed	Key focus	Technology related	Process related	People related	Framework development?
6	Powell *et al.* (2022)	2011–2021	216	Contemporary advances in Zero Defect Manufacturing	Eight technologies, from AI to Extended Reality (XR)	Manufacturing processes (e.g., process monitoring, process control, process parameters, etc.)	Vastly overlooked	No
7	Ali and Johl (2022)	1987–2019	87	Total quality management (TQM) and its connection with industry 4.0	Quality big data analysis	Process management CI Product/service design	Leadership/Top management commitment training/learning	Yes (hard and soft dimensions)
8	Souza *et al.* (2022)	1998–2020	72	New concept of TQM 4.0 as a way of adapting QM in I4.0	Technology and quality Technology and people	I4.0 and QC I4.0 and TQM	How to prepare new professionals in quality to obtain the necessary skills	Yes
9	Sader *et al.* (2022)	2015–2019	13	Quality 4.0 features, technologies and applications.	Quality 4.0 technologies	Not discussed	Human-related challenges	No
10	Broday (2022)	1993–2021	104	Main characteristics of the studies on the subject of Quality 4.0	Not discussed	Not discussed	Not discussed	No
11	Nguyen *et al.* (2023)	1998–2023	126	Quality management within circular supply chains, placing a significant emphasis on Industry 4.0 (I4.0) technologies	13 enabling technologies	Supply Chain Quality Management 4.0 process	Top management support, HR and organisational skills, coordination, Culture, leadership	Yes

(*continued*)

Table 1. Continued

No	Authors	Period of study	No. of papers reviewed	Key focus	Technology related	Process related	People related	Framework development?
12	Prashar (2023)	2010–2021	51	Research possibilities for QM in the I4.0 environment	Enabling technologies	Core production and operation function support operation QM activities	Organisational and managerial competencies	No
13	Markatos and Mousavi (2023)	Not specified	37	Benefits and drawbacks of popular quality prediction models in the I4.0 era	Not discussed	Not discussed	Not discussed	No
14	Saihi *et al.* (2023)	2016–2020	52	Industry 4.0 impact on improving quality management aspects and how technology can be leveraged to enhance its practices	13 I4.0 technologies reviewed	Focused on the quality control (QC) and inspection, quality assurance (QA), quality planning (QP), predictive quality, continuous improvement (CI) and supply chain quality management (SCQM)	Not discussed	No
15	Tewary and Jadon (2024)	1985–2022	90	Training for Quality 4.0	Not discussed	Not discussed	A number of people related barriers discussed	No
16	Alsadi *et al.* (2024)	2010–2023	*45	State of research on Quality 4.0 across various sectors	Six primary Industry 4.0 technologies (machine learning, deep learning, AI and supporting technologies)	Not discussed	Not discussed	No

(*continued*)

Table 1. Continued

No	Authors	Period of study	No. of papers reviewed	Key focus	Technology related	Process related	People related	Framework development?
17	El Jaouhari *et al.* (2024)	No time limit applied	182	Metaverse-based quality 4.0 in achieving manufacturing resilience	9 industry 4.0 technologies (i.e. AI, big data analytics, AR/VR)	Not discussed	Not discussed	Yes Quality 4.0 for manufacturing resilience
18	Kushwaha and Talib (2025)	2011–2023	99	Quality 4.0 current knowledge, emerging areas, and trends	16 industry 4.0 technologies	Not discussed	Not discussed	No
19	Mahin *et al.* (2024)	2015–2023	62	The benefits, challenges and critical success factors of Q4.0 implementation	Not mentioned	Critical success factors are people related	Not discussed	Yes
20	Chiarini (2020)	No time limit applied	75	Relationship between Industry 4.0, quality management and TQM	Cyber-physical systems and ERP for QA and QC	Creating value through quality data Customer value co-creation	Q4.0 skills and culture for quality people	No
21	Caiazzo *et al.* (2022)	2018–2020	109	state-of-the-art about Zero Defect manufacturing (ZDM) strategies	Digital twins, CNN, fuzzy, Failure Mode & Effects Analysis (FMEA), etc.	Detection, repair, prediction and prevention	Not discussed	No
22	Thekkoote (2022)	No time limit applied	28	factors that contribute to the successful implementation of Q4.0	Data, analytics and connectivity	Development of application, scalability and compliance	Collaboration, organisation culture, leadership and training for Q4.0	No
23	Sureshchandar (2022)	No time limit applied	27	dimensions contribute to Quality 4.0	New-age technological tools	Quality management system, compliance and data governance	Strategic leadership, competence, culture, etc.	The 12 axes of Quality 4.0

(*continued*)

Table 1. Continued

No	Authors	Period of study	No. of papers reviewed	Key focus	Technology related	Process related	People related	Framework development?
24	Oliveira *et al.* (2025)		146	General features of Q4.0 and skill requirement of quality professionals	New technologies, information technologies, AI and predictive software. Automated document control	Digital QMS, and combination of quality tools and lean methods	Knowledge and skills	Yes
25	Komkowski *et al.* (2023)	2015–2021	37	The integration of QM and Industry 4.0	General Industry 4.0 technologies	Focus on integration with QM methods	Soft elements are underrepresented	No
26	Sarker and Dunston (2025)	2018–2023	57	Approaches and challenges of the Quality 4.0 implementation and root causes of unsuccessful implementation	Data analytics, cyber-physical systems, digital twins, AR/VR, etc.	Build up a new management system and a new production system, making new frameworks and automating the process	Training, motivation, technical support and build up team	Yes

Note(s): *Review paper excluded

3. Quality 4.0: concepts and frameworks

The concept of I4.0 has gained prominence since 2011, giving rise to related terms such as Construction 4.0 (Sawhney *et al*., 2020), Lean Construction 4.0 (González *et al*., 2022), Quality 4.0 (Sader *et al*., 2022) and many others. These new terms showed that the use of I4.0 has penetrated many industries and disciplines. In the QM discipline, several review papers have explored Quality 4.0 in a general context (Prashar, 2023; Sader *et al*., 2022). This section provides an overview of Quality 4.0 before focusing on construction.

Attempts were made to coin the term “Quality 4.0”, but it is certainly not an easy task to find just one definition of what Quality 4.0 is (Broday, 2022). In a Boston Consulting Group report, Küpper *et al*. (2019) simply defined it as “the application of I4.0’s advanced digital technologies to enhance traditional best practices in QM”. Sader *et al*. (2022) defined Quality 4.0 as an extended approach to QM, integrating advanced technologies with traditional practices like quality control (QC), quality assurance (QA) and total quality management (TQM). Similarly, Antony *et al*. (2022) proposed a working definition: “*the use of technologies such as [. . .] through quality planning (QP), QA, QC and quality improvement to achieve new optimums in performance, operational excellence and innovation to meet the vision, mission and goals of an organisation”*. Not surprisingly, these definitions are predominately technology-focused with little acknowledgement of people. As Broday (2022) highlighted the definition seems to suggest digitalisation is the natural path that quality will follow, not replacing the traditional methods but improving them. A recent definition of Q4.0 from Chiarini and Kumar (2022) is of particular interest, as it highlights three key themes, namely people, process and technology, as central to its conceptualisation.

Apart from coining the term Quality 4.0, other similar terms such as TQM 4.0 (Souza *et al*., 2022; Nguyen *et al*., 2023) were also used. Interestingly, Souza *et al*. (2022) described TQM 4.0 as a term that represents a technological update of the way to manage quality, driven by I4.0, aiming at the total quality of an operation’s processes, products and people. In fact, these definitions do not differ much from Quality 4.0. Further, Souza *et al*. (2022) integrate I4.0, TQM and QC into a so-called TQM 4.0 ecosystem. In view of this, it seems to infer that Quality 4.0 and QM4.0 may refer to the same thing and hence can be used interchangeably. Asif (2020) did not use the term QM4.0, but the author argued that the traditional QM models are not aligned with I4.0 due to a few misalignments.

The previous literature-review-styled studies did clarify many aspects around Quality 4.0, such as benefits (Antony *et al*., 2022), impacts (Kushwaha and Talib, 2025), challenges (Zonnenshain and Kenett, 2020) and many others. However, Prashar (2023) pointed out that these studies failed to conceptualise an implementation framework. This study attempts to explore if any frameworks for Quality 4.0 were proposed. We particularly focus on three areas – technology, process and people. This is because our review highlights their strong presence in Quality 4.0 discussions while also recognising that Quality 4.0 extends beyond just technology. Kushwaha and Talib (2025) did provide a summary of the review papers of Quality 4.0 studies but only outlined what their focus and type of review were, without detailing their emphasis on technology, process or people. In view of this gap, Table 1 summarises existing literature review studies on Quality 4.0 based on 26 review papers on this topic.

