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Model of Quality and Safety Management Based on the Industry 4.0 Approach

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A B S T R A C T

Technological transformations resulting from the Fourth Industrial Revolution (Industry 4.0) have led to a paradigm shift in quality and safety management practices within manufacturing industries. In this regard, the present study aims to design an integrated model for quality and safety management under the Industry 4.0 framework. This research is exploratory in nature and adopts a qualitative methodology based on grounded theory using the Strauss and Corbin (1998) approach. Data were collected through semi-structured interviews with 15 experts from industry, academia, and technology organizations. The data were analyzed using open, axial, and selective coding methods. As a result, 22 conceptual categories were extracted and organized into six core dimensions: causal conditions, contextual conditions, intervening factors, core phenomenon, strategies, and outcomes. The central category was identified as "Designing an Integrated Model of Quality and Safety Management in the Context of Industry 4.0." According to the findings, factors such as weak technological infrastructure, cultural resistance, insufficient professional training, and lack of supportive policies are among the key barriers to the implementation of this model. Conversely, strategies such as process digitalization, formulation of modern standards, and the development of employees' digital competencies play a crucial role in the realization of the model. The outcomes of implementing this model include enhanced productivity, improved product quality, and increased safety within industrial environments. By presenting a localized and data-driven model, this study offers a strategic framework that can guide industrial managers, policymakers, and educational institutions on the path toward digital transformation and the simultaneous advancement of organizational quality and safety.

Keywords: *Quality Management, Safety Management, Industry 4.0 Approach, Grounded Theory.*

1. Introduction

The evolution of science and technology has always been of great importance since the emergence of the Industrial Revolution. This human enthusiasm and curiosity for further development has enabled humanity to advance significantly (Chiarini, 2020). Since the beginning of the Industrial Revolution in the 1700s, each industrial revolution has played a key role in shaping today's developmental trajectory. Mechanized looms powered by water and steam operating mechanical equipment were first introduced during the First Industrial Revolution (IR 1.0) in the 1700s, replacing agricultural sectors and transforming the economic structure (Saihi et al., 2023).

Additionally, the Second Industrial Revolution (IR 2.0), spanning from 1870 to 1914, revolutionized industry through technology-based innovations such as mass steel production, the telegraph, and affordable, widely-used railroads (Martínez-Costa & Martínez-Lorente, 2021). Electrical energy, introduced in the 1870s, enabled the development of mass production systems. The advent of the internet, information technology, and widespread access to personal computers in the late 1950s initiated a new digital revolution that digitized mechanical and analog processes (Polak-Sopinska & Wisniewski, 2020).

As a result, the emergence of electronics in the 1970s marked the beginning of the Third Industrial Revolution (IR 3.0). Microchips and supercomputers transformed industries. However, humanity's desire for innovation did not end there (Santos et al., 2024). In the late 20th century, a multitude of research and technological advances led to the emergence of the Fourth Industrial Revolution. Built upon the digital revolution, IR 4.0 has facilitated the integration of humans, machines, and data (Alizadeh & Jalali Filshour, 2023; Alizadeh & Larijani, 2018; Zorzenon et al., 2023).

This new wave encompasses robotics, augmented reality, artificial intelligence, cyber-physical systems, cloud computing, and advanced automation (Koh & Tan, 2024). In technical and engineering industries, quality and safety are of paramount importance, and the Fourth Industrial Revolution has also transformed these domains (Darbanhosseiniamirkhiz & Shamsuzzoha, 2021).

Despite technological advancements, the widespread application of IR 4.0 in industries remains challenging (Frank et al., 2019). The utilization of smart factories, intelligent equipment, and digital manufacturing systems has improved quality and safety in many industries (Chiarini, 2020). These factories can respond swiftly to customer needs and function as a network of humans, machines, and data (Rowse, 2024).

