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REVIEW ARTICLE

Attractive features of digital health care and big data analytics: A critical infrastructure for nation building and shaping the future of innovation

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Abstract

Digital health care and smart health care are emerging as transformative paradigms for modernizing traditional healthcare infrastructure, recognized as a critical pillar of nation-building and aligned with the United Nations Sustainable Development Goals (SDG-17). The seamless integration of big data analytics with healthcare systems enables the development of advanced data-driven ecosystems capable of managing massive, complex, heterogeneous, and real-time patient-centric information. A wide spectrum of information and communication enabling technologies—including the Internet of Things, cloud and edge computing, artificial intelligence (AI), machine learning, 5G, smart biosensors, bioinformatics, biomarkers, and mathematical optimization techniques—are converging to deliver personalized and patient-centric healthcare solutions. Furthermore, AI-based drug discovery and multi-omics approaches (genomics, proteomics, metabolomics, and pharmacogenomics) accelerate innovation in precision medicine. The fusion of medical sciences, computer science, and AI technologies is reshaping innovation, healthcare delivery, and public policy, although the absence of unified global standards remains a challenge. This study explores the attractive features of digital health care and big data analytics, highlighting their potential to revolutionize healthcare innovation and policy reform for sustainable nation-building. Although this work highlights the potential of digital and smart health care in reshaping healthcare infrastructures, it remains largely descriptive and conceptual. In this review, an effort is made to assess the attractive features of digital health care and big data analytics and their impact on reshaping innovation in medical sciences and AI technologies for nation-building. Public policy is undergoing a changing phase, with active consideration and massive reforms.

Keywords: Digital health care; Big data analytics; MEDICAL 4.0; Sustainable Development Goal 3; E-health; M-health; Bioinformatics; Critical infrastructure

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1. Introduction

Traditional healthcare services and existing infrastructure are facing crucial challenges due to a rapidly growing population with chronic diseases and an acute shortage of advanced clinical and diagnostic research, personalized medicine, and medical infrastructure to address the complex set of problems. It is estimated that in the future, an additional 30% in funding will be needed to maintain the quality of healthcare services in developing countries, which represents an excessively demanding cost. Through the advancement of smart medical services—emerging from the integration of advanced computer-communication technologies and medical sciences—healthcare delivery is becoming increasingly accurate and data-driven, with a stronger focus on patient-centric treatment. However, this transformation requires a highly favorable doctor–patient ratio, skilled medical and paramedical staff, and a capable workforce to manage the digital divide and support the critical infrastructure necessary for nation-building.

Innovation in healthcare results from the convergence of value-based technologies, artificial intelligence (AI), machine learning (ML), medical sciences, biological processes, clinical research, biosensors, wireless communication, and drug discovery processes. This convergence enhances the quality of medical support systems, increases operational efficiency, and drives the development of data-driven, value-based personalized healthcare services.

Seamless integration of big data analytics, new generation computer-communication technologies, and information and communication technologies (ICTs) at the forefront into traditional healthcare systems can create a highly complex, multidimensional, fragmented, heterogeneous, real-time, widely distributed, and evolving digital healthcare system. This body of science, assisted by soft computing and digital technologies, has laid the foundation for developing a novel capacity-building model for traditional public health care. Moreover, the seamless integration of big data analytics with digital health care has evolved into a powerful, transformative critical infrastructure referred to as "MEDICAL 4.0." It places the well-being of people at the center stage and effectively satisfies the requirements of Sustainable Development Goal 3 (SDG-3). It involves multiple stakeholders, such as medical professionals, researchers, and scientists, with a wide range of expertise across the subject domains. As a result, digital healthcare produces massive, highly complex medical datasets (unstructured, semi-structured, and structured) collected from a large number of sources. Digital healthcare analytics are responsible for developing value-based, patient-centric, disruptive health information systems across medical fields. Thus, technology optimizes resources, enhances operational and functional efficiencies, improves value extraction, and facilitates knowledge discovery from complex datasets. A robust framework for greater accessibility should enhance the quality of healthcare services, expand coverage, and deliver cost-effective, patient-centric solutions to the hard-to-reach population. Therefore, digital healthcare requires the powerful integration of advanced mathematical tools, computer-communication techniques, and AI to realize descriptive, diagnostic, predictive, prescriptive, and cognitive analytics from digital healthcare products.

This paper aims to identify the attributes and quality of service (QOS) parameters to develop an evidence-based, data-driven MEDICAL 4.0 technology to enhance patient outcomes, early disease detection, personalized treatment plans, high-quality public healthcare services, and proactive management of chronic conditions.[1-5]

1.1. SDG3

Digital health and big data analytics represent a critical infrastructure for nation-building, directly aligning with the United Nations' SDGs proposed in 2015. These 17 global goals aim to eradicate poverty, ensure prosperity, and protect the planet, with a target for achievement by 2030. Among them, SDG-3 (Good Health and Well-Being) is pivotal, comprising 13 targets and 28 indicators, according to the Development Report.[6]

The progress on SDG-3, as outlined in the 2022 Sustainable Development Report,[6] is categorized into four qualitative parameters: Very good, good, fair, and poor. Achieving these targets remains a significant challenge, particularly in regions with high disease burdens and inadequate public healthcare systems. According to the World Health Organization (WHO), at least 400 million people lack access to basic healthcare, over 1.6 billion live in fragile conditions, and more than 4 million are without essential social protection. Bridging these gaps requires innovations driven by advanced technologies and data analytics to address healthcare inequities.[6-9]

1.2. Big data analytics

Big data are defined by the National Institute of Standards and Technology as the vast and complex datasets generated in a networked, sensor-driven, and information-centric environment. It is characterized by volume, velocity, variety, veracity, variability, visualization, and value (7Vs). Big data necessitates new architecture and advanced analytics tools to extract meaningful insights. Analytics encompasses processes, frameworks, algorithms, and technologies designed to extract valuable information from datasets, particularly in the healthcare domain.

According to the WHO, digital health is a multidisciplinary concept that leverages digital transformation to optimize healthcare delivery. It includes integrating software, hardware, and services to manage illnesses, mitigate health risks, and promote well-being.

WHO's global strategy on digital health emphasizes strengthening healthcare systems through innovative technologies to ensure health equity for all.[10-12]

Digital health systems generate massive, real-time datasets from diverse sources, such as electronic health records, medical imaging, wearable devices, and genomic sequencing. However, most of these data are semi-structured or unstructured, making traditional analytical methods insufficient for processing. Big data analytics offers solutions by handling complex datasets, filtering valuable insights, detecting emerging trends, and enhancing healthcare quality. It facilitates patient-centric, data-driven decision-making that optimizes costs and improves outcomes.

1.3. The growing impact of big data in health care

The healthcare sector contributes approximately 30% of the world's data volume, with a compound annual growth rate of 36% anticipated by 2025. The global market value of big data analytics in health care was estimated at US$23.94 billion (approximately US$74/person in the United States [US]) in 2020, projected to grow to US$101.07 billion (about US$310/person) by 2031, reflecting its transformative potential.

Such datasets, comprising structured, semi-structured, and unstructured information, support decision-making processes across health care, enabling value-based care, resource optimization, and enhanced patient experiences.[13-16]

The convergence of digital health technologies with big data analytics is reshaping the healthcare landscape. By integrating diverse data sources and leveraging cutting-edge technologies, digital health systems aim to build efficient, evidence-based, and patient-centric healthcare models essential to achieving SDG-3 and driving sustainable nation-building efforts.

1.4. Critical infrastructure

According to the European Union Commission's Green Book, critical infrastructure consists of physical resources, services, ICT facilities, communication networks, and assets that, if disrupted or destroyed, would have profound impacts on security, safety, services, the national economy, and government functioning. The following is the list of critical infrastructures that may vary from country to country and be aligned with SDG-17:

(i) Agriculture and food
(ii) Chemistry and biology
(iii) Energy, including renewable energy sources
(iv) Defense and industry
(v) ICT
(vi) Emergency services
(vii) Public health care
(viii) Environment
(ix) Education
(x) Banking and finance
(xi) Commercial facilities
(xii) Transport systems
(xiii) Power plants, generation, transmission, distribution, and utilization of electrical energy.

1.5. Role of emerging technologies in nation-building

Robust, reliable critical infrastructure is a fundamental requirement for nation-building.[17] Such infrastructure has three dimensions—political, economic, and technical—and leverages advanced digital and healthcare technologies to enhance productivity, security, sustainability, and socioeconomic development.

2. Critical literature review

The architecture of traditional healthcare infrastructure was designed to provide essential medical services to ordinary people based on a publicly funded and a private chain of hospitals and clinics. The healthcare services include the collection, formatting, processing, and analytics of medical datasets using advanced AI techniques to improve healthcare delivery, treatment, diagnoses, clinical research, and the supply of standard medicines at a reasonable cost to large sections of the population. The quality of medical support varies from country to country, depending on cost, access, affordability, the healthcare policies adopted, budget allocation, and disease burden. Traditional healthcare systems are facing crucial challenges, especially regarding the availability of quality medical care in low- and middle-income countries with high disease burdens.

Medical professionals, scientists, and policymakers are working to develop an advanced healthcare system empowered by AI, soft computing, big data analytics, wearables, robotics, m-health, smart sensors, and non-invasive biosensors. These technologies sense, collect, store, process, and analyze complex biomedical datasets to address challenges and to propose innovative, patient-centric, value-based smart medical support systems that are low-cost, widely accessible, and capable of delivering services across large geographic areas. One of the crucial goals of integrating digital health, big data analytics, and AI technologies is to create high-quality datasets to achieve multi-objective functions, including accuracy, patient-centric care, and smart healthcare systems.[18] Health care data are a subset of big data collected in different formats, including medical records, laboratory reports, medical images, and even social media posts.[18] This variety makes it challenging to combine and analyze the data. To solve this issue, researchers use conversion methods to standardize the data into formats suitable for analysis.[19,20]

In healthcare datasets, data mining techniques are used to identify hidden patterns in the data.[9] These patterns support treatment decisions[21] and early disease detection to prevent health complications.[22] During the COVID-19 pandemic, big data played a key role in tracking the spread of the virus and supporting public health measures.[23] Healthcare data also support the development of treatment plans[11,24,25] and help create more efficient healthcare systems.[20] From a business point of view, big data analytics improves performance by reducing errors, improving workflow, and cutting unnecessary costs.[25,26] Analytical techniques such as statistical analysis and predictive modeling support the handling of large-scale health records.[27] With the growth of online tools and cloud computing, health data can be processed more rapidly and securely.[28,29] Data processing tools help clean and organize raw data, whereas visualization tools present the data clearly for healthcare professionals and managers to understand.[6,30-35]

New technologies, such as real-time streaming analytics, allow experts to analyze data from wearable devices or hospital monitors on the spot.[9,27,36,37] This supports faster and more accurate decisions, especially with live physiological data.[26,30,38,39] However, there are still challenges. These include a lack of trained staff, resistance to adopting new systems, and issues with data sharing.[40] Even with these challenges, healthcare technologies help reduce costs[7] and support smarter and more efficient healthcare systems. Electronic health records, including patient history and laboratory results, form the core of most healthcare data systems.[8,41] These data also guide decisions on future healthcare policies, staffing, and patient care management.[27]

According to the existing literature, health care is divided into specific areas that offer clear benefits.[42-44] In addition, many agents are involved in the success of big data in health care: Patients, healthcare workers, managers, and policymakers. Their cooperation is essential to turn data into meaningful actions that benefit everyone.[45]

2.1. Convergence of healthcare technologies

Health care worldwide is undergoing a major transformation through the integration of medical science with the latest technologies. The convergence of technologies is generating massive amounts of specialized medical datasets, which have unique frequency spectrums and are collected from diverse sources. These datasets are challenging to format, extract, store, and analyze using conventional computer-communication systems and existing mathematical tools and techniques. By 2025, the compound annual growth rate of healthcare data will reach approximately 36%—6% faster than manufacturing, 10% faster than financial services, and 11% faster than media and entertainment. It is a substantial challenge to access and utilize massive medical datasets in hard-to-reach populations and in countries with high disease burdens. Thus, the ongoing research and development aim to design global networks to track healthcare activities and critical health information, thereby providing massive connectivity, improved communications between doctors and patients, and real-time recording of medical conditions, especially among elderly populations having limited mobility and suffering from chronic diseases. The technology under development remained fragmented, complex, and ambiguous, and it faces numerous challenges related to its practical implementation and the assessment of QOS in smart health care.[46-49]

2.2. Critical components of the digital healthcare system

A digital healthcare system is the product of integrating emerging technologies to address the complex QOS parameters of public health and serves as a critical infrastructure for nation-building, aligning with SDG-17. The following components are identified for building blocks of smart healthcare technologies, creating a connected, data-driven, human-centric, well-structured, and proactive healthcare ecosystem:

(i) Data sources: Populations suffering from various diseases, disease carriers, registered patients, medical imaging, electrocardiography, electroencephalography, X-rays, computed tomography (CT), magnetic resonance imaging (MRI), glucose level, blood pressure level, peripheral oxygen saturation level, pulse rate, insulin level, implantable medical devices, etc.

(ii) Sensors and biomedical devices: These constitute the second layer, which is responsible for collecting real-time patient data, including physiological signals and biosignals generated and collected by medical devices.

(iii) Data processing and analytics: This is a key component of health care. The medical datasets collected from smart sensors, medical devices, and wearables are massive, complex, unstructured or semi-structured, and need to be processed, stored, formatted, visualized, organized, and analyzed using advanced computer-communication technologies, modern mathematical tools, and techniques for value extraction and knowledge discovery.

(iv) Connectivity and networks: The proposed digital healthcare system generates health datasets for further action, facilitating information sharing through cloud platforms, wireless communication networks, and Bluetooth. It supports very high-throughput data transmission among various stakeholders with well-defined objectives such as improved operational efficiency, data-driven decision-making, cost-effective solutions, reliable data communication, and management of multidimensional activities within a patient-centric healthcare ecosystem tailored to individuals' unique data and characteristics. In addition, it emphasizes protecting sensitive and confidential data from unauthorized access.