We concur with Prashar’s observation that many studies did not land in a framework. Among the 26 review papers analysed in this study, only 10 proposed a conceptual framework, accounting for less than half of the total. This is “surprising” given many of these papers claimed to adopt an SLR approach, which typically aims to synthesise review findings into frameworks. Nonetheless, there are a few exceptions. For example, Zonnenshain and Kenett (2020) presented a framework of Quality 4.0 for a quality discipline supporting the Fourth Industrial Revolution. Kumar *et al*. (2022) was one of the few to contribute to the field by constructing a conceptual framework that highlights key aspects of Quality 4.0 across three dimensions: people, process and technology, along with their sub-dimensions. Dias *et al*. (2022) did not propose a framework but noted that besides quality itself, the three dimensions become evident in the literature on Quality 4.0: people, technology and management system. Dias *et al*. (2022) also gave a definition of Quality 4.0, which is based on these three ingredients: Quality 4.0 is the delivery of superior quality, using modern technology to augment the capabilities of both people and quality tools and methods. Sureshchandar (2022) proposed a framework comprising 12 axes of Quality 4.0, offering a multidimensional view of quality transformation in the digital era. Despite such contributions, the majority of existing frameworks are not tailored to construction or other project-based sectors, where industry nature and delivery models differ significantly from manufacturing contexts. Furthermore, there is a consistent under-representation of the "people" dimension, which is a critical component in Quality 4.0 implementation. Additionally, neither of these frameworks is validated – in other words, the practical applicability of these models remains uncertain.

4. Quality 4.0 in construction

4.1 Overview

To our knowledge, there is neither a framework of Quality 4.0 established for construction nor CONQ4.0 discussions. However, recent studies have explored the digital technologies for construction quality (Luo *et al*., 2022; Ghansah and Edwards, 2024), while Emblemsvåg (2020). Emblemsvåg (2020) noted QM in project-based industries is outdated and emphasised the need to recognise the peculiarity of these industries, for which construction is an exemplar case. Although Emblemsvåg (2020) did not provide a specific framework, the combination of Quality 4.0 and new contracting regimes provides interesting perspectives. It is worth reiterating that the construction industry is very different from manufacturing due to (1) the one-of-a-kind nature of projects, (2) site production, (3) temporary multi-organisation and (4) regulatory intervention. Each of these distinct features, particularly the first three, was often not taken into account in general Quality 4.0 research; however, according to Emblemsvåg (2020), these are indeed challenges for QM approaches.

The classic QM is defined as any approach used to achieve and sustain a high-quality output by *conforming* to requirements and meeting customer satisfaction requirements (Sullivan, 2011). This definition is well received in the construction industry, interpreting quality projects as fit for purpose and conforming to the approved requirements (The Victorian Government, 2024). An interesting observation made by Emblemsvåg (2020) is that the construction project quality is given by the contract, and quality towards the customer becomes ensuring that the product *conforms* to the contract. The Code of QM (Flanagan and Jewell, 2019) also acknowledged that standard forms of contract require QM plans to be incorporated within the contract. Inspection and test plans (ITPs) and certification of the compliance of subcontractors "/consultants" plans, and ITPs are also required in contracts. In other words, the contractual arrangements provide the framework of a quality system comparable to those described in quality system standards. Netto *et al*. (1997) have pointed out that standard forms of building contract provide QA through the maintenance of a purchaser's representative (i.e. resident architect/engineer and clerk-of-works) on site to "watch and supervise" the works.

4.2 Quality 1.0 to Quality 3.0 in construction

Before the term Quality 4.0 emerge, little was discussed about Quality 1.0, 2.0 and 3.0. The number here (from 1.0 to 4.0) likely marks key milestones in the evolution of QM. There is a general consensus that there were three industrial revolutions before the advent of I4.0, each driving advancements in QM (see Table 2). The evolution of QM aligns with the quality models through a few milestones (Zonnenshain and Kenett, 2020) and can be roughly labelled as follows:

(1) Production quality (Quality 1.0),

(2) Process quality (Quality 2.0),

Table 2. Quality management development and its milestones

Industry revolution	Phases	Quality X.0	Production strategy	Key characteristics
The first industrial revolution	Quality inspection and quality control	Quality 1.0	Craft/machine production	Using inspection and measurement Specification of parts is set
The second industrial revolution (early 20th century)	Quality control Quality assurance statistical QC (SQC)	Quality 2.0	Mass production	Process-oriented approach Statistical process control Adherence to standards
The third industrial revolution (early 1970)	TQM/design quality/ information quality	Quality 3.0	Lean production	Managerial approach ISO9001 emerged innovation

Source(s): Adapted from Sader *et al.* (2022), ASQ (2024), Zonnenshain and Kenett (2020) and Park *et al.* (2020)

(3) Management quality (Quality 3.0) and now

(4) Design quality and information quality (Quality 4.0).

It is also worth noting that in the Quality 3.0 era the key development includes TQM, design quality, etc. It does not mean that the previous development such as inspection, QC and QA is outdated. These approaches still remain as part of TQM. QC aims to ensure that all products meet the specifications, which were defined to fulfil customers' needs, whereas QA is to ensure that the processes and procedures developed are standardised, documented and maintained at the same level of quality of products at every time (Sader *et al*., 2022). In fact, there is no shortage of writings on QC and/or QA (Thorpe and Sumner, 2017) and TQM (Low and Peh, 1996; Arditi and Gunaydin, 1997) in the construction industry, though much of it dates back to the last century. However, according to Sullivan (2011), three increasingly popular QM programs, namely TQM, Lean production and Six Sigma, were gaining traction in construction. TQM seems to be the most successful one, as much research has documented its successful implementation since the early 1990s. In contrast, Six Sigma as a quantitative approach for improvement received little attention. Han *et al*. (2008) highlighted it is hard to evaluate performance improvement, as the defects are removed in the production process. This seems to suggest that the construction industry lacks sophisticated quality-related data collection. With mixed success, Sullivan (2011) concluded that existing QM programs have not been correctly translated into the construction industry. Meanwhile, the rise of the quality management system (QMS) and ISO 9001 has led many construction firms to seek certification (Low and Teo, 2003). According to the ISO 2023 survey (ISO, 2024), close to 50,000 construction firms globally had been ISO 9001 certified. Brooks *et al*. (2021), however, cautioned that regulatory decoupling between the operation of the companies and their ISO 9001 system is taking place, and disconnection of the QMS to quality "on the ground" is evident.

4.3 The technological advancement

Küpper *et al*. (2019) identified five applications of Quality 4.0, ranging from manufacturing to logistics and sales, with Sader *et al*. (2022) adding decision-making processes as another key area. Strangely, none of these studies mentioned Quality 4.0 application in construction – an industry notoriously known for slow innovation adoption (Gambatese and Hallowell, 2011). Sader *et al*. (2022) listed a number of Quality 4.0 technologies such as big data, connectivity, connection and data presentation. When these I4.0 technologies applied in construction, these fall under "Construction 4.0", which, according to Sawhney *et al*. (2020), is a framework that is a confluence and convergence of the following themes:

(1) Industrial production: prefabrication, 3D printing and assembly and offsite manufacture reduce the issues and challenges caused by on-site construction;

(2) CPS: robots for repetitive and dangerous processes and drones for surveying and lifting, moving and positioning and actuators.

(3) Digital technologies: BIM, laser scanning, IoT, sensors, AI and cloud computing, big data and data analytics, reality capture, blockchain, AR, etc.

Technically, several of these technologies have been explored in the construction sector, but the extent of their adoption in the context of QM (QC, QA and TQM) is unclear. To address that, Table 3 shows various I4.0 technologies applied to QM in the construction context. Based on Table 3:

(1) QC technologies focus on controlling production, correcting errors and ensuring product quality, including IoT, AI, digital twin, CPS, robotics, drones, computer vision, AR, big data and 3D printing.

(2) QA emphasises process optimisation using (1) data collection, (2) decision-oriented and (3) collaborative technologies (Ghansah and Edwards, 2024). Most digital technologies focus on data collection and decision-making; however, scholars (Sullivan, 2011) still argue that the construction industry lacks quality data. This raises an important question: Are we collecting useful and meaningful quality-related data?

(3) Technologies supporting the TQM adhere to TQM principles, encouraging all-employee involvement in QM and driving continuous improvement. These include AI, BIM, digital twin, blockchain, cloud computing, VR, CPS and big data.