Safety control in smart factories is critically important, as failures in automation systems can lead to human and environmental harm (Gianatti, 2020). Therefore, precise evaluation and real-time alerts in production processes are essential (Moore, 2019). Technological changes without concurrent cultural changes in management can lead to increased risks (Howard, 2019).

Smart wearable devices, sensors, and advanced cameras can process environmental data in real time and issue warnings in case of danger (Alizadeh & Larijani, 2018). Moreover, data mining and machine learning are important tools for preventing production hazards (Rowse, 2024).

In alignment with the objectives of this study, several recent works have explored the integration of Industry 4.0 technologies in enhancing safety, product development, and quality management. Studies investigated the application of Industry 4.0 technologies to improve health and safety issues in Malaysia's construction sector using the Analytic Hierarchy Process (AHP). These findings revealed that Building Information Modeling (BIM) and wireless monitoring systems held the highest prioritization scores (0.3855 and 0.3509 respectively), indicating their significant potential in transforming health and safety practices in construction (ComplianceQuest, 2025). Similarly, Santos et al. (2024) conducted a systematic literature review to examine the influence of the Fourth Industrial Revolution on product design and development processes (PDDP). Their analysis demonstrated that the effects of IR 4.0 extend beyond manufacturing systems to encompass the entire value chain, emphasizing the need for intelligent design engineering to fully leverage technological advancements (Santos et al., 2024). Additionally, another study provided a comprehensive review of performance measurement systems and quality management within data-driven Industry 4.0 environments. Their study focused on how manufacturing industries utilize industrial standards, performance indicators, and case-based insights to adapt quality management systems and improve performance within smart manufacturing contexts (Saihi et al., 2023). Collectively, these studies underscore the transformative potential of Industry 4.0 across domains of safety, design, and quality, and highlight the strategic need for integrated models to guide industrial adaptation.

Predictive analytics and worker localization through the Internet of Things enable pre-incident control and prevention (Zorzenon et al., 2023). Augmented reality technology also enables real-time display of safety warnings (Polak-Sopinska & Wisniewski, 2020). Therefore, based on the significance of technological transformations in the Fourth Industrial Revolution in quality and safety management, this study seeks to answer the following question: What is the model of quality and safety management under the Industry 4.0 approach?

2. Methods and Materials

The present study is categorized as qualitative research. Given the existing theoretical gap, the study employed the systematic approach of Strauss and Corbin (1998) for grounded theory development in the domain of quality and safety management as its primary qualitative methodology. This approach seeks to provide a model for a deeper understanding of quality and safety management. Grounded theory is a type of qualitative research method that inductively applies a series of systematic procedures to develop a theory about the phenomenon under investigation.

The statistical population consisted of academic experts and specialists in the fields of quality and safety management. The sample included 15 participants selected using purposive sampling of the snowball type. Interviewees were asked to recommend other experts in this domain, which reflects the snowball sampling strategy commonly used in qualitative studies. Purposive sampling in qualitative research refers to the intentional selection of individuals who are likely to contribute effectively to understanding the research problem and the core phenomenon of the study.

To collect data, in-depth semi-structured interviews were conducted. Prior to each interview, participants were provided with a summary of the research design, definitions of key terms used in the study, research objectives, and main research questions via email, Telegram, or in person to ensure their initial preparedness. At the beginning of each interview session, a brief explanation of the study and its progress was given.

The characteristics of the research participants are presented in Table 1.