(v) Applications and protocols: Some of the basic aims of digital health care—as a new enabling technology—are early disease detection, remote monitoring, preventive care, interoperability, and the integration and modernization of existing public health systems. It also focuses on scalability, high resolution, and accuracy, building confidence, supporting clinical trials, knowledge discovery, and delivering personalized, patient-centric treatment. In addition, digital health care seeks to remove demographic barriers, assess disease burdens in hard-to-reach populations, and comply with regulatory frameworks and protocols developed by the WHO and other regulatory bodies. Ultimately, it strives to make medical care models more user-friendly, affordable, implementable, simple, and intelligent.

3. Digital health care

Digital health care is in an active research and development phase aimed at modernizing traditional healthcare infrastructure. It is increasingly regarded as critical infrastructure for nation-building and is embedded in SDG-17. The seamless integration of big data analytics and digital health care may create an advanced data-driven ecosystem to address the challenges of building a very large, complex, heterogeneous, fragmented, multidimensional, real-time, time-variant, and dynamically distributed patient-centric system. A set of ICT technologies enables personalized medicine and pharmacogenomics to accelerate digital health care (a combination of digital health care and big data analytics systems). The fusion of technologies is creating a fragmented global landscape of solutions under development, as there are limited global standards and frameworks approved by the WHO or other recognized regulatory bodies. In this research article, an effort is made to assess the attractive features of digital health care and big data analytics, and their impact on reshaping the future of innovation—emerging from the fusion of medical sciences, computer-communication, and AI technologies—for nation-building. Public health care is undergoing a changing phase globally, with active consideration of massive reforms.[50-52]

3.1. Health analytics

In general, the terms "health data" and "health analytics" are used ubiquitously to encompass crucial components of the digital healthcare ecosystem. They include a set of emerging technologies and a systematic approach to the collection, processing, and analysis of medical datasets for knowledge extraction. They encompass datasets that are big, complex, time-variant, heterogeneous, and sometimes vague, originating from diverse medical devices, biosensors, and non-invasive techniques. Initially, the datasets are classified as unstructured or semi-structured, massive, and having specific frequency spectra (e.g., electroencephalography, electrocardiography, heart rate, and blood pressure). This complexity poses difficulty for storage, processing, and analysis using conventional data communication networks, which have limited capacity to handle such large-scale datasets. Therefore, health care data analytics needs to be properly moderated, organized, planned, and systematically formatted to extract valuable insights from raw data related to diseases, drugs, clinical research, and diagnostics, enabling effective adoption by medical professionals.

Medical and data professionals, system analysts, scientists, and statisticians are deeply involved in formatting, processing, and analyzing data to improve medical services to hard-to-reach populations and those with high disease burden. The complex process of turning raw, massive, and complex data into valuable insights and knowledge discovery includes the following steps:

(i) Data collection: The first step is to capture data from massive, heterogeneous, unstructured, and diverse biomedical sources, wireless body area networks, and the Internet of Things (IoT) for better management and accessibility purposes.

(ii) Data processing: The second step involves organizing health data into appropriate formats and loading them into a data storage system to achieve accurate analytical outcomes. This process may include aggregating data and converting it into formats suitable for batch and distributed computing, as well as handling real-time data batches.

(iii) Data denoising: The raw data consists of two components, namely information-bearing signals and unwanted noise signals. Both components have different frequencies and gain bandwidths. Regardless of characteristics, size, complexity, and variability, raw data need to be filtered and cleaned for proper processing, ensuring accuracy and reliability.

(iv) Data analysis: Advanced analytics tools and techniques such as clustering, feature extraction, data mining, descriptive, diagnostics, predictive, prescriptive, preventive, clinical, and cognitive analytics (referred to as the 2D 3P 2C model). Basic statistics, linear algebra, graph theory, integration, differential equations, Markov chains, fuzzy logic, optimization techniques, digital signal processing, structured query language, AI, ML, deep ML, and Power BI are used to design a critical decision healthcare ecosystem that addresses crucial quality-of-care issues and other complex challenges.[38,42,53,54]

3.2. Importance of healthcare data analytics

The proposed healthcare data analytics 2D 3P 2C model has enormous potential to transform the sector and create new waves of innovation and creativity in managing multiple aspects of the medical sector, quality medical services, and cost-effective solutions, thereby enhancing reliability and accuracy and expanding the canvas of digital health care that is highly suitable for hard-to-reach populations and those with a considerable disease burden. Moreover, the model ensures that all biomedical devices are clinically validated for accuracy and satisfy the highest international standards for precision, reliability, and biomarker specifications set by the relevant regulatory bodies. Health care analytics has enormous capacity to transform operating conditions, inform intelligent decisions, and create an environment of innovations and a patient-centric decision support system for dealing with massive, complex, and real-time health datasets. Big health data analytics has the following benefits:

(i) Knowledge-based decision-oriented public healthcare system: Medical professionals, scientists, researchers, and relevant stakeholders can propose intelligent decisions based on actual data, thereby reducing uncertainty and improving the quality of care and outcomes.

(ii) Clinically validated results: With the advancement of digital devices, sensors, fusion techniques, and clinically validated approaches, precise test results are accessible to healthcare providers, thereby providing improved treatment and quality healthcare services to low-income groups.

(iii) Operational efficiency: Analyzes formatted data, utilizes advanced optimization techniques, identifies the constraints, and streamlines the systematic operations that improve productivity.

(iv) Personalized and patient-centric care: By advancing hardware, software, data communication, IoT, and wireless sensor networks, health service providers can collect and efficiently process massive unstructured data generated from individuals with disease burden, thereby enabling personalized, patient-centric, and impactful decisions.

(v) Innovation and intelligence: Medical data analytics is an emerging technology to extract valuable insights from large-scale populations. It creates new research opportunities in the health sector. This opens a new space for innovation, creativity, and data-driven business models.

(vi) Real-time intelligence: One of the key goals of big data analytics is the power to integrate the complex, time-variant, massive data for value extraction, knowledge discovery, and real-time intelligence operations in healthcare services.

(vii) Cost savings: Big data analytics are a set of powerful emerging technologies and have multiple advantages, including enhanced operational efficiencies, reliable, faster response, and, more importantly, cost-saving and the ability to streamline the operations of analysis, thereby enhancing responses and productivity. Moreover, it is suitable for the proposed 2D 3P 2C model formulations and capable of future trend prediction, real-time analysis, and the prevention of costly missteps in health care.

(viii) Risk management strategies: Understanding the dynamics of patient-centric outcomes and big data analytics provides the scientific tools to gain insight into disease classification data. Subsequently, healthcare professionals can plan risk management strategies accordingly.

The proposed 2D 3P 2C model provides digital healthcare services that integrate big data analytics to offer the following advantages to address crucial issues of public health care:

(i) High-speed processing and information sharing among connected stakeholders.

(ii) Quality treatment and services to hard-to-reach populations at low cost.

(iii) Better prediction of patient outcomes and personalized care.

(iv) Improved quality of life for people in general and enhanced health outcomes for nations in particular.

(v) Creation of knowledge discovery from raw datasets by transforming them into a digital format.

(vi) Intelligent, smart, efficient, reliable, and cost-effective system for countries with high disease burdens.[10,42]

3.3. Big data analytics in digital health care

Advanced medical facilities rely on past and present datasets, as well as projected future data. The goals and objectives of data analytics are identified and tailored for

each specific application. Health care data analytics are classified using the proposed 2D 3P 2C model. Figure 1 depicts the healthcare data classification model.
(i) Descriptive analytics
(ii) Diagnostic analytics
(iii) Predictive analytics
(iv) Prescriptive analytics
(v) Preventive analytics
(vi) Clinical analytics
(vii) Cognitive analytics.

The key objectives are as follows:
(i) Extract value and information from raw, complex, vague, and time-variant medical data generated from bioprocesses of human beings to develop an information-driven decision support and knowledge discovery system.
(ii) Improve QOS parameters.
(iii) Collect and format datasets.
(iv) Develop cost-effective smart solutions.
(v) Optimize the ICT resources.
(vi) Achieve well-defined goals.
(vii) Identify patterns.
(viii) Analyze risks.
(ix) Design, model, and analyze data.
(x) Enhance processing speed, reliability, and accuracy.
(xi) Ensure security and safety.
(xii) Improve data quality and critical infrastructure to achieve SDG-3.

3.3.1. Descriptive analytics

Descriptive analytics deals with past data to convert it into a format that can be presented for analysis after preprocessing for value extraction, knowledge discovery, event and trend analysis, and pattern identification using statistical tools and techniques. The following steps are carried out:

- Data collection (raw medical datasets)
- Cleaning, denoising, preprocessing, and formatting (structured)
- Data analysis (statistics and linear algebra)
- Compilation
- Visualization
- Interpreting
- Testing and validation
- Developing a data-driven support system using AI, ML, and big data
- Extract features, derive value, and enable knowledge discovery
- Prepare a report for suitable actions.

3.3.2. Diagnostic analytics

Diagnostic analytics consists of the analysis of past datasets to examine the circumstances that led to specific events and patterns. It answers the question, "Why did it happen?" by regularly collecting physiological data from biosensors and predicting causes and potential reasons using diagnostic computing techniques (e.g., mean, variance, minimum, and maximum).

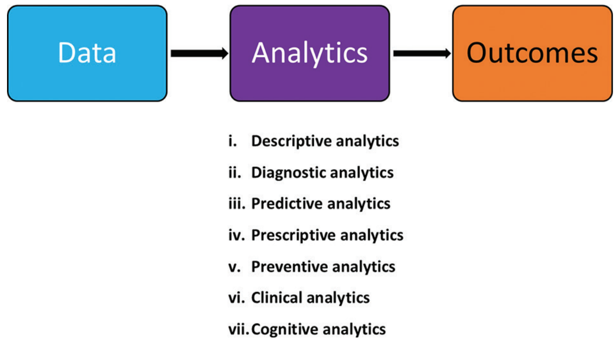

Figure 1. Healthcare data classification model. Image created by the authors.

3.3.3. Predictive analytics

Predictive analytics are used to predict the outcomes of an event or to forecast future trends, responses, and patterns using regression and ML algorithms. It answers "What is likely to happen/what might happen in the future?" For example, predicting whether breast cancer is benign or malignant. It is based on an algorithm-enabled medical advancement system and powerful technology for rule-based decision-making to predict future outcomes and gain insights into the dataset.

3.3.4. Prescriptive analytics

Prescriptive analytics involves evaluating current actions and decisions to forecast potential outcomes. Analyzing trends, patterns, and scenarios helps organizations or individuals to anticipate future events and make informed decisions. This prescriptive approach supports strategic planning by offering insight into the potential consequences of present choices, thereby minimizing risks and maximizing benefits.

3.3.5. Preventive analytics

Preventive analytics is a proactive and assertive technology to assess risks utilizing a range of data analytics tools, advanced ML algorithms, and predictive analytics to reduce the adverse impacts of potential disease occurrence. This is a forecasting method used regularly to assess the negative effects of illness and to propose practical solutions. It requires a combination of historical health datasets and trained and experienced medical professionals to maintain the healthcare infrastructure in optimal condition.

3.3.6. Clinical analytics

Clinical analytics involves using healthcare data to improve the quality, efficiency, and effectiveness of the digital healthcare system. It focuses on the collection, analysis, and interpretation of clinical data to gain insights that can support clinical decision-making, improve patient outcomes, and enhance operational efficiency. It is also used to maximize the value of clinical research data and gain access to real-time analysis. Clinical analytics uses data from multiple sources, such as lab results, medication lists, doctors' notes, and medical images, including X-ray and MRI images. It includes both structured data (e.g., numbers and codes) and unstructured data (e.g., written notes).

By carefully studying this information, healthcare teams can identify important patterns and trends. For example, they can see which treatments work best for specific conditions or which patients are at a higher risk of complications. Thus, it helps to predict what may happen next and makes more thoughtful decisions for each patient. Clinical analytics helps doctors decide the optimal treatments, track patient progress, and improve care for everyone. It also supports ongoing research and helps hospitals improve their services. By turning raw data into clear insights, clinical analytics makes it easier to deliver care that is more personal and effective. This approach helps ensure patients get the proper treatment at the right time.

Overall, clinical analytics is a key tool in modern health care, transforming patient data into practical advice, making health care more personal, effective, and up to date.

3.3.7. Cognitive analytics

Cognitive analytics is a digital technology that helps make sense of complex healthcare data. Health care data are vast, varied, and constantly changing. It includes patient records, medical images, videos, and real-time monitoring data—types that traditional methods struggle to analyze effectively.

Cognitive analytics uses advanced tools such as AI, ML, natural language processing, and cloud computing to mimic human thinking and learning. It can process and interpret diverse types of data—text, images, and videos—to uncover hidden patterns and valuable insights. This empowers doctors and healthcare professionals to make faster, better-informed decisions. Cognitive analytics can detect health risks early, suggest personalized treatments, and improve patient care. Its ability to continuously learn and enhance enables real-time problem-solving, making health care more accessible, efficient, and reliable for both patients and providers.[49,51,55-57]

3.4. Importance of mathematics in the analysis of health care

The ongoing research in digital healthcare has created enormous challenges for healthcare professionals, system analysts, AI scientists, mathematicians, and other regulatory experts to develop smart solutions to highly complex health problems and minimize critical gaps in public healthcare. Globally, the market is poised to reach US$62–65 billion on account of an aging population, chronic disease burdens, and structural healthcare reforms. Health care datasets are a special class of big data. In general, mathematics plays a crucial role in analyzing, modeling, extracting value, and discovering knowledge from massive, heterogeneous, real-time, and complex health datasets. These datasets are essential for improving medical treatment, service delivery, diagnosis, and preventive clinical analytics. Concepts from statistics and probability, linear algebra, calculus, discrete mathematics, fuzzy logics, neuro-fuzzy logics, and other advanced mathematical tools are used to design and implement algorithms for data summarization, pattern recognition, modeling, knowledge discovery, and optimization.