Notably, only the digital twin offers direct support, while others contribute indirectly through systemic enhancements. It seems to infer that digital technologies and their impact on QM have certainly attracted researchers' attention. Luo *et al*. (2022) noted digital technologies mainly focus on construction safety, cost and schedule rather than quality. Their review (Luo *et al*., 2022) found BIM, AR, IoT, computer vision and blockchain are used primarily for (1) defects identification and assessment, (2) dimensional deviation assessment and (3) code compliance check. All these three areas are product and process-related, technically Quality 1.0 and Quality 2.0 but with the assistance of digital tools. According to Dias *et al*. (2022), two groups of technologies are particularly important for the new era of quality: automation and integration. The former delivers higher quality by standardising operations and processes, reduces human errors and frees people from repetitive tasks. The latter allows information to be closely monitored and synchronises the physical and cyberspace. Whichever technologies are used, those that enhance trust and collaboration by improving transparency and credibility are essential for effective QM (Emblemsvåg, 2020).

Overall, existing research on I4.0 technologies and QM remains limited, especially within the construction sector. Technologies such as robotics and digital twins are particularly underexplored, despite their significant potential to enhance quality performance. As shown in Table 3, scholarly interest in this intersection has only gained momentum since 2020, indicating that the field is still in its early stages. This recent growth highlights a significant gap in knowledge and best practices, which this study aims to address with a conceptual framework.

Table 3. Areas of Industry 4.0 technologies in construction addressing quality issues

Construction 4.0 technology	Supported QM phase QC	QA	TQM	Support type	Support rationale
Internet of Things (IoT)	●	◎	N.A	Real-time monitoring and process control	- QC: Sensors monitor construction environments (e.g., temperature, humidity, vibration), and automatically detect anomalies (Lekan *et al.*, 2022; Wang *et al.*, 2021) - QA: IoT devices enable data traceability to ensure compliance with quality standards (Lekan *et al.*, 2022; Wang *et al.*, 2021)
Artificial intelligence (AI)	●	●	◎	Defect detection, predictive analytics and continuous optimisation	- QC: Computer vision detects construction defects (e.g., cracks, misaligned reinforcement) automatically, reducing human errors (Pan and Zhang, 2021) - QA: AI analyses historical data to optimise construction processes and improve process quality (Pan and Zhang, 2021) - TQM: AI leverages big data analytics to identify quality improvement opportunities and enhance organisational quality management (Pan and Zhang, 2021)
Building information modelling (BIM)	N.A	●	◎	Design optimisation and collaboration	- QA: Provides 3D clash detection to minimise design errors during construction, enhancing quality assurance (Chen and Luo, 2014) - TQM: Facilitates collaboration among contractors, suppliers, and maintenance teams to improve overall quality management (Chen and Luo, 2014; Ma *et al.*, 2018)
Digital twin	●	●	●	Real-time simulation and lifecycle quality optimisation	- QC: Enables proactive prevention and real-time management of quality issues, enhancing the intelligence of the quality control process (Boje *et al.*, 2020; Liu *et al.*, 2023) - QA: Simulates real-time construction processes to predict and prevent defects (Boje *et al.*, 2020) - TQM: Combines IoT and AI to enable continuous quality monitoring and process improvements throughout the entire lifecycle (Boje *et al.*, 2020)

(*continued*)

Table 3. Continued

Construction 4.0 technology	Supported QM phase QC	QA	TQM	Support type	Support rationale
Blockchain	N.A	●	◎	Supply chain transparency and traceability	-QA: Ensures data integrity and traceability, supports automated compliance checks, and maintains regulatory adherence (Sheng *et al.*, 2020; Lu *et al.*, 2022) - TQM: Ensures authenticity of construction materials and data, improving supply chain transparency and maintaining quality consistency throughout the lifecycle (Sheng *et al.*, 2020; Lu *et al.*, 2022)
Cloud computing	N.A	●	◎	Data storage and collaboration optimisation	- QA: Provides real-time data storage and sharing to improve access to construction information (Bello *et al.*, 2021; Oke *et al.*, 2023) - TQM: Enhances enterprise-level collaboration and quality improvement through cloud platforms (Bello *et al.*, 2021; Oke *et al.*, 2023)
Augmented reality (AR)	N.A	●	N.A	Construction guidance and quality inspection	- QA: Uses AR for construction guidance, reducing human errors and improving precision (Chalhoub *et al.*, 2021)
Virtual reality (VR)	N.A	●	◎	Training and design optimisation	- QA: Used for worker training to enhance construction quality (Albahbah *et al.*, 2021; Shakil, 2019) - TQM: Simulates construction processes during the design phase, optimising lifecycle quality management (Albahbah *et al.*, 2021; Shakil, 2019)
Cyber-physical systems (CPS)	●	●	◎	Real-time monitoring and intelligent control	- QC: Integrates IoT and AI for automated quality monitoring and process control (Jiang *et al.*, 2021) - QA: Ensures intelligent management of construction equipment and materials, enhancing quality assurance (Akanmu *et al.*, 2021) - TQM: Uses data feedback to optimise management strategies and support continuous improvement (Akanmu *et al.*, 2021)

(*continued*)

Table 3. Continued

Construction 4.0 technology	Supported QM phase QC	QA	TQM	Support type	Support rationale
Robotic systems	●	●	N.A	Automated construction and precision control	- QC: Robots execute high-precision construction, reducing human errors (Gamlath *et al.*, 2020) - QA: Robots autonomously detect and correct construction defects, ensuring consistency (Gamlath *et al.*, 2020)
Drones and aerial photography	●	◎	N.A	Site monitoring and quality inspection	- QC: Drones capture aerial images of construction sites in real time to identify quality issues (Li and Liu, 2019) - QA: Uses AI for quality assessments to enhance quality assurance (Li and Liu, 2019)
Computer vision	●	◎	N.A	Automated quality inspection and defect recognition	- QC: Uses image recognition technology to detect construction defects such as cracks and uneven concrete strength (Dorafshan *et al.*, 2018; Liu and Yeoh, 2021) - QA: Integrates AI for real-time quality detection to improve construction quality (Dorafshan *et al.*, 2018)
Big data	●	◎	◎	Decision support and process optimisation	- QC: Supports real-time monitoring and analysis, improves defect detection (Liu *et al.*, 2022) - QA: data-driven quality prediction and process optimisation (Sang *et al.*, 2021) - TQM: Analyses large-scale quality-related data to identify patterns, optimise processes, and improve organisational learning for quality enhancement (Sang *et al.*, 2021)
3D printing (additive manufacturing)	●	●	N.A	Precision manufacturing and material quality control	- QC: Ensures precision in construction components by automating material layering (Quah *et al.*, 2023) - QA: Improves material consistency and minimises defects in prefabrication (Buswell *et al.*, 2022)

Note(s): ●: direct Support; ◎: indirect Support
Direct support refers to technologies that directly impact target processes or products, immediately resolving issues or achieving goals without relying on intermediate steps. Indirect support involves technologies that contribute to longer-term, systemic, or holistic improvements, with their effects becoming apparent gradually through intermediate links

4.4 Process

The construction projects are made up entirely of processes and operations. Koskela *et al*. (2019) wrote that quality is embedded in the *flow conceptualisation* of production. Rooke *et al*. (2007) noted the flow view is appropriate for the analysis of *processes*, rather than of operations. At the project level, this is where Lean principles, I4.0 and QM practices intersect. Studies have demonstrated how lean thinking contributes to process improvement. The reduction of temporal "variability" is a key principle according to the flow model (Koskela, 2000). For example, a defect that needs rework is a variability that hampers the flow of the process. To eliminate defects, the concept of built-in quality was widely recognised as a core lean principle (Liker, 2004). In the well-known Toyota Production System house, *jidoka* – or automation with a human touch – is one of the two foundational pillars, reflecting Toyota's strong commitment to quality. According to Koskela *et al*. (2019), the concept of *Jidoka* shows that quality was approached from inside production, and simple devices, such as source inspection and *poka-yoke* (foolproof), were promoted for ensuring zero defects in produced parts. In the context of Quality 4.0, the fundamental concept of built-in quality remains as a core principle, while *poka-yoke* can be enhanced with digital technologies like computer vision and AI to detect defects with their ability to detect these "variability" in real time. At the same time, lean tools like *Andon* play a crucial role – when defects are identified, the process can be stopped, triggering the supervisor's assistance to resolve the issue. This ensures that defects are never passed to the next stage.