Table 1

Participant Characteristics in the Research Process

Education Level	Field of Study	Position	No.
Ph.D.	Quality Management	Executive Vice President	1
M.A.	IT Management	Planning Deputy	2
Ph.D.	Economics	CEO	3
Ph.D.	Executive Management	Deputy Minister	4
M.A.	Marketing Management	Company Vice President	5
Ph.D.	Public Administration	Parliamentary Representative	6
M.A.	Economics	Planning Deputy	7
Ph.D.	Budget Management	Executive Vice President	8
Ph.D.	Economics	Executive Vice President	9
Ph.D.	Public Administration	Member of Parliament	10
M.A.	Technology Management	Planning Deputy	11
M.A.	Quality Management	Executive Vice President	12
Ph.D.	Quality Management	University Professor	13
Ph.D.	Quality Management	University Professor	14
Ph.D.	Strategy	University Professor	15

Furthermore, according to Creswell and Creswell (2018), qualitative researchers should utilize validation strategies in every study. The validation of this research was carried out through dual coding and member checking. The coding process was conducted separately by two individuals (the researcher and a colleague), and the extracted codes were compared. Cohen's Kappa coefficient was calculated to be 86.9%, with a significance level of $p = .001$, indicating almost perfect agreement between the two sets of coding.

Additionally, three experts in the field of quality and safety management, in collaboration with the research supervisor and advisors, reviewed and refined the categories and the proposed model to enhance its rigor and accuracy. For member checking, three interviewees with relevant academic backgrounds reviewed the results of the coding, categorization, and modeling processes. Their feedback was incorporated into the final revisions.

3. Findings and Results

In this study, data were documented concurrently with the collection of interviews based on the Strauss and Corbin

(1998) process through audio recordings and simultaneous note-taking. The content of the interviews was transcribed into textual files, which were then analyzed and coded. After reviewing the data obtained from the 15 conducted interviews, 22 categories were extracted, as presented in tables below.

In this model, causal conditions refer to events that generate situations and issues related to a phenomenon, explaining why and how individuals and groups respond in particular ways (Strauss & Corbin, 2008). Causal conditions include categories that directly impact the quality and safety management model under the Industry 4.0 approach or serve as generating and developing factors of the phenomenon. The categories related to causal conditions are shown in Table 2.

Table 2

Causal Categories (Main and Sub-Categories)

No.	Sub-Category	Sample Concepts Extracted from Interviews	Interviewee Code
1	Weak Technological Infrastructure	Lack of digital infrastructure in production lines / incompatibility of existing equipment with Industry 4.0 / outdated control equipment / limited access to real-time data / weak automation / absence of sensors and smart systems	P1, P2, P4, P5, P6
2	Cultural and Organizational Resistance	Preference for traditional methods over technological ones / fear of data transparency / lack of acceptance at management levels / conflict with hierarchical culture / concern over job loss / distrust in new technologies	P1, P10, P12, P9, P11, P3
3	Insufficient Training and Awareness	Lack of technology-oriented training programs / insufficient digital skills / unawareness of safety 4.0 requirements / no experience with smart tools / traditional view of quality / unfamiliarity with data analysis	P12, P7, P5, P6
4	Weak National Supportive Policies	Absence of governmental incentives / lack of expert consultation from policy institutions / weakness in developing a digital transformation roadmap / insufficient financial support for industries / challenges in obtaining smart transformation permits / weak intermediary institutions	P10, P14, P5

Contextual conditions refer to the specific set of characteristics related to the phenomenon, generally pointing to the location of events and occurrences. These conditions include factors without which the realization of the quality and safety management model under the Industry 4.0 approach would not be possible. They form the context within which strategies for managing, controlling, and responding to the phenomenon are applied. These are composed of various concepts, categories, and contextual variables. The main contextual factors of the model in this study are shown in Table 3.

Table 3

Contextual Categories (Main and Sub-Categories)

No.	Sub-Category	Sample Concepts Extracted from Interviews	Interviewee Code
1	Traditional and Inefficient Organizational Structure	Centralized and slow decision-making / resistance from management levels to change / severe bureaucracy / lack of agility in responding to technological change / rigid hierarchical structure / neglect of internal innovation	P9, P11, P12, P7
2	Lack of Skilled Human Resources	Shortage of technically skilled personnel / lack of practical knowledge about Industry 4.0 / lack of motivation to learn / weak data literacy / failure to update employee capabilities / limited specialization	P1, P2, P9, P11
3	Lack of Interdepartmental Coordination	Ineffective communication between departments / fragmented decision-making / activity overlap / conflict between safety and production units / absence of a common execution framework / lack of data sharing	P13, P15, P12
4	Financial Problems and Budget Constraints	Insufficient capital for modernization / inadequate R&D budget allocation / low priority of safety in resource allocation / no resources for technological training / limits in smart equipment procurement / financial instability	P1, P2, P3, P6, P7, P10