The proposed model facilitates the extraction of valuable insights through various types of healthcare analytics, including descriptive, diagnostic, predictive, prescriptive, preventive, clinical, and cognitive analytics. The following are commonly used mathematical tools:

- Basic statistics and probability theory
- Generalized n-body problems
- Linear algebra
- Graph theory
- Linear and non-linear optimization techniques
- Integration and calculus
- Non-linear differential equations
- Alignment problems
- Fuzzy and neuro-fuzzy logic
- Advanced ML
- Convolutional neural networks
- Regression
- Principal component analysis
- Clustering
- Markov chain
- Monte Carlo
- Set theory
- Gradient descent
- Matching
- Data mining
- Digital signal processing
- Linear programming.

4. Technical features of healthcare datasets

Health datasets are developed by capturing data from bioprocesses and transforming them into digital health datasets. They have the following technical features (Figure 2):

- Bioprocesses are poorly understood due to limited knowledge.

- Models developed to understand bioprocesses are highly non-linear, complex, coupled, multidimensional, and time-variant, and are associated with uncertainties, vagueness, vulnerabilities, and poor assumptions.
- Biosensing and biomedical devices, data acquisition systems, and computer-communication technologies have inherent inaccuracies and imprecision in the measurement, processing, and estimation of biosignals.
- Bioprocesses generate health datasets that have a special frequency spectrum and can be classified as unstructured, semi-structured, and structured. They are represented by 7Vs for the processing, analysis, computation, storage, communication, management, and development of smart health delivery and decision support for value-added services.
- Biomedical datasets are always associated with unique frequency spectra and gain bandwidth products (0–100 Hz, millivolt, microvolt, and nanovolt).
- Health care datasets are collected from multiple bioprocesses characterized by complexities, uncertainties, and ambiguities. Hence, it is challenging to propose a global standard.[50,52]
- Data growth is unpredictable and growing exponentially with time. Much of the data is extracted from text, audio, multimedia, and medical images. Conventional computer-communication techniques and mathematical tools face real challenges in handling such datasets.
- Real-time data analysis, efficiency, innovation, speed, and data-driven solutions become increasingly challenging to achieve.
- Digital health and big data analytics (smart health) have become critical components of the infrastructure for nation-building across countries and are included in SDG-17.

Digital healthcare systems can be developed by combining several technologies, including specialized technologies, processes, mathematical tools, algorithms, and soft computing methods, to extract values and desired information contents from raw health datasets. Medical professionals, scientists, and researchers are using advanced ICT and new mathematical tools. Figure 3 depicts the technical features of healthcare datasets, which are also listed as follows:

- Data security
- Data skills
- Data redundancy
- Data quality improvement
- Data integration.

4.1. Health data quality metrics

Data quality metrics are quantifiable measurements used to assess the specific quality standards of the health industry (Figure 4). The following terms are commonly used to estimate data quality.[8,58-60]

- Data accuracy
- Data completeness
- Data consistency
- Data validation
- Data timeliness
- Data integrity
- Data uniqueness
- Data fitness for purpose
- Data trustworthiness
- Data privacy and security
- Data resource constraints.

4.2. Characteristics of healthcare datasets

Health care datasets are generally categorized as a subset of big data that have immense complexity, vagueness, real-time, heterogeneous, unstructured, and large volume. These datasets are collected from various human organs and biosources and further organized through processes such as capturing, storing, analyzing, and value extraction. Moreover, they are used for establishing mathematical correlations among various components of bioprocesses

Figure 2. Key health data quality metric. Image created by the authors.

to extract medically relevant information from patients. Digital healthcare data can be described using frameworks such as the 5Vs, 7Vs, and 8Vs, where the number of Vs determines the complexity and pattern characteristics of health data. The key characteristics of healthcare datasets are summarized by the 7Vs, as illustrated in Figure 5.[50-52]

4.2.1. Volume

The range of health data, more than gigabytes, is considered big data. It can be petabytes, terabytes, exabytes, and zettabytes. Such large datasets cannot be stored, formatted, and analyzed accurately using conventional single-digit machines. Therefore, specialized tools, techniques, and frameworks are required. The massive volume of data generated by smart healthcare systems, IoT, cloud computing, and edge computing is growing exponentially, leading to lower processing costs and improved quality.

4.2.2. Velocity

The velocity of healthcare data refers to the speed of data generation from biomedical devices and wearables, as well as the speed of data collection, processing, and analysis using advanced tools and techniques. Biomedical devices, wearables, m-Health, and e-health infrastructures are used to record and monitor the physiological signals of patients in real time under medical supervision in hospitals and remote locations. The healthcare datasets are shared among patients and doctors using wireless, 4G, 5G, or satellite communication networks with high-speed transactions between the source and destination.

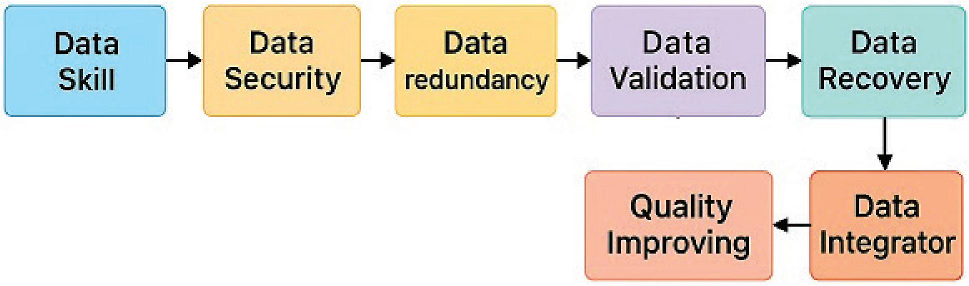

Figure 3. Technical features of health care. Image created by the authors.

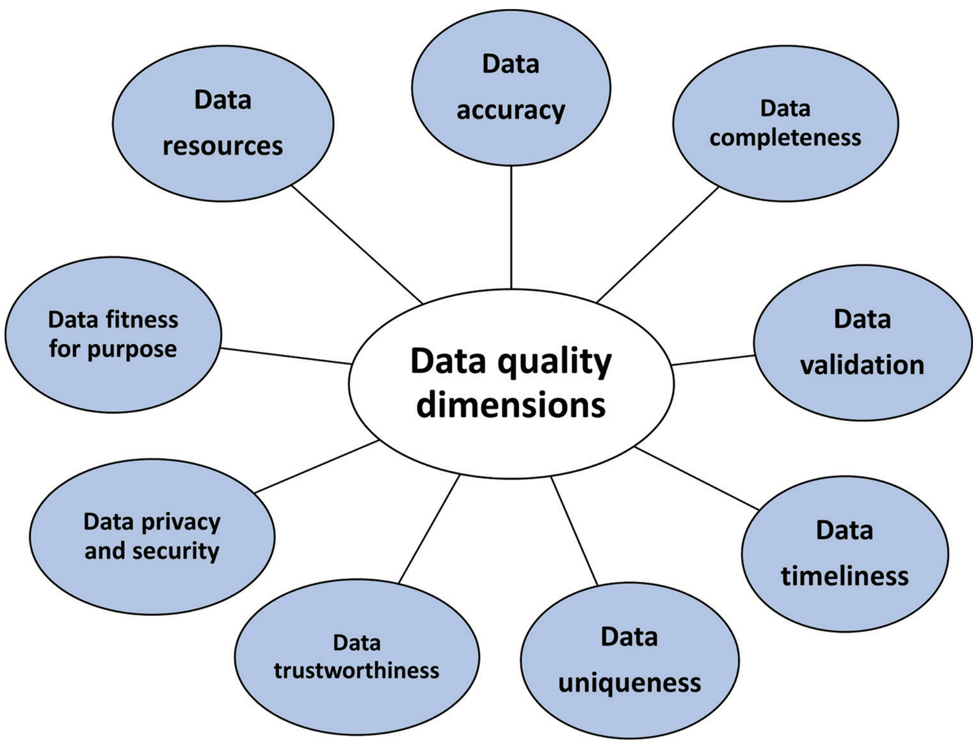

Figure 4. Health measurements process. Image created by the authors.

4.2.3. Variety

Variety represents the heterogeneity of data and the shape of healthcare data patterns. Healthcare data originates from patient monitoring systems in unstructured, semi-structured, or structured forms, including text, audio, videos, multimedia, and data from X-ray, MRI, CT, and smart wireless sensors. Variety is related to a wide range of data collected from several sources, and it is difficult to organize, integrate, visualize, and analyze.

4.2.4. Veracity

Veracity focuses on the quality and correctness of data. It specifies the level of reliability. It is vital to remove undesirable content and convert it into a dataset that is compatible with processing, as most healthcare datasets collected are unstructured, vague, and noisy.

4.2.5. Variability

A health care dataset can be collected from clinical research, biomedical devices, and wearables. Medical imaging systems are inherently associated with inconsistency, having degrees of uncertainty and difficulty in modeling and deriving desired information.

4.2.6. Visualization

Visualization translates medical datasets into visual formats that are easier to understand. This includes graphs, maps, charts, and dashboards, which can be implemented using tools such as Power BI.

4.2.7. Value

The objectives of big data analytics are to discover information from highly complex, real-time datasets characterized by the 7Vs. These datasets are time-variant, non-linear, and coupled systems generated from multiple biomedical sources and often contain unwanted noise. Big data analytics aims to develop a smart, cost-effective, and efficient patient-centric support system to manage critical infrastructure for nation-building, especially in regions with high disease burden.[29]

5. Health of the nation

The "health of the nation" is a multidimensional term used to describe the overall health status of a country's population and is considered one of the critical infrastructures for nation-building. It consists of several components and is treated as a set of fuzzy parameters characterized by vagueness, uncertainties, non-linearities, time-variance, fragmentation, and complexity, which are difficult to model using conventional mathematical tools to obtain desired results. The following variables are used to assess the quality of health of a country:[56,57]

- Gross domestic product
- Human Development Index

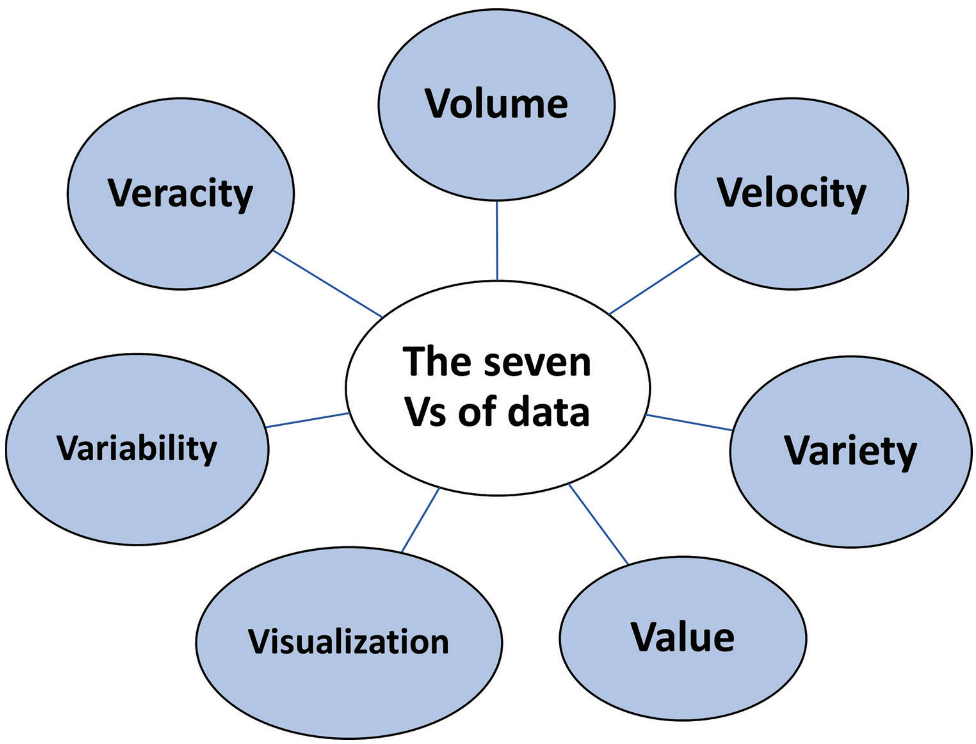

Figure 5. Characteristics of health data. Image created by the authors.

- Population density and regional divide
- Education and literacy rate
- Healthcare infrastructure, m-health, e-health, and telemedicine
- Budget allocation to health care
- Age of marriage
- Medical professionals/1000
- Paramedical support/1000
- Number of beds/1000
- Digital health care/smart health care
- Digital divide/rural–urban divide
- Medical access facilities
- Public versus private hospitals
- Insurance facility
- National health policy
- Genuine progress indicator
- Clinical and diagnostic research facilities
- Disease burden
- Environmental conditions/safe drinking water
- Reachability/transport systems
- Scalability
- New business opportunities
- Socioeconomic development
- Smart city
- Diversity.

An emerging transformation in the healthcare sector is occurring worldwide based on the integration of medical sciences, AI, ML, big data analytics, IoT, biosensors, 5G mobile communication networks, cloud and edge computing, wireless body area networks, new biomedical devices, and advanced mathematical techniques, including neuro-fuzzy modeling.

6. Conclusion

Digital health care and smart health care are regarded as an advanced technology still in active research and development. Ongoing extensive clinical trials use new big data analytics tools to develop a health technology capable of meeting the requirements of SDG-3 and addressing key aspects of nation-building, QOS, health metrics, and disease-specific biomarkers. The new healthcare ecosystem requires innovative solutions to expand demographic reach, particularly for hard-to-reach populations, and to ensure patient-centric treatment and improved access to medical services across diverse, underserved regions with limited medical infrastructure. Advancements such as 5G and beyond-5G wireless networks, smart biosensors, advanced data acquisition techniques, wearables, and powerful data centers (e.g., edge computing, 5G, AI, advanced ML algorithms, and convolutional neural networks) are essential for reducing latency, enabling faster real-time responses, and enhancing medical delivery services. The key advanced technologies, such as digital signal processing, high-resolution data techniques, complexity-reduction methods, advanced mathematical tools, and soft computing algorithms, play a crucial role in improving reliability, operational efficiency, robustness, accuracy, and affordability in patient-centric, data-driven healthcare research. Neuro-fuzzy models can further support the identification of gaps in current digital healthcare systems. It is proposed that collective and collaborative research efforts be initiated, involving highly trained medical professionals, AI scientists, system engineers, mathematicians, and representatives from regulatory bodies. Such collaboration can help develop and design an affirmative, dynamic digital healthcare reference model (the proposed 2D 3P 2C model) to meet the critical requirements of the public healthcare system, ensuring better feasibility, access, affordability, and patient-centricity to address the needs of humanity in the 21st century.