At the organisation level, according to Kumar *et al*. (2022), the process dimension consists of the activities that organisations perform based on the systems, procedures and protocols. ISO9001 QMS also acknowledged its process approach, which incorporates the plan-do-check-act cycle and risk-based thinking. The standard (ISO 9001, p.2) noted that "*the organisation shall determine the processes needed for the QM system and their application throughout the organisation*". It is understandable that these processes are organisational-level focused and can be divided into QP, QA, QC and quality improvement. It is also worth noting here that there are paper-based records associated with these processes and QMS including QMP, ITP and other related registers. An opportunity for digital technology to play a role here is to digitise the QM system (Elg *et al*., 2021). This is applicable in construction thanks to several technical solution providers for digitalisation service.

4.5 People and partners

ASQ (2024) reminded us that Quality 4.0 is more than technology, and many studies acknowledged its people aspects (Kumar *et al*., 2022). This is especially true in the labour-intensive construction sector, where workmanship plays a crucial role. Thus, we maintain that people have an important role in the CONQ4.0 framework. Kumar *et al*. (2022) discussed leadership, culture and competence in the people aspects. Leadership and quality-driven culture are important to ensure that all stakeholders, including temporary teams, align with the principles of I4.0 (Dahlgaard-Park and Dahlgaard, 2020). Effective leadership can drive the adoption of new technologies and foster a culture of continuous improvement. In fact, leadership and quality culture never get to miss out on the key milestone in the development of QM, particularly for TQM and QMS, for which leadership is always a key ingredient.

As for competence, it is widely accepted that the successful implementation of Quality 4.0 in the construction industry relies on enhancing the capabilities of human resources, including workers, managers and subcontractors (Dahlgaard-Park and Dahlgaard, 2020; Calvetti *et al*., 2020). Given the project-based and fragmented nature of the workforce, companies must establish clear competency frameworks that integrate both QM and digital skills (Demirkesen and Tezel, 2022). Antony *et al*. (2022) highlighted that the quality curriculum for future quality professionals will consist of core fundamentals of QM and modern tools and digital technologies. Especially for the latter, emerging technologies such as the IoT, AI-driven QC and digital twins require workers to adapt to new tools and workflows. As Newman *et al*. (2021)

pointed out, traditional manual measurement methods will be replaced by relevant technologies, which demand that employees master the application of these technologies. To address the skill gap, continuous training, knowledge transfer mechanisms and collaborative learning environments must be prioritised (García de Soto *et al*., 2022).

What is missing in the discussion in relation to people is the unique workforce structure in construction, where people are not self-employed by the construction firms but heavily subcontracted out due to its temporary nature. Most workers, subcontractors and even key managerial roles such as project managers change from project to project, leading to fragmented responsibility and inconsistent quality practices. This contrasts with manufacturing firms such as Toyota, which maintain long-term relationships with a small, stable supplier base. In contrast, construction firm take the opposite approach, working with a large base of subcontractors and suppliers, often following the mindset of "the more, the better". These characteristics have implications for the subcontractors which work for construction firms. Many subcontractors in construction are small-scale businesses that lack the capacity to innovate in QM independently. Research also found a lack of knowledge and motivation to learn new technologies is one of the significant barriers to the application of I4.0 technologies (Newman *et al*., 2021). Instead, they depend on contractors' systems. However, since they work with multiple construction firms, each using different approaches and digital systems, adapting to these variations becomes an added burden. The point is that Quality 4.0 strategies in construction must extend to subcontractors. Engaging them early and aligning systems will help enhance their capabilities, ensuring a more consistent and effective approach to QM.

5. Development of Construction Quality 4.0 framework

5.1 The framework

We propose the framework of CONQ4.0 (see Figure 2). The development of the framework follows a three-stage approach. First, the literature review points out the core of Quality 4.0 is the QM approaches and process, and as observed in the historical progression from Quality 1.0 to Quality 4.0, there is a clear evolution from QC to QA and then to TQM and now towards the

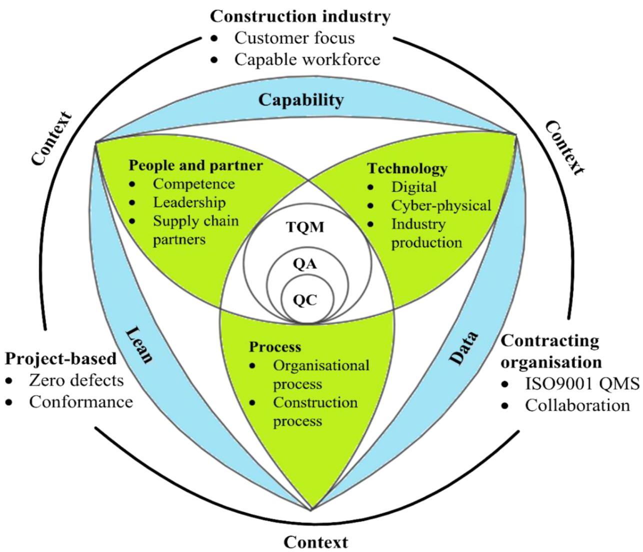

Figure 2. The conceptual framework of Construction Quality 4.0 (CONQ4.0). Source: Authors

digitalisation of the quality procedures. As noted by Sarker and Dunston (2025), Q4.0 does not replace the traditional process but rather enhances it through digitalisation. The evolution of QM forms the conceptual core of the CONQ4.0 framework, which provides a foundation upon which modern-day digital technologies are adopted to make improvements to it. Second, building on the core, the framework incorporates three critical elements, namely technology, process and people, as three anchoring petals. These three dimensions consistently emerged as key themes through a review of existing conceptual frameworks on Quality 4.0 (see Table 1) and are widely recognised as essential components for implementing Quality 4.0 across sectors. This study posits that these three elements are relevant in the construction industry, given its project-based nature, reliance on labour and subcontractors, and increasing push toward digital transformation. Third, to connect the petals and support operational integration, three enablers were derived: lean principles, data management and capability development. Each enabler bridges two petals:

(1) *Lean* connects processes with people, promoting flow, defect prevention and continuous improvement;

(2) *Data* links process and technology, enabling real-time monitoring, predictive analytics and informed decision-making and

(3) *Capability* links people and technology, emphasising the need for upskilling and digital literacy in quality functions.

Lastly, this framework acknowledges that it is developed specifically for and intended to operate within the construction industry, where project-based work and contracting are key characteristics. With these features in mind, this study defines CONQ4.0 as the integration of technological advancements, particularly digital construction technologies, into QM processes by competent professionals in the project-based construction industry, through a data-driven approach supported by collaborative contracting, with the aim of enhancing overall quality performance.

5.2 The core

The core of the CONQ4.0 should still be QM. In other words, the key QM movement, from QC to QA to TQM, forms the core of the conceptual framework. Each has a different focus: QC focuses on product quality, QA on both product and process and TQM is a holistic management approach (Sader *et al*., 2022). Since TQM includes QA and QA includes QC, they are in a container relationship. It's worth mentioning that all three QM approaches are applied in the construction industry to a certain extent.

5.3 The petals

These three petals – represented by technology, process and people – overlay the core.

Technology. First, the application of I4.0 technologies in quality is the most evident among the three petals. This is evident from the definition of Quality 4.0. Some scholars even argued that Quality 4.0 is a branch of I4.0 (Ramezani and Jassbi, 2020), with the “4.0” also implying the application of I4.0 technologies. This element sheds light on “*what tools and technologies*” can be applied in construction QM. The previous section listed the various applications of I4.0 technologies in QM within the construction industry (see Table 3). Influenced by Sawhney *et al*. (2020), these technologies are referred to as Construction 4.0. We argue that each layer of Construction 4.0 technologies – digital, cyber-physical and industry production – has potential for QM, although current literature predominantly focused on the application of digital technologies. Before the advent of I4.0 technologies, QC heavily relied on human intervention to identify and assess defects within processes. Typically, defects were addressed only after they occurred, with teams engaging in post-event analysis to prevent future issues. However, with the integration of I4.0 technologies – particularly AI-based computer vision – these tools now assist in proactively managing processes by detecting potential defects before they occur, thus enhancing overall QM. This leads to a new requirement for the "operators" in terms of using these digital technologies; thus, their digital capability needs to be invested in. Moreover, as shown in Table 3, different technologies impact QM in various ways – some directly, like digital twins, while others are indirectly related to different stages of QM. It does not mean that construction firms have to adopt the entire suite of technologies but should select those best suited to improving product, process and management of quality.