Intervening conditions include broader circumstances such as time, space, and culture that act as enablers or barriers to strategies. These conditions influence the facilitation or limitation of action/interaction in a specific context. Each condition forms a continuum, with its impact ranging from very distant to very immediate. The intervening categories in this study are shown in Table 4.

Table 4

Intervening Categories (Main and Sub-Categories)

No.	Sub-Category	Sample Concepts Extracted from Interviews	Interviewee Code
1	Role of Technological and Scientific Institutions	Collaboration of universities in safety system design / technical consulting from incubators / research support from technology parks / development of local platforms / provision of specialized training / engagement with top academic institutions	P2, P3, P4, P11, P12, P14
2	Existence of Knowledge and Communication Networks	Presence of industrial clusters / experience sharing by successful firms / innovation exchange platforms / networking with tech companies / collaboration between industry and academia / experience-sharing sessions	P14, P13, P7
3	Access to Digital Infrastructure	Availability of stable internet networks / possibility of using cloud platforms / access to data acquisition systems / integration of control systems with monitoring software / use of IoT / data analytics platforms	P1, P7, P8, P9, P10, P12

The phenomenon under investigation must serve as the core, meaning that all other major categories can be related to it and that it appears repeatedly throughout the data. In this context, a core phenomenon refers to the central idea or process that integrates all other main categories. In this study, the core category is presented in Table 5.

Table 5

Core Categories (Main and Sub-Categories)

No.	Sub-Category	Sample Concepts Extracted from Interviews	Interviewee Code
1	Designing an Integrated Model of Quality and Safety Management	Integration of quality management systems with safety requirements / designing intelligent alert systems / coordination between safety and quality standards / process-based approach to safety / modeling safety systems in digital environments / data-driven error analysis	P1, P7, P8, P9, P10, P12
2	Reengineering Operational Processes	Reanalysis of workflow using digital tools / eliminating quality bottlenecks / increasing automated monitoring of operations / electronic documentation of processes / streamlining quality control pathways / integration of data with control systems	P3, P4, P5, P6, P10, P13, P14
3	Developing Employees' Digital Skills	Designing Industry 4.0-based training courses / motivating employees for technological learning / training on smart safety systems / empowering employees in safety data analysis / training in the use of quality control dashboards / fostering a culture of continuous learning	P1, P2, P8, P10, P12, P9, P11

Strategies refer to the action plans and responses that emerge from the core category of the model and lead to the outcomes. Strategies are sets of measures taken to manage, operate, or respond to the phenomenon under study. In this study, the strategic categories are presented in Table 6.

Table 6

Strategic Categories (Actions/Responses – Main and Sub-Categories)

No.	Sub-Category	Sample Concepts Extracted from Interviews	Interviewee Code
1	Formulation and Implementation of Industry 4.0 Standards	Development of integrated safety-quality guidelines / digital process control checklists / use of data-based KPIs / expansion of digital inspection requirements / alignment with global standards / localization of successful models	P3, P4, P5, P6, P10, P13, P14
2	Implementation of Targeted Educational Programs	Designing internal training platforms / on-the-job training for Industry 4.0 tools / enhancing digital safety literacy / developing error analysis competencies / training in dashboard usage / integrated quality and safety workshops	P1, P2, P5, P7, P9
3	Digitization of Operational Systems	Use of smart alert systems / real-time process monitoring / installation of safety sensors / connecting equipment to cloud platforms / automated error reporting / real-time analysis of quality and safety data	P4, P5, P6, P10, P15, P14, P13, P7, P8, P11
4	Institutionalizing a Digital Transformation Culture	Creating a change-accepting environment / strengthening communication between managers and staff / identifying transformation leaders / conducting interactive team sessions / leveraging successful experiences / increasing employee ownership of change	P1, P2, P8, P11, P12