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ARTICLE

Interactions among cost of quality factors in Indian manufacturing: An interpretive structural modeling approach

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Abstract

Quality-related costs represent a significant concern for manufacturing organizations, as they directly influence competitiveness, efficiency, and long-term sustainability. Understanding how these costs interact is crucial for developing effective quality management strategies, particularly in emerging economies such as India. This study investigates the interactions among cost of quality (CoQ) factors in the Indian manufacturing sector using an interpretive structural modeling (ISM) approach. A comprehensive literature review identified critical CoQ components, which were then structurally interrelated through ISM to develop a hierarchical framework that clarifies the relationships between driving and dependent factors. This framework provides insight into how specific CoQ elements influence one another, offering actionable guidance for quality management. The study not only advances theoretical understanding but also contributes a practical tool for decision-makers in manufacturing. Key findings indicate that prevention-related factors act as strong drivers, whereas appraisal- and failure-related costs are more dependent. The proposed ISM-based framework provides a strategic lens for prioritizing quality improvement initiatives.

Keywords: Cost of quality; Interpretive structural modeling; Cross-impact matrix multiplication applied to classification; Soft systems methodology

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1. Introduction

Quality control experts argue that effective quality management is the best approach to enhancing customer satisfaction, reducing manufacturing costs, improving productivity, and achieving competitiveness. Many businesses emphasize quality as the most important consumer value and regard it as a crucial success factor. Companies adopt management systems to ensure that quality meets customer needs, and success is often quantified using monetary and non-monetary metrics.[1] Any genuine attempt to improve quality must consider the expenses associated with achieving it, because meeting customer needs is no longer sufficient; it must also be accomplished at the lowest feasible cost. This requires the systematic identification and measurement of quality-related expenses, which in turn facilitates their reduction.[2] Therefore, the measurement and reporting of the "cost of quality" (CoQ) concept should be considered a critical issue for managers.[3]

The CoQ is a measurement system that translates management language into a monetary language that is universally understood, influencing customer needs, operating costs, and profitability. It accounts for roughly 30% of total manufacturing expenses and is thus a crucial cost driver that companies must effectively manage to maintain a competitive advantage.[4] CoQ, or quality costs, broadly include the costs of designing, implementing, operating, and maintaining a quality management system (QMS). These costs also comprise resources dedicated to continuous improvement, product- and service-failure-related costs, system costs, and all additional necessary expenditures and non-value-added activities required to deliver a quality product or a service.[5]

Quality management begins with a well-documented and directed preventive maintenance program that reduces costs significantly compared with reactive maintenance. There are always tangible–intangible or direct–indirect costs associated with production to maintain quality. According to Crosby,[6] CoQ is composed of the cost of conformance—the amount spent on preventing poor quality and ensuring that tasks are performed correctly the first time (e.g., inspection, training of laborers, supervisors, or quality inspectors, and quality appraisal). Second, the cost of non-conformance—the amount wasted when work fails to conform to customer requirements, leading to product and service quality failures (e.g., handling, reworking, recalls, and returns). The cost of conformance is further divided into prevention and appraisal costs, whereas the cost of non-conformance is divided into internal failure and external failure costs.

In order to maintain quality and deliver satisfactory customer value, an associated cost arises—either in the form of prevention costs or at the detection and correction stages of failures. Costs are also incurred when the final output has defects and its delivery to the customer must be halted, so that the problem can be resolved within the organization rather than leading to customer rejection. Several methods can be used to collect, categorize, and measure quality costs. Juran[7] and Feigenbaum[8] proposed the prevention, appraisal, and failure (P-A-F) method, which divides quality costs into three categories: P-A-F. This method is the traditional and widely accepted approach for classifying CoQ. Prevention costs are associated with actions taken to ensure that a process provides quality products and services, while appraisal costs relate to measuring the level of quality attained by the process, and failure costs refer to correcting quality in products and services before delivery (internal) or after delivery (external) to the customer.

ABC Die-casting is a manufacturing ancillary firm established in 1965, located in Aligarh, a city prominently known for its hardware production in India. ABC Die-casting—an International Organization for Standardization 9001:2008-certified organization—is a well-established and professionally managed company engaged in manufacturing, exporting, trading, and supplying a wide range of aluminum and zinc die-cast components for automotive, electronics, electric switchgear, and home-appliance original equipment manufacturers. Its clientele includes companies such as Havells, Mitsubishi, TVS, Standard Electric, Whirlpool, Escorts, Mahindra, and Kirloskar. For decades, ABC Die-casting has thrived in providing quality products and has established a firm foothold in the market. The company has achieved this success through timely delivery of orders, state-of-the-art infrastructure, and assured quality as well as by consistently upgrading its processing and manufacturing facilities. For organizations engaged in typical manufacturing, such as ABC Die-casting, a large product portfolio of more than 1,000 different components, ranging from screw-sized miniature parts to large metallic engine casings, makes quality management an imperative tool for achieving sustainable competitive advantage.

In this study, we proposed a conceptual framework, as shown in Figure 1, focusing on understanding the CoQ framework from a holistic perspective of the organization's current environment, drivers of adoption, and the value delivered to the organization. The concept of CoQ is broad and inherently subjective, with numerous ways of being interpreted, analyzed, and concluded. The proposed conceptual framework seeks to capture CoQ from a renewed perspective, using a selected firm to demonstrate its application in an organizational setting and thereby provide a practical view. The framework can be interpreted in the sense that the ultimate objective of every business is to deliver value to customers by considering their expectations and specifications in line with customer norms. For example, ABC Die-casting produces a wide range of die-casting products for a diverse set of firms—from home-appliance manufacturers to electronics producers—each with distinct requirements and specifications. Every new order requires steps such as designing, prototyping, and testing before production can commence. In such situations, where adherence

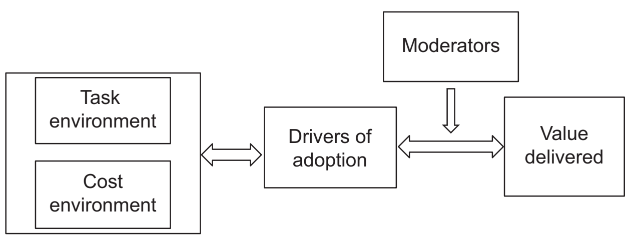

Figure 1. Conceptual framework

to customer specifications plays an important role, the organization needs to remain agile and dynamic in responding to ever-changing customer requirements. This responsiveness not only affects the organization's task environment but also carries associated costs, which are incurred to deliver value or maintain quality.[9]

To achieve this diverse product portfolio with assured quality, approaches such as continuous improvement, *Kaizen*, and Six Sigma are required to address questions such as: "What must be adopted to move toward value delivery?" and "Why are we pursuing quality, or what factors are driving its adoption?" Hence, these approaches are considered drivers of adoption. In addition, there are routine tasks that must be performed with a focus on maintaining quality, which incur associated costs, such as maintenance costs. The value delivered through quality-oriented production management includes lower customer rejection rates and reduced lead times, which ultimately lead to greater customer satisfaction and profit maximization. There are factors referred to as moderators, which may be favorable or unfavorable and can regulate the process. They are included in this flow diagram because they influence the value-delivery process. The double-sided arrows indicate the bidirectional nature of interactions among the various components of quality delivery (Figure 1).

2. Literature review

Quality costs can be used as a criterion for evaluating an organization's quality, but only if meaningful comparisons can be performed between different sets of cost data. Notably, the definitions of the cost categories and items used in producing the data significantly affect the comparability of datasets. However, finding general terminology to represent specific jobs or activities across diverse sectors, organizations, and both manufacturing and service industries with the same basic aims is challenging. This makes collecting and comparing data from multiple sources extremely difficult.[5,10]

In previous studies, several researchers expressed dissatisfaction with how businesses track and analyze quality costs.[11,12] Yusuff[13] discovered that most organizations implement only a rudimentary CoQ system and suggested that its application should be enhanced. According to Šatanová *et al.*,[14] about one-third of businesses are interested in implementing a CoQ system.

Based on a review of various quality cost models focused on the manufacturing industry, Plunkett and Dale[15] categorized and discussed these models. Many were found to be flawed and misleading, casting considerable doubt on the concept of an optimum quality level. They identified several notional models in the literature that purportedly show the links between the major categories of quality costs and some sets of real data. Despite all models being built on the same conceptual foundation, significant disparities exist both among the models and between the models and actual data.

Khaled and Murgan[16] developed a quality cost simulation model using published literature and input from a semiconductor company's quality control manager and supervisor to design various quality control plans and analyze their impact on quality costs within a specific section of the company's process. As a future direction, they suggested expanding the model to accommodate more complex process configurations.

Filipovic and Glogovac[17] conducted a survey for both service- and manufacturing-based companies to provide information on the current state of quality cost management in practice, as observed in relation to various company characteristics, along with insights on variables identified as critical for achieving better results in quality cost management. They noted that despite its relevance, awareness of the CoQ concept is limited, and companies primarily adopt it to fulfill the requirements of ISO 9001:2015 certification. They also suggested that, instead of using questionnaires, conducting interviews to collect quality cost-related data could provide a better scope for future research.

There are few empirical studies or case studies on the CoQ front in India.[4] According to Fraser *et al.*,[18] emphasizing empirical evidence from operations and management practitioners, alongside academics, is vital for CoQ researchers and practitioners, as it allows theoretical models to be tested in real-world settings rather than relying solely on theory. Case studies provide a strong foundation for relating activities to results. Using the case study of a manufacturing company where P-A-F-based CoQ analysis is applied, Arsalan *et al.*[19] investigated inspection strategies through evaluation of the quality-cost trade-off and suggested applying the same general systems engineering technique for quality improvement across various types of sectors to better assess the framework's validity.

With a sample of 400 observations, Sturm *et al.*[20] indicated that long-term results show significantly greater quality performance and lower quality costs. Quality expenses grow at a rate of less than half that of sales volume, indicating a considerable scale effect in quality cost reduction. In addition, long-term changes in conformance and non-conformance costs per unit of sales show a positive association. Increasing prevention and appraisal costs does not consistently correspond to

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lowering internal and external failure costs in the selected sample. As a result, enhancing internal and external quality performance (e.g., reducing internal and external failure costs) while lowering product conformance costs can be achieved in the long run.

This systematic literature review of 97 research papers, focusing on sectors such construction, manufacturing, service, food, agro, and miscellaneous sectors, suggests that future research on CoQ can be structured around 11 relevant themes, including the impact on CoQ elements, CoQ data and information, methods and analysis, CoQ effects, CoQ integration with other management approaches, and CoQ failure and success factors. In addition, this study highlights the importance of extending CoQ research to different sectors, subsectors, or units.

Many CoQ research publications provide comprehensive quality cost models, methodologies, and strategies, along with extensive insights into the subject. Despite quality being regarded as a critical concern, a review of the literature on the practical use of CoQ reveals that the CoQ methodology is not fully utilized. Organizations value quality costing, but only a small percentage adopt a formal quality costing strategy.

3. Problem description and objectives of the study

Most businesses have quality control systems in place and strive for continuous improvement. Quality improvement and cost containment are pursued through various approaches. As a result, many organizations achieve their desired objective without explicitly employing CoQ as a strategy to reduce quality costs.[2]

Every organization has an identified list of different types of costs incurred in quality management, and there exists a non-linear relationship among these cost elements.[8] Therefore, this study has taken a distinct approach to defining CoQ factors based on the experts' perspectives, which are specific to the firm under study. There are numerous possible connections and linkages between them, where one type of cost can influence or depend on another. The problem is not simply about cutting costs, as quality costs are never eliminated; instead, they are optimized according to a cost-benefit trade-off. In this scenario, where the main quality attribute is conformance, it becomes essential to understand the criticality and interdependence of all CoQ elements. In addition, for any ancillary company—defined as a firm that serves as an intermediary and supplier—the level of complexity is even higher. This is due to the wide product range and the diversity of customers across various industries. CoQ must be applied across different sectors. In this study, a die-casting ancillary firm was selected to illustrate the broad range leading to complexity and quality cost-related concerns. Following the recommendation of Fraser *et al.*,[18] both academicians and company experts were collectively involved in this study.

In this study, the soft systems methodology (SSM) is applied as a solution to address complexity by dividing the CoQ factors into rational hierarchical levels using an interpretive structural modeling (ISM) digraph. This study focuses on the linkages and hierarchical order among the CoQ factors at ABC die-casting rather than on economic models for calculating and determining quality costs. It identifies CoQ factors in the context of ABC die-casting and establishes relevant relationships among them. The study logically outlines which factors are dependent, which ones are drivers, and which fall in between. It contributes to a better understanding of the contextual relationships between factors under conditions of non-linearity and complexity. The factors are listed based on the rationale provided by experts rather than adopting the conventional approach to classifying CoQ factors. Dividing CoQ factors into different levels can help quality control managers make more informed decisions. It also highlights the critical factors that require primary focus to effectively drive other factors.

3.1. Objectives

There are three objectives of the study:

(i) To identify the CoQ factors.
(ii) To establish the relevant relationships among the identified factors using an ISM-based digraph.
(iii) To classify the identified drivers of technology adoption based on the cross-impact matrix multiplication applied to classification (*Matrice d'Impacts Croisés Multiplication Appliquée á un Classement* [MICMAC]) analysis.

To address the gaps identified in previous literature—such as the lack of contextual specificity, underutilization of formal CoQ systems, and the need for models that reflect organizational complexity—this study contributes a novel approach by identifying and structuring CoQ factors through expert input within a specific manufacturing context. Unlike prior research that relies heavily on predefined cost categories or generalized models, this study adopts a bottom-up perspective using SSM and ISM to reflect real-world interdependencies. This approach not only enhances the practical relevance of the CoQ framework but also introduces a firm-specific, structurally dynamic model that aligns with the pluralistic and evolving needs of quality management in ancillary manufacturing.