Process. For QM, processes have become the immediate focus (Seiß, 2021). Here, we focus on two types of processes, namely the organisational and project levels. The internal process and external QA are designed at the organisational level. For the former, we must attend to the *contract* first, as the contract is a key vehicle in QA. The latter leads up to the QM items such as audits, procedure reviews (Emblemsvåg, 2020), final inspections, etc. At the project level, the construction process refers to activities at the delivery stage, where there are opportunities to leverage technologies for better quality. These are the processes that, from continuous improvement point of view, have less muda and a leaner process. The process element answered "*where*" the modern-day technologies can be applied in construction QM.

People and partners. Last but not least are the people who are often described as the most important aspect (Kumar *et al.*, 2022). Traditional craftsmanship remains essential and is closely related to task processes (Calvetti *et al.*, 2020), although recent years have witnessed robotics being operated to undertake several repetitive tasks such as painting, demolition, tiling and others. As an important resource, many countries' construction suffers severe labour shortages. Many discussions are focused on people and leadership (Sony *et al.*, 2020). Maskuriy *et al.* (2019) emphasised that technology drives a paradigm shift in management, requiring leaders to facilitate cross-departmental collaboration and knowledge sharing. With the widespread application of digital technologies in QM, personnel need to master the application capabilities of data analysis, AI, IoT and other emerging technologies (Newman *et al.*, 2021). For example, operators need to be proficient in using smart devices for real-time data collection and analysis, while managers need the ability to interpret complex data to formulate data-driven quality improvement strategies (Maskuriy *et al.*, 2019). While capability and leadership are well discussed, the role of partners is often overlooked. In the Quality 4.0 era, partners play a crucial role, as data cannot exist in a silo (Sony *et al.*, 2020), and studies acknowledged the end-to-end integration, real-time information and/or data sharing and the data may begin with the supplier flow into the construction firms. For that, partners need to be on the same page and need to be included in the Quality 4.0 transformation. Lessons from lean adoptions in the supply chain are that if only the contractors are implementing lean without the subcontractors and/or suppliers, it will not be a successful lean adoption.

5.4 The enablers

In the conceptual framework, we used three enablers linking three petals. These are Lean principles, data management and capability.

Lean principles. There has been much writing about lean and lean construction. We argued that the lean principles including value, value stream, pull, flow and perfection should also serve as the guiding principles for CONQ4.0 because both Lean and QM focus on maximising value for customer, while minimising waste (defects in particular). In view of that, we use "Lean" as an enabler linking the process petal to people due to the fact that the Lean principles bring value to the process.

(1) Value: Emphasising customer needs ensures that quality aligns with project goals.

(2) Value stream: Mapping processes helps identify inefficiencies, leading to better quality outcomes.

(3) Pull: This principle encourages producing only what is needed, reducing excess and ensuring higher quality. Importantly, in the context of construction quality, internal customer such as different trades needs to be acknowledged.

(4) Flow: Build-in quality never passing the defective work to the next station

(5) Perfection: Aiming for continuous improvement fosters a culture of quality and innovation.

Data. Data are essential for Quality 4.0, with several studies highlighting data science as a key area. Reliable, accurate and real-time data are a crucial feature of I4.0 (Kushwaha and Talib, 2025) and are the most critical enabler for adopting Quality 4.0 (Kumar *et al.*, 2022) and also will change the way of an organisation's quality culture (Kushwaha and Talib, 2025). Zonnenshain and Kenett (2020) discussed a few elements of Quality 4.0 that relate to data, i.e. quality as a data-driven discipline, Quality 4.0 and data science and information quality. This is an important observation that the I4.0 is data-driven, thanks to the availability of sensors, big data analytics and many digital technologies. The data enablers link process and technology, as data are generated from processes by technologies (i.e. IoT) and will be used by technology for monitoring, control, evaluation and better decision-making. Sullivan (2011) noted that the construction industry struggles with measuring its performance, including quality. In Kang *et al.* (2020), it is stated that good-quality data are not always available. This can negatively affect the potential of digital technology application (i.e. machine learning algorithms). We concur with Kushwaha and Talib (2025) that it is necessary to have deep and current knowledge of the Quality 4.0 concept as to when and how to use the data.

Capability. We particularly place the capability enabler between people and technology adoption. As is shown in Table 1, raising the capability of people in the use of technology and others was discussed in the literature. It is foreseeable the use of advanced technology in QM will result in a need for training for Quality 4.0, with the aim to raise their digital literacy (Yang *et al.*, 2022) in the quality domain. To facilitate that, proactive and supportive digital leadership (Zulu and Khosrowshahi, 2021) is required. Equally important are the quality fundamentals that should remain and the Lean knowledge that enables the people to pursue perfection in the quality world. The construction firms really need to specify the competencies in quality and in digital for better accommodation Quality 4.0 in the future.

5.5 The context

This framework is set within the construction context, recognising its unique characteristics – one-of-a-kind projects, site production, temporary organisations and regulatory constraints (Koskela, 2000). This is an important start pointing to understanding the context in which the construction industry operates. These contextual factors, often overlooked in general Quality 4.0 discussions, are frequently cited as barriers to innovative QM practices in construction.

In such a context, we also outlined the goal of the CONQ4.0 on three fronts. Overall, it is about enhancing quality performance at the industry, organisation and project levels. At the industry level, as Kumar *et al.* (2022) wrote, the ultimate objective of Quality 4.0 is to support *organisations* to meet customer and societal requirements. Customer focus, according to Kumar *et al.* (2022), is a central theme of quality, but the authors did not elaborate on the societal requirements. ASQ (2024) also outlined a few value propositions for Quality 4.0, including improving human intelligence, decision-making, transparency, adaptability, trust and continuous learning. It is interesting to see that a number of value propositions are human-centric, reinforcing that the CONQ4.0 is not about replacing people and quality professionals but adding value to their work and value to the process. From this point of view, a key dimension of societal requirements is developing a capable workforce to integrate I4.0 integrated in QM. At the organisational level, QMS remains central, with digitalisation offering improved efficiency (Singh *et al.*, 2022). According to Brooks *et al.* (2021), an ISO 9001-accredited QMS has become a requirement for tendering for the majority of projects.

This is particularly important for non-accredited construction firms, especially small and medium-sized enterprises (SMEs), as they seek to enhance their competitiveness. Those already accredited aim to maintain their status. Additionally, Emblemsvåg (2020) wrote that Quality 4.0 strengthens the case for relational contracting, which should be a goal for contracting firms and the construction industry. This shift requires a change in attitude and behaviour – from managing conformance and expectations through contracts in an adversarial environment to fostering collaboration and alignment. At the project level, quality is about conformance with the specification, codes and standards, client requirements and others (Emblemsvåg, 2020). In addition to nonconformance, construction projects aim to minimise defects and issues, even striving for zero defects. These are common indicators monitored at the project level, and despite I4.0 advancements, they remain key quality indicators.

6. Implications

6.1 Theoretical implication

This study offers several theoretical contributions by positioning Quality 4.0 within the unique context of the construction industry. First, this study extends the QM research by contextualising Quality 4.0 within the construction industry – a sector that was largely overlooked in prior research. By acknowledging the project-based nature of the construction industry, this study establishes the CONQ4.0 framework as a context-specific contribution to the field. Second, although this study does not draw on a single anchoring theory, it broadens the scope of QM research by drawing on complementary concepts from related fields such as Lean thinking, digital technologies and capability improvement. Third, the proposed CONQ4.0 framework is developed around the people-process-technology triad, which is a well-established model for managing organisational change. This triad is relevant since CONQ4.0 serves as a model for driving change in the construction industry. The emphasis on people and technology resonates strongly with STS theory, which posits that organisational performance depends on the joint optimisation of social and technical subsystems. Through this lens, this study contributes to STS by demonstrating that Quality 4.0 adoption in construction is a sociotechnical transformation. It shows that CONQ4.0 is not merely about introducing digital tools to enhance quality performance, but also it requires the coordinated evolution of digital tools, human capabilities, processes and inter-organisational relationships. The CONQ4.0 framework therefore offers a construction-specific articulation of STS, highlighting how people, process and technology must be jointly optimised to achieve reliable, data-driven and future-ready quality outcomes. Moreover, it strengthens STS thinking by emphasising leadership, workforce capability and subcontractor integration, addressing the people dimension which is often neglected in Quality 4.0 literature.