Outcomes are the results or consequences of actions and responses. Based on open coding, the concepts related to model outcomes were extracted, then through iterative analysis between themes and concepts, the main categories were identified and named. Table 7 presents the categories and concepts related to outcomes.

Table 7

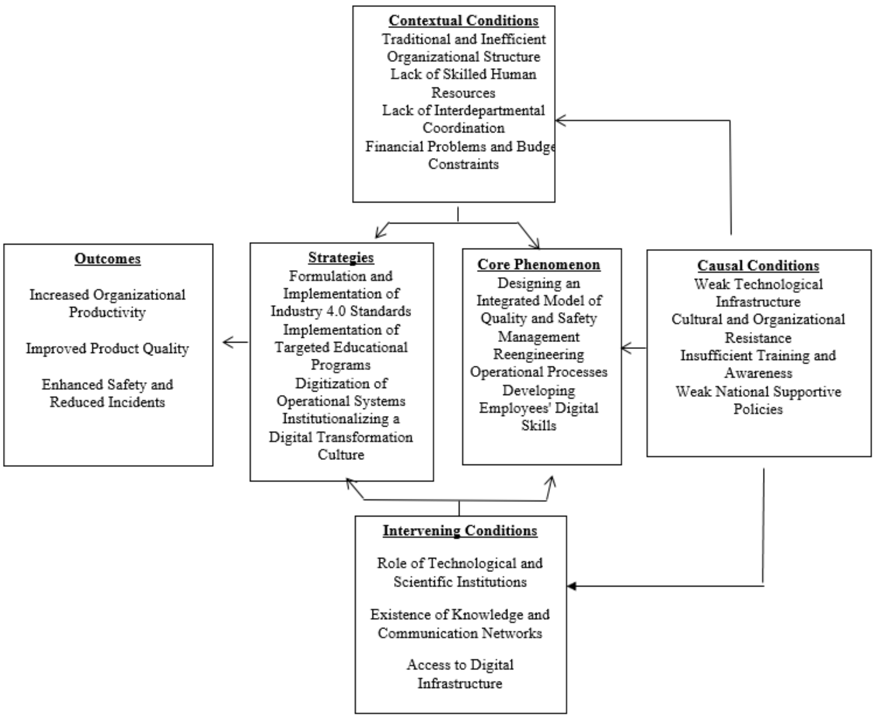
Outcome Categories (Actions/Responses – Main and Sub-Categories)

No.	Sub-Category	Sample Concepts Extracted from Interviews	Interviewee Code
1	Increased Organizational Productivity	Reduction of rework / faster error identification / decreased production downtime / improved equipment efficiency / enhanced interdepartmental coordination / effective use of operational data	P2, P3, P4, P5, P13, P9, P11, P12, P15
2	Improved Product Quality	Increased quality control accuracy / reduced deviation from standards / continuous quality data monitoring / lower product return rates / increased customer satisfaction / data-driven product development	P1, P12, P9, P11, P7
3	Enhanced Safety and Reduced Incidents	Decrease in workplace accidents / preventive alerting in the workplace / improved staff awareness / quick response to safety errors / root cause analysis of incidents / use of smart safety equipment	P3, P5, P6, P10, P15, P14, P7, P8, P14

The paradigmatic model of this research was developed based on the paradigmatic framework of Strauss and Corbin. Given the identified factors and conditions, the model and process of quality and safety management under the Industry 4.0 approach were designed. Identifying the causal factors underlying this subject was also a primary concern of the study. Figure 1 illustrates the relationships among categories according to the paradigmatic model, following evaluation and confirmation by the study participants.