4. Methodology

Soft systems modeling is a suitable tool for dealing with complex situations where the cost elements need to be analyzed within a given contextual scenario, and their hierarchical relationships must be established for better quality-centered decision-making. ISM facilitates the understanding of the interdependence of numerous elements and their overall impact on the system. MICMAC analysis helps in identifying the dependent, autonomous, drivers, and interdependent components, as well as their degree of dependence and driving power. Figure 2 depicts the comprehensive, step-by-step procedure followed in this study.

4.1. Nominal group technique (NGT)

NGT is an extremely effective and efficient method for generating information or ideas for developing consensus under SSM.[21] It is a structured method designed to mitigate the effect of group members who tend to dominate the discussion and to encourage responses from relatively silent individuals. As a result, each member has the opportunity to contribute and vote on each item. NGT involves organized brainstorming and decision-making, ideally conducted among five to nine members.[22] Several recent studies have employed NGT in systems analysis, including exploring linkages among artificial intelligence elements in education,[23] adoption of virtual experiential techniques,[24] and implementation of digital education.[25] This study applied the NGT approach with experts to finalize the list of elements and establish their relevance relationships, ultimately facilitating the development of the ISM and MICMAC frameworks. The expert team comprised seven members, including three academicians

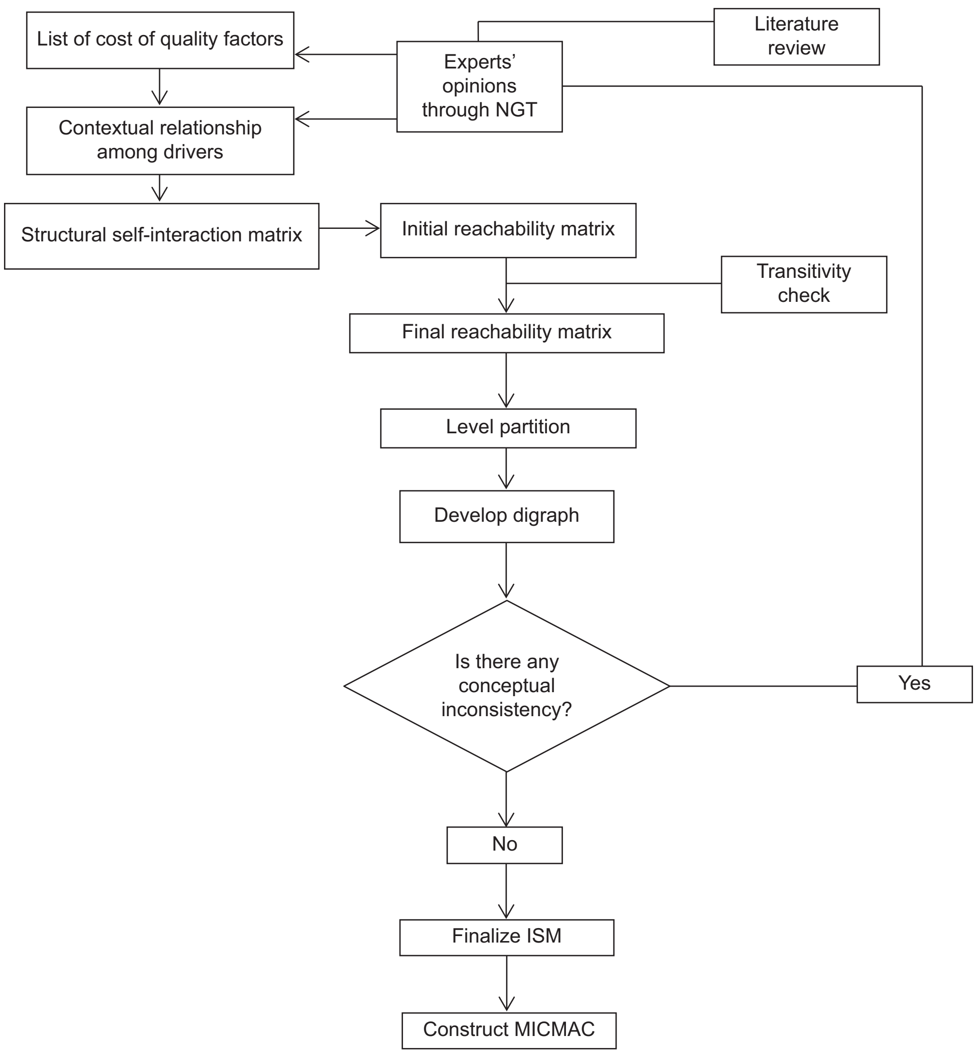

Figure 2. ISM methodology for analyzing the hierarchy among the CoQ factors
Abbreviations: CoQ: Cost of quality; ISM: Interpretive structural modeling; MICMAC: Cross-impact matrix multiplication applied to classification; NGT: Nominal group technique.

and four employees from the operations and quality control departments.

4.2. ISM

Professor J. Warfield developed the ISM method for studying complex socioeconomic systems. ISM can be used to identify contextual linkages between elements related to a topic that requires systemic investigation.[26] It is a structured thinking approach that accommodates a wide range of complex interactions between elements.[27] ISM facilitates the grouping of expert opinions by providing multiple methods for building contextual linkages between elements, including nominal techniques, brainstorming, and affinity diagramming.

4.3. Cross-impact matrix multiplication applied to classification

The MICMAC method—developed by Duperrin and Godet[28]—produces a graph that categorizes the elements under consideration based on their driving and dependence power (Dp). In this study, MICMAC analysis is applied to identify critical elements and validate the interpretive structural model of the identified elements.

5. Findings and analysis

5.1. Identification of quality cost factors

To identify the CoQ factors, an NGT-based group discussion was conducted among experts from ABC die-casting and academicians. The company respondents included a quality control inspector, supervisor, and head- and section-level managers of the operations department. Based on consensus, the factors were initially identified by segregating input–process–output stages.

Table 1 presents the initial list of elements (CoQ factors) generated using the traditional input–process–output model. In the second stage, following the NGT procedure, the experts discussed the relevance of each identified element. At this stage, experts could add, delete, merge, or split elements. The final list of 14 elements was generated, as indicated in Table 2, with each element defined along with the experts' rationale for its relevance to ABC Die-casting.

Table 1. Quality cost factors at various stages of production

Stage	Factors/elements
Input	To improve the quality management system of the supplier based on the customer's requirements
	To inspect and/or test externally provided products (raw material)
	To calibrate and perform measurement system analysis of measuring instruments for incoming material inspection
	Maintenance cost of measuring and test equipment
	Packing, identification, and transportation costs
	Inventory cost of incoming material
	To evaluate the performance of external providers
Process	To control and improve the work environment
	Rejection analysis with corrective and preventive actions
	Improvement activities to enhance the quality of products and processes
	To control the product and process variations through statistical process control
	Measurement system analysis
	To install and implement an effective QMS in the industry
	To review and conclude the effectiveness of QMS
	Storage, handling, identification, and transportation of product and material
	Maintenance cost of machinery
	Training operators, labors, and staff to make QMS more effective
	To implement and install the standard operating procedure of each method of QMS
	In-process inspection cost (measurement testing cost)
Output	Net cost occurred due to scrap/spoilage
	Repair and replacement costs beyond the warranty
	Loss of sales arising from poor quality
	Returns and allowances rose from quality problems
	Product recalls
	Rework cost, including labor and overhead
	Re-inspection costs of reworked defected products
	Handling and taking corrective action on customer and field complaints
	Re-entering data and records of rejected/defected products

Abbreviation: QMS: Quality management system.

1. Cost optimization
   Cost optimization is defined as a process, act, or method of designing a system, product, or decision to be as complete, effective, and functional as possible without compromising quality, thereby achieving cost control. Intense competition drives every organization to reduce costs. This task becomes challenging when the product range is broad and each item requires customized attention. In addition, an increase in the cost of one item can affect the cost of others. Consequently, maximizing output while minimizing expenditure is essential for any firm that cannot simply eliminate a product due to uncontrollable costs, as the product may still be necessary.
2. Conformity to customer expectations
   Crosby[6] provides an operational dimension to the definition of quality as "conformance to requirements."

Table 2. Final list of elements

No.	Elements
1	Cost optimization
2	Conformity to customer expectations
3	Revenue maximization
4	Minimizing the rate of rejection
5	Maintaining a quality management system
6	Standardization
7	Enhance continuous improvement
8	Vendor expertise
9	Quality tools and equipment
10	Rejection analysis and preventive maintenance
11	Employees' expertise
12	Inventory cost management
13	Maintenance cost management
14	Operational cost management

The concept of conformity is further defined under the quality dimensions proposed by Garvin.[29] Organizations need to ensure that the product and quality specifications defined by the customer are delivered within the tolerance of customer expectations.

3. Revenue maximization
The sales revenue maximization model developed by Baumol[30] emphasizes that a company's primary goal is to maximize sales rather than profit. The model states that a firm should aim to maximize sales revenue while maintaining a minimum profit margin. Sales maximization does not only refer to increasing sales volume but also to minimizing the opportunity cost associated with lost sales and product recalls due to defective products. This enhances goodwill and increases the likelihood of receiving additional orders from customers.

4. Rate of rejection
Rejections have a significant impact on cost control. Therefore, organizations should adopt methods such as the plan–do–check–act cycle[31] and Lean Six Sigma[32] to continuously improve processes and reduce the number of defect-related rejections. Such methods are vital for quality and involve monitoring, inspection, and data recording costs.

5. Quality management system
The term "quality management system" was introduced by British management consultant Ken Croucher in 1991.[33] The quality control and operations departments in an organization are responsible for ensuring that the overall production system—from raw material procurement to product delivery—is smooth, efficient, and effective, thereby helping to achieve and maintain the organization's QMS.[34]

6. Standardization
Standardization enhances product quality. Implementing uniform methods reduces waste and saves time and money at every stage. Certain agencies conduct periodic audits and issue ratings or accreditation, such as the International Automotive Task Force. These audits evaluate product, process, and overall performance, with outcomes reflecting the organization's achieved and maintained level of standardization. Although implementing such programs incurs cost, the ultimate goal of delivering the highest quality is achieved.

7. Continuous improvement
Continuous improvement, also known as *Kaizen*, involves the periodic evaluation of product and process quality.[35] The outcome is consistency in procedures across a diverse product portfolio, where each variant must conform to quality standards. It includes identifying benchmarks of best practices and making continuous efforts to implement them.

8. Vendor expertise
In the selected ancillary organization, the raw materials primarily consist of zinc and aluminum, along with their alloys. The size, density, and chemical composition of the materials need to be checked, as there are hundreds of varieties of zinc and aluminum used in producing approximately 1,200 products. Therefore, vendor (supplier) assessment becomes crucial to ensure the provision of appropriate materials. This ultimately affects the value delivered in the form of the product and represents the initial stage at which the organization incurs quality-related costs.

9. Quality tools and equipment
Quality tools and equipment, also referred to as measurement system analysis, involve checking the instruments used to assess raw material and final product quality. They include measuring and testing tools, equipment, and various automated visual and technical inspection machines, such as vernier calipers and screw gauges, which measure physical dimensions (e.g., diameters, length, and breadth). All of these incur costs, either for purchase or maintenance.

10. Employees' expertise
The expertise of employees is a critical factor that directly impacts product and process quality. The value delivered can be influenced by the expertise of employees working on the shop floor, production managers, and personnel in the quality control department. As the organization employs skilled, semi-skilled, and unskilled staff, the scope for imparting necessary skills through training is extensive, which, in turn, entails associated costs.

11. Rejection analysis and preventive maintenance
    The most effective approach is to prevent defects from occurring; however, if a defect occurs, it should be detected internally before reaching the customer. In cases where defects are reported by customers, preventive actions are applied not only to that product but across the entire product portfolio. Costs incurred in this context include rework (e.g., remelting the item to its original form, making minor surface adjustments, or finishing), redesigning, and opportunity costs.
12. Inventory cost management
    Inventory costs may appear as normal operational expenses, but they are included in the CoQ. Managing inventory involves processes such as handling, storing, and transporting. Inventories (e.g., raw materials and work-in-progress) require proper storage facilities, appropriate handling and transportation methods, and organizational arrangements such as warehouses with moisture control and other necessary precautions. Labor is also employed for these tasks, and collectively, these activities contribute to the CoQ.
13. Maintenance cost management
    The entire manufacturing process depends on the machinery used. Maintenance costs include both planned and unplanned maintenance. Planned maintenance involves periodic inspections of machinery after a specified duration, assessing machine performance, and calibrating equipment as needed to maintain quality. In contrast, unplanned maintenance costs arise from sudden machinery breakdowns.
14. Operational cost management
    Operational cost management encompasses all costs incurred during production to ensure quality control. For example, in ABC Die-casting, these costs are associated with employing quality inspectors, supervisors, and technical experts.

5.2. Relevance relation between identified drivers

5.2.1. Structural self-interaction matrix

Following the listing of elements, the structural self-interaction matrix (Table 3), also known as the VAXO framework, was developed as the next phase in the ISM development to identify the relevant relationships among all 14 elements.

(a) Step 1
    Number the elements and arrange them—row by row and column by column—to form an n×n matrix, where "n" is the total number of identified elements.
(b) Step 2
    Examine each cell individually and ask the experts to describe the type of relationship between the row and column elements.

Table 3. Structural self-intersection matrix

		Column-wise elements "j"													
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Row-wise elements "iI"	1		A	V	A	A	A	A	O	O	X	A	A	A	A
	2			V	X	A	A	A	O	O	A	A	O	O	O
	3				O	O	O	O	O	O	O	O	A	A	A
	4					X	X	A	O	O	O	X	O	O	V
	5						X	X	A	A	O	X	A	A	X
	6							A	O	O	O	A	O	V	V
	7								O	O	O	A	A	A	A
	8									X	O	O	X	O	O
	9										O	O	X	O	O
	10											A	A	O	A
	11												O	X	X
	12													O	V
	13														X
	14														

Write "V" in the cell if the chosen row element "i" influences the corresponding column element "j." Indicate "A" if "i" is influenced by "j." Mark "X" if there is interdependence, indicating that both elements affect each other and "O" if there is no link.