6.2 Practical implication

The proposed CONQ4.0 framework has several key implications for construction professionals, particularly construction quality professionals in the digital era. The implications are largely derived from the framework's "petals" and "enablers" elements. First, managers must understand and appreciate the benefits of digital transformation of QM. As the framework shows, digital technologies such as AI, BIM, IoT and digital twins can support QC and assurance, but their adoption depends on leadership's commitment to resource and a supportive quality culture. Second, managers must adopt a systems-thinking approach to process optimisation. Managers should be clear which processes can be enhanced by specific digital tools and use real-time data and Lean principles to streamline workflows and reduce defects. Managers should invest in upskilling quality personnel, site teams and organisational staff to ensure they can effectively use digital technologies to enhance quality performance. This includes training in data analytics, real-time monitoring tools and collaborative platforms. Capability-building should also extend to subcontractors and partners, who play a critical role in maintaining consistent quality across project sites. Ultimately, the CONQ4.0 framework should not be simply interpreted as the adoption of new technologies for construction quality; rather, it requires committed leadership, a digitally capable workforce and integrated, process-focused management to drive sustainable improvements in quality performance across the construction industry.

7. Conclusion

The construction industry is an important pillar of a country's economy, and quality is a significant issue within this sector. In an era where advancements in QM are stagnating, emerging technologies are unleashing their potential. This study explores the concept of Quality 4.0 within the construction industry, addressing the gap in existing literature and proposing a conceptual framework that integrates technology, process and people as its foundational pillars. While Quality 4.0 has gained attention in process-oriented industries, its application in construction remains largely unexplored. Given the persistent quality challenges in the industry, leveraging I4.0 technologies is essential to improving QM practices. Overall, this study lays the groundwork for advancing Quality 4.0 in construction, emphasising the need for a holistic approach that balances technological innovation, process efficiency and human expertise. It is perhaps one of the first attempts to develop a dedicated Quality 4.0 framework for the construction industry. The proposed framework retains traditional QM principles (QC, QA and TQM) while integrating digital technologies to enhance quality monitoring, defect detection and compliance management. However, technology alone is not sufficient; thus, people remain central to QM, requiring strong leadership, workforce capability development and subcontractor engagement to ensure consistent quality practices across projects. Additionally, the framework considers the unique characteristics of the construction industry. Despite its contributions, this study has limitations. The framework is developed based on a literature review and requires empirical validation in the construction industry. Additionally, while the focus is on construction firms, this study may overlook the perspectives of other critical stakeholders such as designers, regulatory bodies and clients, all of whom play essential roles in assuring construction quality. Thus, future research should explore its applicability to engineering and design firms, particularly in design quality and engineering standards. Other areas worth exploring include understanding the challenges associated with introducing the framework and empirically testing it with construction and design professionals, which are also key directions for future research.

References

Akanmu, A., A.Anumba, C.J. and Ogunseiju, O.O. (2021), "Towards next generation cyber-physical systems and digital twins for construction", *Journal of Information Technology in Construction*, Vol. 26, pp. 505-525, doi: 10.36680/j.itcon.2021.027.

Albahbah, M., Kıvrak, S. and Arslan, G. (2021), "Application areas of augmented reality and virtual reality in construction project management: a scoping review", *Journal of Construction Engineering and Management*, Vol. 4 No. 3, pp. 151-172, doi: 10.31462/jcemi.2021.03151172.

Ali, K. and Johl, S.K. (2022), "Soft and hard TQM practices: future research agenda for industry 4.0", *Total Quality Management andand Business Excellence*, Vol. 33 Nos 13-14, pp. 1625-1655, doi: 10.1080/14783363.2021.1985448.

Alsadi, J., Alkhatib, F., Antony, J., Garza-Reyes, J., A.Tortorella, G. and Cudney, E.A. (2024), "A systematic literature review with bibliometric analysis of quality 4.0", *The TQM Journal*, Vol. 37 No. 5, pp. 1446-1470, doi: 10.1108/tqm-02-2024-0050.

Antony, J., Mcdermott, O. and Sony, M. (2022), "Quality 4.0 conceptualisation and theoretical understanding: a global exploratory qualitative study", *The TQM Journal*, Vol. 34 No. 5, pp. 1169-1188, doi: 10.1108/tqm-07-2021-0215.

Arditi, D. and Gunaydin, H.M. (1997), "Total quality management in the construction process", *International Journal of Project Management*, Vol. 15 No. 4, pp. 235-243, doi: 10.1016/s0263-7863(96)00076-2.

Asif, M. (2020), "Are QM models aligned with industry 4.0? A perspective on current practices", *Journal of Cleaner Production*, Vol. 258, 120820, doi: 10.1016/j.jclepro.2020.120820.

ASQ (2024), "Quality 4.0", available at: https://asq.org/quality-resources/quality-4-0?srsltid=AfmBOootbv2rsr6pJvxihC7S5hflieKJf2vTn7Q69LQVnSsXIHmVgqG5#Study

Baran, E. and Korkusuz Polat, T. (2022), "Classification of industry 4.0 for total quality management: a review", *Sustainability*, Vol. 14 No. 6, 3329, doi: 10.3390/su14063329.

Bello, S., Oyedele, L.A., Akinade, O.O., Bilal, M.O., Delgado, J.M.D., Akanbi, L.A., Ajayi, A.O. and Owolabi, H.A. (2021), "Cloud computing in construction industry: use cases, benefits and challenges", *Automation in Construction*, Vol. 122, 103441, doi: 10.1016/j.autcon.2020.103441.

Boje, C., Guerriero, A., Kubicki, S. and Rezgui, Y. (2020), "Towards a semantic construction digital twin: directions for future research", *Automation in Construction*, Vol. 114, 103179, doi: 10.1016/j.autcon.2020.103179.

Broday, E.E. (2022), "The evolution of quality: from inspection to quality 4.0", *International Journal of Quality and Service Sciences*, Vol. 14 No. 3, pp. 368-382, doi: 10.1108/ijqss-09-2021-0121.

Brooks, T., Gunning, J.G., Spillane, J.P. and Cole, J. (2021), "Regulatory decoupling and the effectiveness of the ISO 9001 quality management system in the construction sector in the UK–a case study analysis", *Construction Management and Economics*, Vol. 39 No. 12, pp. 988-1005, doi: 10.1080/01446193.2021.1983186.

Buswell, R.X., De Becker, J., Dobrzanski, D., Provis, J., J.Kolawole, J.T. and Kinnell, P. (2022), "Geometric quality assurance for 3D concrete printing and hybrid construction manufacturing using a standardised test part for benchmarking capability", *Cement and Concrete Research*, Vol. 156, 106773, doi: 10.1016/j.cemconres.2022.106773.

Caiazzo, B.D., Nardo, M., Murino, T., Petrillo, A., Piccirillo, G. and Santini, S. (2022), "Towards zero defect manufacturing paradigm: a review of the state-of-the-art methods and open challenges", *Computers in Industry*, Vol. 134, 103548, doi: 10.1016/j.compind.2021.103548.

Calvetti, D., Mêda, P., Chichorro Gonçalves, M. and Sousa, H. (2020), "Worker 4.0: the future of sensored construction sites", *Buildings*, Vol. 10 No. 10, p. 169, doi: 10.3390/buildings10100169.

Chalhoub, J., Ayer, S.K. and Mccord, K.H. (2021), "Augmented reality to enable users to identify deviations for model reconciliation", *Buildings*, Vol. 11 No. 2, p. 77, doi: 10.3390/buildings11020077.

Chen, L. and Luo, H. (2014), "A BIM-based construction quality management model and its applications", *Automation in Construction*, Vol. 46, pp. 64-73, doi: 10.1016/j.autcon.2014.05.009.

Chiarini, A. (2020), "Industry 4.0, quality management and TQM world. A systematic literature review and a proposed agenda for further research", *The TQM Journal*, Vol. 32 No. 4, pp. 603-616.

Chiarini, A. and Kumar, M. (2022), "What is quality 4.0? An exploratory sequential mixed methods study of Italian manufacturing companies", *International Journal of Production Research*, Vol. 60 No. 16, pp. 4890-4910, doi: 10.1080/00207543.2021.1942285.

Dahlgaard-Park, S.M. and Dahlgaard, J.J. (2020), "Key challenges and opportunities for quality, sustainability and innovation in the fourth industrial revolution: quality and service management in the fourth industrial revolution-sustainability and value Co-creation".

Demirkesen, S. and Tezel, A. (2022), "Investigating major challenges for industry 4.0 adoption among construction companies", *Engineering Construction and Architectural Management*, Vol. 29 No. 3, pp. 1470-1503.

Dias, A.M., Carvalho, A.M. and Sampaio, P. (2022), "Quality 4.0: literature review analysis, definition and impacts of the digital transformation process on quality", *International Journal of Quality and Reliability Management*, Vol. 39 No. 6, pp. 1312-1335, doi: 10.1108/ijqrm-07-2021-0247.