Figure 1

Paradigmatic Model of the Study



4. Discussion and Conclusion

The aim of this study was to design a model for quality and safety management based on the Fourth Industrial Revolution (Industry 4.0). Data were collected through 15 semi-structured interviews with experts in the fields of quality, safety, digital transformation, and industrial management and were analyzed using the systematic method of Strauss and Corbin (1998). The analysis resulted in the extraction of 22 key categories under the dimensions of causal, contextual, and intervening conditions, strategies, consequences, and the core category. The core category of the study was identified as "Designing an Integrated Model for Quality and Safety Management Based on Industry 4.0."

Findings revealed that the primary causes of failure to implement modern quality and safety management models in industries include weak technological infrastructure, cultural resistance, insufficient training, and lack of institutional support. These results align with global literature (Alizadeh & Jalali Filshour, 2023; Koh & Tan, 2024; Rowse, 2024; Saihi et al., 2023; Santos et al., 2024; Zorzenon et al., 2023) which emphasize the importance of digital maturity and cultural readiness. In terms of intervening conditions, the significant roles of universities, technology parks, and knowledge networks were confirmed, which is consistent with the prior findings (Darbanhosseiniamirkhiz & Shamsuzzoha, 2021; Martínez-Costa & Martínez-Lorente, 2021; Polak-Sopinska & Wisniewski, 2020) regarding industry-academia interaction. The strategies adopted—such as process reengineering, smart equipment deployment, and employee training—are also in accordance with operational models proposed by ISO 45001:2018 and ISO 9001:2015, validating the reliability of the proposed model.

1. Recommendations for Industrial Managers

Organizational Structure Review: Managers should dismantle traditional hierarchical structures and promote interdisciplinary teams to enhance organizational agility in adopting Industry 4.0 technologies.

Targeted Investment in Infrastructure: The development of smart equipment, monitoring systems, and data analytics platforms should be prioritized in budgeting to mature the digital infrastructure of industries.

Fostering a Digital Culture: By organizing consultative meetings and dialogues with staff on the benefits of smart systems, managers can reduce cultural resistance and enhance technology acceptance.

Establishment of a Digital Transformation Unit: Organizations are advised to establish a dedicated unit responsible for policy-making, training, and monitoring the transition to Industry 4.0.

2. Recommendations for Policymakers and Governmental Institutions

Development of a National Digital Quality and Safety Framework: Relevant ministries should develop strategic documents for localizing international standards (e.g., ISO 45001 and ISO 9001) in the context of Industry 4.0.

Targeted Financial Support for SMEs: Providing loans and financial incentives for equipping small and medium-sized enterprises with advanced technologies and smart safety tools is essential.

Creation of Knowledge Networks and Industrial Clusters: The government should build communication infrastructure between industry, academia, and incubators to facilitate knowledge transfer and innovation.

Expansion of Training Capacity in Vocational Centers: Planning to provide specialized training related to digital safety and quality in technical and vocational education centers is crucial for empowering the workforce.

3. Recommendations for Educational Institutions and Universities

Design of Interdisciplinary Programs: Universities should develop majors or concentrations focused on "Quality and Safety Management in Industry 4.0" and offer them in an applied manner.

Establishment of Digital Safety Simulation Laboratories: Utilizing technologies such as augmented reality (AR) and process simulation can support practical training and enhance safety in industrial settings.

Implementation of Joint Research Projects with Industry: Supporting theses and applied projects in collaboration with industrial units can be an effective step in addressing real-world industrial challenges.

In line with the above recommendations, future researchers are advised to use the fuzzy Delphi technique to identify and prioritize the components of quality and safety management. Moreover, it is recommended that the impacts of the quality and safety management model based on the Industry 4.0 approach be evaluated against conceptually relevant constructs using appropriate semantic proximity analysis.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethics Considerations

In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were considered.

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