5.2.2. Formation of initial reachability matrix

The next step is to convert the structural self-interaction matrix into a binary matrix, referred to as the initial reachability matrix.[36] The diagonal cells, from left-top to right-bottom, are marked as "1" due to the self-relationship. The rules for this step are as follows:

(i) In place of "V" at any cell location (i, j), write 1 and write 0 at cell (j, i). For example, the relation between element 6 (row) and element 13 (column) is defined as "V," so cell (6, 13) is marked as 1 and cell (13, 6) is marked as 0.
(ii) In place of "A" at any cell location (i, j), write 0 and write 1 at cell (j, i). For example, the relation between element 1 (row) and element 4 (column) is defined as "A," so cell (1, 4) is marked as 0 and cell (4, 1) is marked as 1.
(iii) In place of "X" at any cell location (i, j), write 1 and write 1 at cell (j, i). For example, the relation between element 4 (row) and element 5 (column) is defined as "X," so cell (4, 5) is marked as 1 and cell (5, 4) is also marked as 1.
(iv) In place of "O" at any cell location (i, j), write 0 and write 0 at cell (j, i). For example, the relation between element 2 (row) and element 8 (column) is defined as "O," so cell (2, 8) is marked as 0 and cell (8, 2) is also marked as 0.

The initial reachability matrix is presented in Table 4.

5.2.3. Deriving the final reachability matrix

The initial reachability matrix is transformed into the final reachability matrix using the Floyd–Warshall algorithm.[37] The final reachability matrix (Table 5) is constructed using the transitivity check rule for any missing relationships. This means that if the relationship between A and B, as well as B and C, is defined, but the relationship between A and C is inadvertently left undefined, such transitivity errors are identified and corrected (represented with 1*). The resulting rectified matrix, called the final reachability matrix, represents logically established contextual relationships among the identified elements and serves as a foundational building block of ISM.

Table 4. Initial reachability matrix

		Column-wise elements "j"													
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Row-wise elements "i"	1	1	0	1	0	0	0	0	0	0	1	0	0	0	0
	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0
	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	4	1	1	0	1	1	1	0	0	0	0	1	0	0	1
	5	1	1	0	1	1	1	1	0	0	0	1	0	0	1
	6	1	1	0	1	1	1	0	0	0	0	0	0	1	1
	7	1	1	0	1	0	1	1	0	0	0	0	0	0	0
	8	0	0	0	0	1	0	0	1	1	0	O	1	O	O
	9	0	0	0	0	1	0	0	1	1	0	0	1	0	0
	10	1	1	0	0	0	0	0	0	0	1	0	0	0	0
	11	1	1	0	1	1	1	1	0	0	1	1	0	1	1
	12	1	0	1	0	1	0	1	1	1	1	0	1	0	1
	13	1	0	1	0	1	0	1	0	0	0	1	0	1	1
	14	1	0	1	0	1	0	1	0	0	1	1	0	1	1

Table 5. Final reachability matrix

		Column-wise elements "j"													
	1	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Row-wise elements "i"	1	1	1*	1	0	0	0	0	0	0	1	0	0	0	0
	2	1	1	1	1	0	0	0	0	0	1*	0	0	0	0
	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	4	1	1	1*	1	1	1	1*	0	0	1*	1	0	1*	1
	5	1	1	1*	1	1	1	1	0	0	1*	1	0	1*	1
	6	1	1	1*	1	1	1	1*	0	0	1*	1*	0	1	1
	7	1	1	1*	1	1	1	1	0	0	1*	1*	0	1*	1*
	8	1*	1*	1*	1*	1	1*	1*	1	1	0	0	1	0	1*
	9	1*	1*	0	1*	1	1*	0	1	1	0	0	1a	0	0
	10	1	1	1*	0	0	0	0	0	0	1	0	0	0	0
	11	1	1	1*	1	1	1	1	0	0	1	1	0	1	1
	12	1	1*	1	1*	1	1*	1	1	1	1	0	1	0	1
	13	1	1*	1	1*	1	1*	1	0	0	1*	1	0	1	1
	14	1	1*	1	1*	1	1*	1	0	0	1	1	0	1	1

Following the transitivity check, the row and column totals for each element are determined. The driving power (Dr) of each element is represented by the row total, while the Dp is represented by the column total. The strength of an element is defined as the number of factors over which it has a dependent or driving influence. These values are then used in the development of the MICMAC analysis. The rank for both Dp and Dr is used to verify the correctness of the transitivity check. In an ideal scenario, the number of ranks in rows and columns should be equal. As shown in Table 6, the rows and columns have six (VI) ranks. Tables 7 and 8 indicate the ranking of elements according to their Dr and Dp, respectively.

5.2.4. Level partitioning

Level partitioning is the next step required to complete the ISM. This step is used to determine the number of levels in the ISM hierarchy and the positions of elements at different levels. Level partitioning is achieved by categorizing elements into the reachability set, antecedent set, intersection set, and level. The procedure begins with determining the reachability of each individual element that affects other elements. The reachability set comprises all elements whose value is 1 for the chosen row element. Subsequently, all elements with value "1" in the chosen column form the antecedent set, representing elements upon which other elements are dependent. The common elements between the reachability and antecedent sets constitute the intersection set.

The first iteration (Table 9) is derived by repeating the process for all elements. Next, rows with identical reachability and intersection sets are deleted, and the corresponding elements are removed from the list. This step identifies the first (top) level elements in the ISM hierarchy. The rows deleted in the first iteration provide the list of elements at level 1. This process is repeated for the remaining three iterations until each element is assigned a level (Tables 10-12). Thus, the position of each driver in the diagraph levels is described using level partitioning. Table 13 presents the classification of the elements across four levels.

5.3. Developing the interpretive structural model for quality cost

Based on Figure 3, the elements distributed across four levels in the ISM hierarchical model are listed below:

(i) Level I: Revenue maximization.

(ii) Level II: Cost optimization, conformity to customer

Table 6. Final reachability matrix with corresponding ranks and powers

		Column-wise elements "j"															
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**Dr**	**Rank**
Row-wise elements "i"	1	1	1*	1	0	0	0	0	0	0	1	0	0	0	0	4	V
	2	1	1	1	1	0	0	0	0	0	1*	0	0	0	0	5	IV
	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	VI
	4	1	1	1*	1	1	1	1*	0	0	1*	1	0	1*	1	11	II
	5	1	1	1*	1	1	1	1	0	0	1*	1	0	1*	1	11	II
	6	1	1	1*	1	1	1	1*	0	0	1*	1*	0	1	1	11	II
	7	1	1	1*	1	1	1	1	0	0	1*	1*	0	1*	1*	11	II
	8	1*	1*	1*	1*	1	1*	1*	1	1	0	0	1	0	1*	11	II
	9	1*	1*	0	1*	1	1*	0	1	1	0	0	1*	0	0	8	III
	10	1	1	1*	0	0	0	0	0	0	1	0	0	0	0	4	V
	11	1	1	1*	1	1	1	1	0	0	1	1	0	1	1	11	II
	12	1	1*	1	1*	1	1*	1	1	1	1	0	1	0	1	12	I
	13	1	1*	1	1*	1	1*	1	0	0	1*	1	0	1	1	11	V
	14	1	1*	1	1*	1	1*	1	0	0	1	1	0	1	1	11	V
	Dp	13	13	13	11	10	10	9	3	3	11	7	3	7	9		
	Rank	I	I	I	II	III	III	IV	VI	VI	II	V	VI	V	IV		

Abbreviations: Dp: Dependence power; Dr: Driving power.

Table 7. Ranking of elements based on dependence power

Dependence power	
Rank	**Element**
I	1, 2, and 3
II	4 and 10
III	5 and 6
IV	7 and14
V	11 and 13
VI	8, 9, and 12

Table 8. Ranking of elements based on driving power

Driving power	
Rank	**Element**
I	12
II	4, 5, 6, 7, 8, 11, 13, and 14
III	9
IV	2
V	1 and 10
VI	3

specification, and employee expertise.

(iii) Level III: Continuous improvement, operational cost management, rejection rate, QMS, standardization, preventive maintenance, and maintenance cost management.

(iv) Level IV: Vendor expertise, inventory cost management, and quality tools and equipment.

Revenue maximization is positioned at the top (Level I). The element at Level I indicates that it is the most dependent factor, with all elements at lower levels ultimately driving it. The direction of the hierarchical arrows progresses from the bottom to the top, indicating that the elements at the base level (Level IV in this case) drive the elements at higher levels. All elements associated with the lower levels ultimately influence the organization's revenue; therefore, revenue maximization is dependent on the other elements.

Based on the diagraph interpretation, the elements at the same level are interrelated. At Level II, cost optimization, conformity to customer specifications, and employee expertise are present. This level consists of elements that are dependent on the CoQ factors at Levels III and IV. With a focus on initiatives such as continuous improvement, standardization, and the QMS, the final output will better conform to customer specifications, resulting in improved acceptance rates and cost optimization. Employee expertise plays the role of a moderator, limiting the extent to which other elements influence CoQ factors, since the delivery of quality-centered output is directly proportional to the employees' skill set.

Level III includes continuous improvement, operational cost management, rejection rate, QMS, standardization, preventive maintenance, and maintenance cost management. Continuous improvement and operational

Table 9. Results of the first iteration in the level partitioning process

Element	Reachability set	Antecedent set	Intersection set	Level
1	1, 2, 3, and 10	1, 2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, and 14	1, 2, and 10	
2	1, 2, 3, 4, and 10	1, 2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, and 14	1, 2, 4, and 10	
3	3	1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13, and 14	3	I
4	1, 2, 3, 4, 5, 6, 7, 10, 11, 13, and 14	2, 4, 5, 6, 7, 8, 9, 11, 12, 13, and 14	2, 4, 5, 6, 7, 11, 13, and 14	
5	1, 2, 3, 4, 5, 6, 7, 10, 11, 13, and 14	4, 5, 6, 7, 8, 9, 11, 12, 13, and 14	4, 5, 6, 7, 11, 13, and 14	
6	1, 2, 3, 4, 5, 6, 7, 10, 11, 13, and 14	4, 5, 6, 7, 8, 9, 11, 12, 13, and 14	4, 5, 6, 7, 11, 13, and 14	
7	1, 2, 3, 4, 5, 6, 7, 10, 11, 13, and 14	4, 5, 6, 7, 8, 11, 12, 13, and 14	4, 5, 6, 7, 11, 13, and 14	
8	1, 2, 3, 4, 5, 6, 7, 8, 9, 12, and 14	8, 9, and 12	8, 9, and 12	
9	1, 2, 4, 5, 6, 8, 9, and 12	8, 9, and 12	8, 9, and 12	
10	1, 2, 3, and 10	1, 2, 4, 5, 6, 7, 10, 11, 12, 13, and 14	1, 2, and 10	
11	1, 2, 3, 4, 5, 6, 7, 10, 11, 13, and 14	4, 5, 6, 7, 11, 13, and 14	4, 5, 6, 7, 11, 13, and 14	
12	1, 2, 3, 4, 5, 6, 7, 10, 12, and 14	8, 9, and 12	12	
13	1, 2, 3, 4, 5, 6, 7, 10, 11, 13, and 14	4, 5, 6, 7, 11, 13, and 14	4, 5, 6, 7, 11, 13, and 14	
14	1, 2, 3, 4, 5, 6, 7, 10, 11, 13, 14	4, 5, 6, 7, 8, 11, 12, 13, and 14	4, 5, 6, 7, 11, 13, and 14	

Table 10. Results of the second iteration in the level partitioning process

Element	Reachability set	Antecedent set	Intersection set	Level
1	1, 2, and 10	1, 2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, and 14	1, 2, and 10	II
2	1, 2, 4, and 10	1, 2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, and 14	1, 2, 4, and 10	II
4	1, 2, 4, 5, 6, 7, 10, 11, 13, and 14	2, 4, 5, 6, 7, 8, 9, 11, 12, 13, and 14	2, 4, 5, 6, 7, 11, 13, and 14	
5	1, 2, 4, 5, 6, 7, 10, 11, 13, and 14	4, 5, 6, 7, 8, 9, 11, 12, 13, and 14	4, 5, 6, 7, 11, 13, and 14	
6	1, 2, 4, 5, 6, 7, 10, 11, 13, and 14	4, 5, 6, 7, 8, 9, 11, 12, 13, and 14	4, 5, 6, 7, 11, 13, and 14	
7	1, 2, 4, 5, 6, 7, 10, 11, 13, and 14	4, 5, 6, 7, 8, 11, 12, 13, and 14	4, 5, 6, 7, 11, 13, and 14	
8	1, 2, 4, 5, 6, 7, 8, 9, 12, and 14	8, 9, and 12	8, 9, and 12	
9	1, 2, 4, 5, 6, 8, 9, and 12	8, 9, and 12	8, 9, and 12	
10	1,2,10	1, 2, 4, 5, 6, 7, 10, 11, 12, 13, and 14	1, 2, and 10	II
11	1, 2, 4, 5, 6, 7, 10, 11, 13, and 14	4, 5, 6, 7, 11, 13, and 14	4, 5, 6, 7, 11, 13, and 14	
12	1, 2, 4, 5, 6, 7, 10, 12, and 14	8, 9, and 12	12	
13	1, 2, 4, 5, 6, 7, 10, 11, 13, and 14	4, 5, 6, 7, 11, 13, and 14	4, 5, 6, 7, 11, 13, and 14	
14	1, 2, 4, 5, 6, 7, 10, 11, 13, and 14	4, 5, 6, 7, 8, 11, 12, 13, and 14	4, 5, 6, 7, 11, 13, and 14	

cost management are positioned at the same level of configuration, which indicates that both elements are symbiotic, where the presence of one leads to the occurrence of the other. When a firm pursues continuous improvement, it impacts operational cost, and conversely, operational cost optimization requires continuous improvement initiatives. The same reasoning applies to QMS, standardization, and rejection rate minimization: the stronger the QMS and standardization, the lower the rejection rate. Conversely, when the rejection rate increases, the firm needs to revisit its QMS, which in turn affects standardization. Similarly, preventive maintenance and maintenance cost management are grouped together, as one defines the other. In totality, continuous improvement, QMS, and standardization are identified as key linkages in the hierarchy, since overall processing and quality control practices directly affect these elements, and the presence of such operations management techniques enhances the performance of other CoQ factors.[38]

The base elements at Level IV are vendor expertise, inventory cost management, and quality tools and equipment. These factors require particular attention in quality-oriented production processes, as they shape the