Dorafshan, S., Thomas, R.J. and Maguire, M. (2018), "Comparison of deep convolutional neural networks and edge detectors for image-based crack detection in concrete", *Construction and Building Materials*, Vol. 186, pp. 1031-1045, doi: 10.1016/j.conbuildmat.2018.08.011.

El Jaouhari, A., Arif, J., Samadhiya, A., Kumar, A., Jain, V. and Agrawal, R. (2024), "Are metaverse applications in quality 4.0 enablers of manufacturing resiliency? An exploratory review under disruption impressions and future research", *The TQM Journal*, Vol. 36 No. 6, pp. 1486-1525.

Elg, M., Birch-Jensen, A., Gremyr, I., Martin, J. and Melin, U. (2021), "Digitalisation and quality management: problems and prospects", *Production Planning and Control*, Vol. 32 No. 12, pp. 990-1003, doi: 10.1080/09537287.2020.1780509.

Emblemsvåg, J. (2020), "On quality 4.0 in project-based industries", *The TQM Journal*, Vol. 32 No. 4, pp. 725-739, doi: 10.1108/tqm-12-2019-0295.

Flanagan, R. and Jewell, C. (2019), *Code of Quality management-guide to Best Practice Construction Quality Management*, Chartered Institute of Building, Bracknell.

Gambatese, J.A. and Hallowell, M. (2011), "Factors that influence the development and diffusion of technical innovations in the construction industry", *Construction Management and Economics*, Vol. 29 No. 5, pp. 507-517, doi: 10.1080/01446193.2011.570355.

Gamlath, M., Waidyasekara, K. and Pandithawatta, S. (2020), "Feasibility of robotic technology for the advancement of construction industry in Sri Lanka", *Proceeding of 2020 Moratuwa Engineering Research Conference (MERCon)*, Moratuwa, Sri Lanka.

García De Soto, B., Agustí-Juan, I., Joss, S. and Hunhevicz, J. (2022), "Implications of construction 4.0 to the workforce and organizational structures", *International Journal of Construction Management*, Vol. 22 No. 2, pp. 205-217, doi: 10.1080/15623599.2019.1616414.

Ghansah, F.A. and Edwards, D.J. (2024), "Digital technologies for quality assurance in the construction industry: current trend and future research directions towards industry 4.0", *Buildings*, Vol. 14 No. 3, p. 844, doi: 10.3390/buildings14030844.

Giri (2025), "The UK construction industry could save up to £25 billion a year by avoiding error".

González, V.A., Hamzeh, F. and Alarcón, L.F. (2022), *Lean Construction 4.0: Driving a Digital Revolution of Production Management in the AEC Industry*, CRC Press, Boca Raton.

Han, S.H., Chae, M.J., Im, K.S. and Ryu, H.D. (2008), "Six sigma-based approach to improve performance in construction operations", *Journal of Management in Engineering*, Vol. 24 No. 1, pp. 21-31, doi: 10.1061/(asce)0742-597x(2008)24:1(21).

Ho, P.T., Albajez, J.A., Santolaria, J. and Yagüe-Fabra, J.A. (2022), "Study of augmented reality based manufacturing for further integration of quality control 4.0: a systematic literature review", *Applied Sciences*, Vol. 12 No. 4, p. 1961.

Iso (2024), "The ISO survey", available at: https://www.iso.org/the-iso-survey.html

Jiang, W., Ding, L. and Zhou, C. (2021), "Cyber physical system for safety management in smart construction site", *Engineering Construction and Architectural Management*, Vol. 28 No. 3, pp. 788-808, doi: 10.1108/ecam-10-2019-0578.

Kang, Z., Catal, C. and Tekinerdogan, B. (2020), "Machine learning applications in production lines: a systematic literature review", *Computers and Industrial Engineering*, Vol. 149, 106773, doi: 10.1016/j.cie.2020.106773.

Komkowski, T., Antony, J., Garza-Reyes, J. A., Tortorella, G. L. and Pongboonchai-Empl, T. (2023), "A systematic review of the integration of Industry 4.0 with quality-related operational excellence methodologies", *Quality Management Journal*, Vol. 30 No. 1, pp. 3-15.

Koskela, L. (2000), *An Exploration Towards a Production Theory and its Application to Construction*, VTT Technical Research Centre of Finland, Espoo.

Koskela, L., Tezel, A. and Patel, V. (2019), "Theory of quality management: its origins and history", pp. 1381-1390, doi: 10.24928/2019/0259.

Kumar, R.R., Ganesh, L.S. and Rajendran, C. (2022), "Quality 4.0–a review of and framework for quality management in the digital era", *International Journal of Quality and Reliability Management*, Vol. 39 No. 6, pp. 1385-1411, doi: 10.1108/ijqrm-05-2021-0150.

Küpper, D., Knizek, C., Ryeson, D. and Noecker, J. (2019), *Quality 4.0 Takes More than Technology*, Boston Consulting Group (BCG), Boston, Vol. 20.

Kushwaha, D. and Talib, F. (2025), "A bibliometric analysis of quality 4.0: current status, trends and future research directions", *International Journal of Quality and Reliability Management*, Vol. 42 No. 2, pp. 474-503, doi: 10.1108/ijqrm-10-2023-0322.

Lekan, A., Clinton, A., Stella, E., Moses, E. and Biodun, O. (2022), "Construction 4.0 application: industry 4.0, internet of things and lean construction tools' application in quality management system of residential building projects", *Buildings*, Vol. 12 No. 10, 1557, doi: 10.3390/buildings12101557.

Li, Y. and Liu, C. (2019), "Applications of multirotor drone technologies in construction management", *International Journal of Construction Management*, Vol. 19 No. 5, pp. 401-412, doi: 10.1080/15623599.2018.1452101.

Liker, J.K. (2004), *The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer*, McGraw-Hill, New York.

Liu, Y. and Yeoh, J.K.W. (2021), "Automated crack pattern recognition from images for condition assessment of concrete structures", *Automation in Construction*, Vol. 128, 103765, doi: 10.1016/j.autcon.2021.103765.

Liu, Y.Y., F.Ji, Y., Tong, W., Liu, G., Li, H.X. and Hu, X. (2022), "Quality control for offsite construction: review and future directions", *Journal of Construction Engineering and Management*, Vol. 148 No. 8, 03122003, doi: 10.1061/(asce)co.1943-7862.0002317.

Liu, Z., Wu, L., Liu, Z. and Mo, Y. (2023), "Quality control method of steel structure construction based on digital twin technology", *Digital Twin*, Vol. 3 No. 5, p. 5.

Low, S.P. and Peh, K.W. (1996), "A framework for implementing TQM in construction", *The TQM Magazine*, Vol. 8 No. 5, pp. 39-46, doi: 10.1108/09544789610146033.

Low, S.P. and Teo, J.A. (2003), "Implementing total quality management in construction through ISO 9001: 2000", *Architectural Science Review*, Vol. 46 No. 2, pp. 159-165, doi: 10.1080/00038628.2003.9696979.

Lu, W., Wu, L., Xu, J. and Lou, J. (2022), "Construction E-inspection 2.0 in the COVID-19 pandemic era: a blockchain-based technical solution", *Journal of Management in Engineering*, Vol. 38 No. 4, 04022032, doi: 10.1061/(asce)me.1943-5479.0001063.

Luo, H., Lin, L., Chen, K., Antwi-Afari, M.F. and Chen, L. (2022), "Digital technology for quality management in construction: a review and future research directions", *Developments in the Built Environment*, Vol. 12, 100087, doi: 10.1016/j.dibe.2022.100087.

Ma, Z., Cai, S., Mao, N., Yang, Q., Feng, J. and Wang, P. (2018), "Construction quality management based on a collaborative system using BIM and indoor positioning", *Automation in Construction*, Vol. 92, pp. 35-45, doi: 10.1016/j.autcon.2018.03.027.

Mahin, M., Kadasah, N., Alsabban, A. and Albliwi, S. (2024), "Exploring the landscape of quality 4.0: a comprehensive review of its benefits, challenges, and critical success factors", *Production and Manufacturing Research*, Vol. 12 No. 1, 2373739.

Mann, W. (2018), "QM inadequate say 75% in CIOB survey", *Construction Manager*, available at: https://constructionmanagement.co.uk/three-quarters-construction-professionals-say-qual/

Markatos, N.G. and Mousavi, A. (2023), "Manufacturing quality assessment in the Industry 4.0 era: a review", *Total Quality Management and Business Excellence*, Vol. 34 No. 13-14, pp. 1655-1681.

Maskuriy, R., Selamat, A., Maresova, P., Krejcar, O. and David, O.O. (2019), "Industry 4.0 for the construction industry: review of management perspective", *Economies*, Vol. 7 No. 3, p. 68, doi: 10.3390/economies7030068.