Table 11. Results of the third iteration in the level partitioning process

Element	Reachability set	Antecedent set	Intersection set	Level
4	4, 5, 6, 7, 11, 13, and 14	4, 5, 6, 7, 8, 9, 11, 12, 13, and 14	4, 5, 6, 7, 11, 13, and 14	III
5	4, 5, 6, 7, 11, 13, and 14	4, 5, 6, 7, 8, 9, 11, 12, 13, and 14	4, 5, 6, 7, 11, 13, and 14	III
6	4, 5, 6, 7, 11, 13, and 14	4, 5, 6, 7, 8, 9, 11, 12, 13, and 14	4, 5, 6, 7, 11, 13, and 14	III
7	4, 5, 6, 7, 11, 13, and 14	4, 5, 6, 7, 8, 11, 12, 13, and 14	4, 5, 6, 7, 11, 13, and 14	III
8	4, 5, 6, 7, 8, 9, 12, and 14	8, 9, and 12	8, 9, and 12	
9	4, 5, 6, 8, 9, and 12	8, 9, and 12	8, 9, and 12	
11	4, 5, 6, 7, 11, 13, and 14	4, 5, 6, 7, 11, 13, and 14	4, 5, 6, 7, 11, 13, and 14	III
12	4, 5, 6, 7, 12, and 14	8, 9, and 12	12	
13	4, 5, 6, 7, 11, 13, and 14	4, 5, 6, 7, 11, 13, and 14	4, 5, 6, 7, 11, 13, and 14	III
14	4, 5, 6, 7, 11, 13, and 14	4, 5, 6, 7, 8, 11, 12, 13, and 14	4, 5, 6, 7, 11, 13, and 14	III

Table 12. Results of the fourth iteration in the level partitioning process

Element	Reachability set	Antecedent set	Intersection set	Level
8	8, 9, and 12	8, 9, and 12	8, 9, and 12	IV
9	8, 9, and 12	8, 9, and 12	8, 9, and 12	IV
12	12	8, 9, and 12	12	IV

Table 13. List of elements after level partitioning

Level	Element
I	3
II	1, 2, and 10
III	4, 5, 6, 7, 11, 13, and 14
IV	8, 9, and 12

final outcome. It is possible that some factors at one level do not directly affect all the elements on the above level. Therefore, we see that vendor expertise and inventory cost management drive continuous improvement, operational cost, rejection rate, QMS, and standardization directly, but not preventive maintenance and maintenance cost.

5.4. Cross-impact matrix multiplication applied to classification analysis for quality cost factors

The MICMAC analysis is performed based on the Dr and Dp of elements calculated from the final reachability matrix, along with their ranks and powers. Dr and Dp values for each element are presented in Table 14 and are used to create a grid plot, where Dr is placed on the y-axis and Dp on the x-axis. Since there are 14 elements, half of that number (7) is considered the partition point (for both the x- and y-axes) to segregate the four major categories of elements according to the MICMAC criterion, as shown in Table 15.

The factors with low Dr and Dp are termed "autonomous factors." No element in the present study falls into this category, indicating that every factor affects CoQ and that no identified element functions in isolation. The factors with low Dr and high Dp are termed "dependent factors." The elements in this category include revenue maximization (Element 3), which has the highest Dp, signifying that revenue is the outcome of the performance of all other elements.

Conformity to customer expectation (Element 2) involves specification checks, which are performed once the production task is complete. It acts as a report card for the overall production process and reveals whether the base-level factors are progressing in the right direction. Cost optimization (Element 1) is achieved when all cost elements are optimized to the fullest, thereby increasing overall profitability. Employees' expertise (Element 10) has the lowest Dp and acts as a performance moderator that influences other elements. For example, the knowledge and experience of staff can lead to changes—positive or negative—in overall performance.

The factors with high Dr and low Dp are termed "drivers." These factors include elements such as inventory cost management (Element 12), which has the highest Dr and is a primary-level task in the production chain. It drives or supports the functioning of other elements in the operational chain. This is justified because quality management at the inventory phase requires accurate raw material handling, storage, transportation, and maintenance of favorable storage conditions.

Vendor expertise and material check (Element 8) have the next highest Dr. This indicates that identifying and selecting an effective supplier, along with providing technical assistance, plays a crucial role in quality management. It ensures the supply of raw materials with

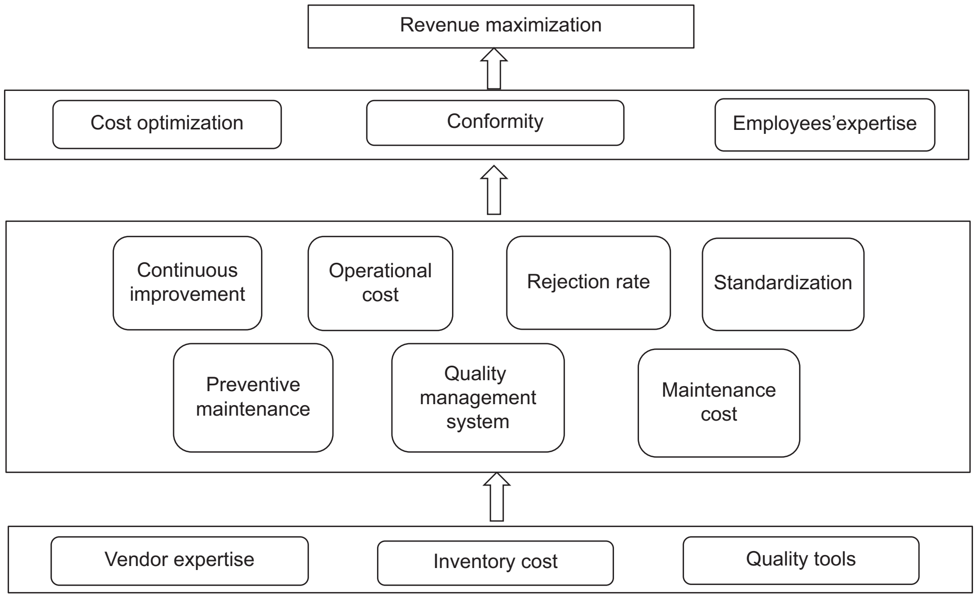

Figure 3. Interpretive structural modeling for quality cost factors

Table 14. Driving and dependence powers of the elements

Elements	Driving power	Dependence power
1	4	13
2	5	13
3	1	13
4	11	11
5	11	10
6	11	10
7	11	9
8	11	3
9	8	3
10	4	11
11	11	7
12	12	3
13	11	7
14	11	9

Table 15. Cross-impact matrix multiplication applied to classification analysis

Driving element | Linkage element

Driving power		1	2	3	4	5	6	7	8	9	10	11	12	13	14
High	14														
	13														
	12			12											
	11			8				11, 13		7, 14	5, 6	4			
	10														
	9														
	8			9											
	7														
	6														
	5													2	
	4											10		1	
	3														
	2														
Low	1													3	

Low — Dependence power — High

Autonomous element | Dependent element

minimal variation, thereby guaranteeing quality from the outset. Rejection analysis and preventive maintenance (Element 11) and maintenance cost management (Element 13) fall into the same category. They have high Dr but also show some degree of dependence. The costs incurred from analysis and preventive maintenance arise when deficiencies occur in the production process, justifying their dependence on other factors. However, they ultimately drive total cost by contributing to opportunity costs associated with additional time required.

Maintenance cost management is an umbrella term encompassing maintenance costs not only in relation to products and machinery but also the costs of technological advancements for quality enhancement, as well as other miscellaneous maintenance expenses. Quality tools and equipment (Element 9) are moderate drivers, as they serve as instruments for assessing raw material quality, which in turn influences raw material performance and thereby affects production quality.

The factors with high Dp and high Dr are termed "linkages factors" and include elements such as minimizing the rejection rate (Element 4), which has the highest Dp and Dr. This is because the rejection rate, on the one hand, depends on raw material quality and process quality, whereas, on the other hand, it drives the overall conformity cost, including operational cost. QMS (Element 5), standardization (Element 6), and continuous improvement (Element 7) are also classified as linkage factors due to their feedback cycle.

Adoption of a QMS leads to standardization, which remains effective until a disruptive technology redefines the procedure. This, in turn, triggers a new cycle of continuous improvement based on QMS and standardization. This continuous improvement cycle simultaneously drives other processes and costs, while its level of achievement depends on the performance of other elements.

Operational cost management (Element 14) is dependent upon rejections, time factors, and maintenance costs, and it drives overall revenue and profitability. For example, if operational costs are higher, the available profit margin will be lower. Furthermore, sales are dependent on prices, which in turn depend on cost.

6. Conclusion

This study successfully addressed all three research objectives through a case-based, systems-oriented approach. For the first objective, a novel set of CoQ factors that reflect the operational reality of a die-casting ancillary firm was identified, going beyond conventional P-A-F categorizations by incorporating expert insights. For the second objective, the ISM (Figure 3) enabled the establishment of a hierarchical digraph that revealed explicit relationships among the factors. This digraph highlighted foundational drivers such as inventory cost management and vendor expertise, which structurally influence dependent elements such as revenue maximization and conformity to customer expectations. For the third objective, the MICMAC analysis (Table 15) classified the factors into autonomous, dependent, driver, and linkage categories, further clarifying the systemic interdependencies. Notably, no factor was found to be completely autonomous, indicating a tightly coupled system in which all CoQ elements impact the broader cost-performance framework. The dual role of some elements as both drivers and dependents supports the idea of feedback loops in quality management, thereby reinforcing the applicability of a systems-thinking approach.

The ISM model helps to clarify the hierarchical structure of the elements within the CoQ framework. This research introduces a novel way of listing CoQ factors. Rather than focusing on conventional CoQ factors, this study adopted a different approach by gathering and defining them through a specific firm's case with the help of domain experts. Previous studies have argued that each type of firm can have a distinct list of CoQ factors depending on the nature of the business, supply chain span, and complexity. Based on expert perspectives, the conceptual framework proposed in this study appears to be well justified. It concludes that certain task- and cost-environment elements both drive and depend on the quality-oriented methodologies adopted, as evident from the ISM and MICMAC analysis, and this two-way relationship has been captured in the framework.

The drivers of adoption for the CoQ framework are continuous improvement, QMS, and standardization, which are broad methodologies. Furthermore, there are a number of tasks (e.g., preventive actions, rejection controls, and quality tools inspections) and cost environment (e.g., inventory, operational, and maintenance) that support the drivers of adoption for value delivery. Value delivery refers to conformity, cost optimization, and revenue maximization. The extent to which the value is delivered is moderated by vendor and employee expertise. Vendors are external parties whose technical expertise may not be fully controllable. Similarly, despite training and supervision, employees may exhibit variation in performance due to differences in learning speed and interpersonal issues.

6.1. Implications

This study adds a novel dimension to CoQ theory by introducing a new way of listing CoQ factors using SSM. SSM serves as a valuable technique for decision-making in complex scenarios. Decision-makers in businesses often deal with pluralistic views, including cost-benefit trade-offs. In addition to trade-offs, the presence of multiple factors and interrelated linkages among them creates a complex scenario. Since the base elements in the digraph have high Dr, this study provides guidance for managerial decision-makers in manufacturing industries to focus on and improve the base factors of the model, which ultimately determine the performance of elements at higher levels.

6.2. Limitations and future scope

The primary limitation of this study is that the digraph development process does not assign quantitative weights to the identified CoQ factors, which could be statistically evaluated using methods such as structural equation modeling. This aspect can be addressed in future studies by incorporating statistical techniques to validate the strength of interrelationships among the CoQ factors and assess the robustness of the proposed model.

Furthermore, future research may focus on developing hybrid models that integrate ISM with data-driven approaches such as structural equation modeling, analytic hierarchy process, or machine learning techniques to enhance the predictive and diagnostic capabilities of the CoQ framework. Another promising avenue is to explore the applicability of the proposed CoQ framework across different industry sectors and organizational sizes to assess its generalizability and scalability. Researchers can also attempt to quantify the financial impact of individual CoQ factors on organizational performance metrics such as defect rates, customer satisfaction, and return on quality investments. In addition, longitudinal studies can be conducted to track changes in CoQ factor dynamics over time, particularly in relation to technological advancements, policy shifts, and supply chain disruptions. Such studies could provide deeper insights into how CoQ drivers evolve and how businesses can proactively adapt their quality strategies.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: Hans Kaushik
Formal analysis: All authors
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Methodology: All authors
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ARTICLE

Privacy and security concerns shaping smart city adoption: Evidence from Qatar

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Abstract

Information security remains a significant concern for the adoption of smart cities (SCs) worldwide, particularly in relation to the development and implementation of digital ecosystems. SCs entail the interconnectedness of networks and systems that collect and process huge volumes of diverse data. This study analyzes the impact of data privacy and data security issues on the citizens' willingness to adopt smart city environments. A critical review of the existing literature was conducted regarding the relationship between data privacy and security concerns and the adoption of the smart city ecosystem. The data collected from two sample groups, experts and citizens, were analyzed using statistical techniques, including independent samples *t*-tests and correlation analysis. The findings indicate that citizens and experts had significantly different perceptions of the characteristics of SCs. Still, both groups exhibited a strong positive correlation between key adoption variables and citizens' readiness to accept SCs. Based on the findings, several recommendations are proposed to increase citizens' acceptance of SCs.

Keywords: Data privacy; Smart city; Smart governance; Concerns; Readiness

1. Introduction

1.1. Smart city and privacy issues

The adoption of smart cities (SCs) by many countries worldwide has significantly increased research interest in the role of digital technology in enhancing urban environments. A "smart city" is defined as "an urban area that integrates the use of the latest technologies to conduct data collection processes, then optimizes data usage to expand service operations within a city and improve the quality of life of local citizens."[1] This process leverages information technologies, artificial intelligence (AI), and the internet of things (IoT) to facilitate real-time decision-making, foster innovation and leadership, and enable interaction between humans, machines, and the urban environment.[2] However, the definition of an SC varies considerably across the literature. Some definitions emphasize technological innovation, while others underscore governance, social inclusion, financial development, and environmental sustainability as key elements.[3] The research notes that SCs are inherently multidimensional, with varying conceptualizations shaped by a city's level of development, local priorities, resources, and citizen aspirations.[3] This plurality of views suggests that the SC concept cannot be reduced to technology alone but must be understood as a holistic framework encompassing digital, social, environmental, and economic transformation.[4] Smart city ecosystems (SCEs) rely on complex technological infrastructures, including interconnected networks, sensors, data platforms, and applications, to deliver a range of services, such as transportation, energy management, environmental monitoring, healthcare, financial services, and public safety.[5] Given their reliance on massive volumes of personal and sensitive data, these ecosystems also present significant challenges for data governance and privacy protection.[6] Thus, the implementation of SCs must have a balance between technological innovation and ethical and regulatory considerations regarding transparency, accountability, and citizen rights.