Netto, A.M., Pheng Low, S. and Ling Lo, A. (1997), "Legal implications of ISO 9000 QMS in standard forms of building contract", *Training for Quality*, Vol. 5 No. 4, pp. 169-177, doi: 10.1108/09684879710188176.

Newman, C., Edwards, D., Martek, I., Lai, J., Thwala, W.D. and Rillie, I. (2021), "Industry 4.0 deployment in the construction industry: a bibliometric literature review and UK-based case study", *Smart and Sustainable Built Environment*, Vol. 10 No. 4, pp. 557-580, doi: 10.1108/sasbe-02-2020-0016.

Nguyen, T.a.V., Tucek, D. and Pham, N.T. (2023), "Indicators for TQM 4.0 model: delphi method and analytic hierarchy process (AHP) analysis", *Total Quality Management and Business Excellence*, Vol. 34 Nos 1-2, pp. 220-234, doi: 10.1080/14783363.2022.2039062.

Oke, A.E., Kineber, A.F., Al-Bukhari, I., Famakin, I. and Kingsley, C. (2023), "Exploring the benefits of cloud computing for sustainable construction in Nigeria", *Journal of Engineering, Design and Technology*, Vol. 21 No. 4, pp. 973-990, doi: 10.1108/jedt-04-2021-0189.

Oliveira, D., Alvelos, H. and Rosa, M. J. (2025), "Quality 4.0: results from a systematic literature review", *The TQM Journal*, Vol. 37 No. 2, pp. 379-456.

Pan, Y. and Zhang, L. (2021), "Roles of artificial intelligence in construction engineering and management: a critical review and future trends", *Automation in Construction*, Vol. 122, 103517, doi: 10.1016/j.autcon.2020.103517.

Park, S.H., Dahlgaard-Park, S.M. and Kim, D.-C. (2020), "New paradigm of lean six sigma in the 4th industrial revolution era", *Quality Innovation Prosperity*, Vol. 24 No. 1, pp. 1-16, doi: 10.12776/qip.v24i1.1430.

Powell, D., Magnanini, M.C., Colledani, M. and Myklebust, O. (2022), "Advancing zero defect manufacturing: a state-of-the-art perspective and future research directions", *Computers in Industry*, Vol. 136, 103596.

Prashar, A. (2023), "Quality management in industry 4.0 environment: a morphological analysis and research agenda", *International Journal of Quality and Reliability Management*, Vol. 40 No. 3, pp. 863-885, doi: 10.1108/ijqrm-10-2021-0348.

Quah, T.K.N., Tay, Y.W.D., Lim, J.H., Tan, M.J., Wong, T.N. and Li, K.H.H. (2023), "Concrete 3D printing: process parameters for process control, monitoring and diagnosis in automation and construction", *Mathematics*, Vol. 11 No. 6, 1499, doi: 10.3390/math11061499.

Ramezani, J. and Jassbi, J. (2020), "Quality 4.0 in action: smart hybrid fault diagnosis system in plaster production", *Processes*, Vol. 8 No. 6, p. 634, doi: 10.3390/pr8060634.

Rooke, J., Koskela, L., Bertelsen, S. and Henrich, G. (2007), "Centred flows: a lean approach to decision making and organisation", Pasquire, C.L. and Tzortzopoulos, P. (Eds), *15th Annual Conference of the International Group for Lean Construction*, pp. 27-36.

Sader, S., Husti, I. and Daroczi, M. (2022), "A review of quality 4.0: definitions, features, technologies, applications, and challenges", *Total Quality Management and Business Excellence*, Vol. 33 Nos 9-10, pp. 1164-1182, doi: 10.1080/14783363.2021.1944082.

Saihi, A., Awad, M. and Ben-Daya, M. (2023), "Quality 4.0: leveraging industry 4.0 technologies to improve quality management practices–a systematic review", *International Journal of Quality and Reliability Management*, Vol. 40 No. 2, pp. 628-650, doi: 10.1108/ijqrm-09-2021-0305.

Sang, L., Yu, M., Lin, H., Zhang, Z. and Jin, R. (2021), "Big data, technology capability and construction project quality: a cross-level investigation", *Engineering Construction and Architectural Management*, Vol. 28 No. 3, pp. 706-727, doi: 10.1108/ecam-02-2020-0135.

Sarker, T.R. and Dunston, J.K. (2025), "Implementation of quality 4.0, a systematic review of approaches, root causes, and challenges", *Quality Engineering*, Vol. 37 No. 2, pp. 204-218, doi: 10.1080/08982112.2024.2373360.

Sawhney, A., Riley, M., Irizarry, J. and Riley, M. (2020), in Sawhney, A., Riley, M. and Irizarry, J. (Eds), *Construction 4.0*.

Seiß, S. (2021), "A literature review on the usage of ontologies for quality management in the construction execution phase", *Computing in Civil Engineering*, Vol. 2021, pp. 514-521.

Shakil, A. (2019), "A review on using opportunities of augmented reality and virtual reality in construction project management", *Organization, Technology and Management in Construction: An International Journal*, Vol. 11 No. 1, pp. 1839-1852, doi: 10.2478/otmcj-2018-0012.

Sheng, D., Ding, L., Zhong, B., Love, P.E.D., Luo, H. and Chen, J. (2020), "Construction quality information management with blockchains", *Automation in Construction*, Vol. 120, 103373, doi: 10.1016/j.autcon.2020.103373.

Singh, J., Ahuja, I.P.S., Singh, H. and Singh, A. (2022), "Development and implementation of autonomous quality management system (AQMS) in an automotive manufacturing using quality 4.0 concept–a case study", *Computers and Industrial Engineering*, Vol. 168, 108121, doi: 10.1016/j.cie.2022.108121.

Sony, M., Antony, J. and Douglas, J.A. (2020), "Essential ingredients for the implementation of quality 4.0: a narrative review of literature and future directions for research", *The TQM Journal*, Vol. 32 No. 4, pp. 779-793, doi: 10.1108/tqm-12-2019-0275.

Souza, F.F., D.Corsi, A., Pagani, R.N., Balbinotti, G. and Kovaleski, J.L. (2022), "Total quality management 4.0: adapting quality management to industry 4.0", *The TQM journal*, Vol. 34 No. 4, pp. 749-769, doi: 10.1108/tqm-10-2020-0238.

Sullivan, K.T. (2011), "Quality management programs in the construction industry: best value compared with other methodologies", *Journal of Management in Engineering*, Vol. 27 No. 4, pp. 210-219, doi: 10.1061/(asce)me.1943-5479.0000054.

Sureshchandar, G.S. (2022), "Quality 4.0–understanding the criticality of the dimensions using the analytic hierarchy process (AHP) technique", *International Journal of Quality and Reliability Management*, Vol. 39 No. 6, pp. 1336-1367.

Tewary, A. and Jadon, V. (2024), "Building a competent workforce in implementing Quality 4.0: a systematic literature review and proposed agenda for future research", *The TQM Journal*, Vol. 36 No. 8, pp. 2618-2656.

The Victorian Government (2024), "Managing quality", available at: https://www.vic.gov.au/tafe-toolkit-managing-quality

Thekkoote, R. (2022), "Enabler toward successful implementation of Quality 4.0 in digital transformation era: a comprehensive review and future research agenda", *International Journal of Quality and Reliability Management*, Vol. 39 No. 6, pp. 1368-1384.

Thorpe, B. and Sumner, P. (2017), *Quality Assurance in Construction*, Routledge, London.

Wang, D., Ren, B., Cui, B., Wang, J., Wang, X. and Guan, T. (2021), "Real-time monitoring for vibration quality of fresh concrete using convolutional neural networks and IoT technology", *Automation in Construction*, Vol. 123, 103510, doi: 10.1016/j.autcon.2020.103510.

Yang, K., Sunindijo, R.Y. and Wang, C.C. (2022), "Identifying leadership competencies for construction 4.0", *Buildings*, Vol. 12 No. 9, 1434, doi: 10.3390/buildings12091434.

Zonnenshain, A. and Kenett, R.S. (2020), "Quality 4.0—the challenging future of quality engineering", *Quality Engineering*, Vol. 32 No. 4, pp. 614-626, doi: 10.1080/08982112.2019.1706744.

Zulu, S.L. and Khosrowshahi, F. (2021), "A taxonomy of digital leadership in the construction industry", *Construction Management and Economics*, Vol. 39 No. 7, pp. 565-578, doi: 10.1080/01446193.2021.1930080.

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