However, the widespread deployment of these technologies also raises significant concerns around data security and user privacy. SC systems routinely collect and process sensitive personal data, including biometric identifiers, health records, real-time location data, financial transactions, video surveillance feeds, and communication logs.[7] This exposes users to potential risks, such as unauthorized access, profiling, data breaches, and other cybersecurity threats.[8,9] Studies have shown a negative relationship between increased digital adoption and citizen trust in data privacy.[7,10] These concerns present an ongoing challenge for governments and service providers, who must build and maintain secure, resilient, and citizen-centered SC environments that promote trust while delivering the intended benefits of sustainability, efficiency, and quality of life.

1.2. Research rationale

The government of Qatar has long encouraged the adoption of SCEs, envisioning the use of advanced technologies to provide critical and regular services to citizens, including substantive deployments in healthcare, transportation, smart housing, environmental protection, and the overall sustainability of the living environment.[11] The concept of the SC has gained significant traction in Qatar, particularly through several initiatives, such as Msheireb Downtown Doha and Lusail City, which are Qatar's flagship SC projects. These developments have received national visibility and been promoted through government campaigns and strategic urban planning aligned with Qatar National Vision 2030.[12] The popularity of SC concepts in Qatar is increasing, particularly in major urban centers, such as Doha and Lusail, where digital technologies are being integrated into transportation, surveillance, energy, and municipal services. The government of Qatar has long supported the adoption of SCEs, envisioning the use of advanced technologies to deliver critical and routine services to citizens.[12,13] These include major initiatives in healthcare, transportation, smart housing, environmental protection, and overall urban sustainability.[11] However, it has also been recognized that the success of such efforts depends significantly on how effectively data privacy, security, and confidentiality concerns are addressed; any breach in data security could reduce citizen trust and lead to underutilization of smart services.[9,10]

Currently, as SC deployments in Qatar approach relative operational maturity,[14] there is a pressing need to assess the actual on-the-ground progress from the perspective of stakeholders. This includes examining whether SCs in Qatar represent a practical urban transformation or merely serve as an "urban brand identity."[15] Thus, this study is warranted to explore perceptions of data privacy and security among the general public and experts involved in SC projects, especially given Qatar's position as a leading national case study. Furthermore, it aims to investigate how data security-related factors influence citizens' willingness to adopt the SCE. This research contributes to the growing body of work on cybersecurity and SC adoption.

1.3. Study aim and objectives

The primary objective of the study is to investigate the relationship between factors related to data security in SCs and willingness to accept SCE in the context of Qatar. In line with this aim, the study seeks to achieve the following specific research objectives:

(i) To establish the privacy and data security concerns related to SCs among citizens and experts.
(ii) To analyze citizens' and experts' readiness to adopt SCs.
(iii) To investigate the relationship between privacy and data security concerns on readiness to adopt SCs.

1.4. Significance of the study

This study has both theoretical and practical implications. In terms of theoretical contributions, this study addresses the need for new research on data security and privacy issues in the context of SCs in Qatar. In addition, this study contributes to theoretical research from the perspective of general citizens and experts on SC projects. In terms of practical contribution, this study has the potential to generate useful insights that can be adopted by administrators of SC projects in various stages of project management. The findings of this study identify the need for stakeholder participation to ensure that SCEs meet all the data privacy and security expectations of users.

2. Literature review

This section of the paper reviews existing research on the interrelationship between data privacy and security concerns, as well as the adoption of SCs. It also examines key factors influencing SC adoption, particularly in the Qatari context, where large-scale SC developments, such as Lusail and Msheireb, have driven the implementation of interconnected technologies. These projects highlight local concerns around data handling, digital surveillance, and cybersecurity. Furthermore, the section discusses how privacy and security concerns are currently addressed in the context of SC. Building on this literature, the study constructs a theoretical framework based on established models, such as the Unified Theory of Acceptance and Use of Technology (UTAUT), integrating variables, including performance expectancy, effort expectancy, and facilitating conditions, to analyze adoption behavior in Qatar.

2.1. Impact of data privacy and security issues on SCs adoption

SCs have the potential to significantly improve residents' quality of life. However, there are growing concerns regarding the adoption of smart applications due to their vulnerability to cybercrimes, such as data and identity theft, ransomware, spam attacks, and even international cyber warfare.[1,8,16-18] These concerns are particularly relevant in Qatar, where the centralization of data and the digitization of public services have raised questions about how securely citizen data is stored and used.[14] Table 1 summarizes the SCEs considered most at risk from cybersecurity threats, based on expert assessments across three dimensions: technical vulnerability, impact of a successful attack, and interest of nation-state attackers. In cases where multiple technologies share the same ranking, for example, four technologies receiving a score of 9 under "Interest of nation-state attackers," which indicates either an equivalent level of perceived threat or limited differentiating data, as assessed by experts. The table reveals that the highest risks are associated with emergency and security alert systems, where breaches could have severe and immediate consequences.

Table 1. Expert assessment of the cybersecurity of smart city technologies.[19]

Technology type	Ranking		
	Technical vulnerability	Impact of a successful attack	Interest of nation-state attackers
Emergency and security alert systems	1	1	1
Street video surveillance	2	3	2
Smart traffic lights/signals	3	2	3
Water consumption tracking	4	6	5
Smart tolling	5	7	8
Public transit open data	8	9	9
Gunshot detection	7	4	9
Smart waste or recycling bins	8	9	9
Satellite water leak detection	9	8	9

Figure 1 depicts the technological and systemic factors that shape cybersecurity in SCs. The convergence of information and operational technology provides the technological ecosystem necessary to control different systems, but it also expands the scope of vulnerability to cyber threats.[20,21] Interoperability pertains to the protocol that enables integration and data exchange between new digital technologies and legacy systems, often with particular vulnerabilities due to disparate technology platforms. Finally, the integration of SC services with various interconnected technologies usually presents the challenge of cascading effects and catastrophic failures due to vulnerabilities or cyber-attacks in one or more systems.[20] For example, research on European countries found that a common feature of SC is the smart mobility system, which relies on automated vehicles and technology-controlled transportation systems.[10]

Cyber-attacks on such systems have the potential to cause widespread damage and loss of lives. Similarly, for IoT sensors, security threats, such as data confidentiality, insecure communication, and interception and jamming of communication, are present during their deployment in an SC environment.[10,21] Another key aspect is the digitization of healthcare records to facilitate a smooth delivery of healthcare services.[20] However, this also presents a vulnerability to hacking or cyber theft of the personal and medical records of the individuals, thereby posing a serious concern regarding the resilience. Here, resilience is defined as the capacity of infrastructure to withstand, absorb, recover from, and adapt to adverse conditions or cyber disruptions.[22,23] These aspects have also been highlighted in academic literature as security threats when relying on a digital ecosystem, especially in a wide range of services in the SCEs.[9,23,24]

Some studies related to cybersecurity threats in the context of SCs also argue for the need for a well-defined regulatory framework that can deter threats to privacy and limit excessive collection of personal data.[25,26] For instance, the European Union's General Data Protection Regulation restricts the collection of personal data and the uses to which it can be put. The regulation aims to achieve a fair balance between the interests of users and technology solution providers.[25] However, there are also challenges arising from

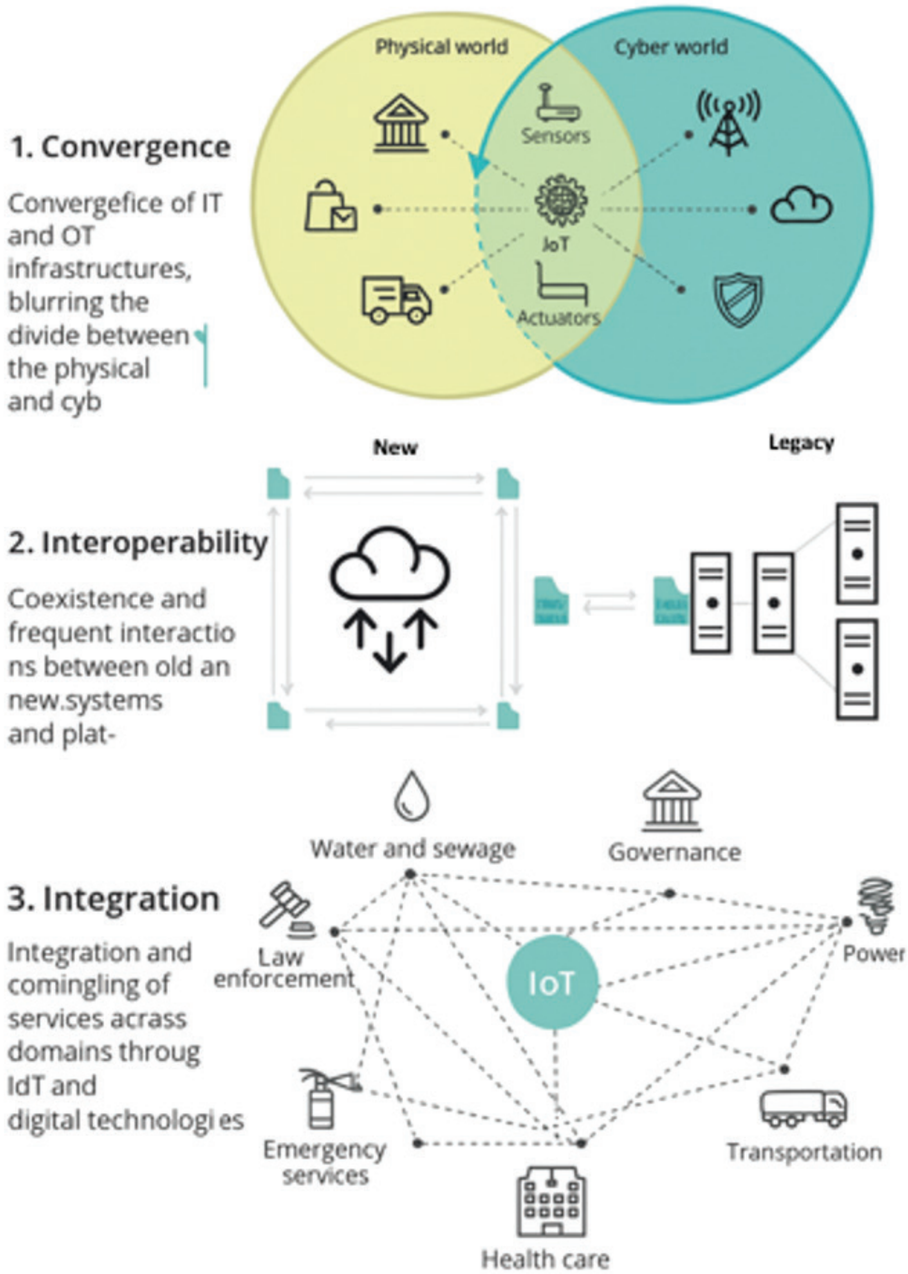

Figure 1. Key factors influencing cybersecurity in smart cities[20]
Abbreviations: IoT: Internet of Things; IT: Information technology; OT: Operational technology.

data collected by global positioning systems, cameras, and sensors, among other devices. These data collections pose a threat to individual privacy and expose them to malicious hackers.[26] Such challenges and threats are also present in smartphones used by citizens, which collect vast and far-reaching forms of personal and financial data that could be used for serious financial crimes, in addition to data theft.[5] Moreover, common standards that different countries can adopt to reduce privacy concerns are lacking.[23]

Consequently, it is challenging to determine the extent to which regulation and control are necessary and possible while using contemporary digital technologies, and it is becoming increasingly difficult for stakeholders in the SCE to establish consumer trust. In the case of Qatar, the National Cybersecurity Strategy has outlined specific regulatory mechanisms to manage these issues. These include mandatory risk assessments, incident reporting procedures, and security compliance standards for organizations operating critical digital infrastructure.[14] Furthermore, Lusail SC initiatives are already implementing policy-led frameworks for data access, encryption, and operational transparency, thereby marking a practical move toward governance-led cybersecurity in Qatar's urban digital ecosystem.[14]

2.2. Key factors of smart city adoption related to information security

There has been considerable interest in the information security aspects in an SC context, in addition to the general use of systems. One of the key determinants for the adoption of SC services is the performance expectancy dimension, which refers to the individuals' level of belief in the extent to which using a system can be beneficial.[27,28] In the context of SCs, research on the performance expectancy of SC services in a mid-sized city in the south-eastern USA shows that it significantly affected app users' intentions to use services.[29] Research based on the UTAUT further notes that these benefits create performance expectations, which determine SC adoption.[30] Another key aspect related to performance expectancy is the scalability of services in an SC as the numbers of users increase.

In this regard, cloud services are needed to reduce reliance on physical servers while optimizing network, computing, and scalability requirements.[2] Bridging cloud and IoT can help administrators and architects of SC move to an integrated platform, offering seamless services in the SCEs.[2] The literature also shows that since most services of SCs in multiple disciplines, such as smart community, smart transportation, and smart healthcare, among others, have become data-driven, there is a need for higher processing power without compromising data integrity, scalability, and intelligent decision-making. Cloud computing fulfils these requirements and addresses the issue of information security.[31] However, it is also crucial that the technological architecture supports the adoption of cloud services and the integration of advanced technologies and data management.[22,24,32]

While scalability and performance issues can be addressed through rapid advances in technology, information security issues always remain at the forefront for users and the technology architects. In this regard, security and privacy concerns are quite common in the context of SC environments, primarily due to tools for monitoring the physical movement of citizens and the data collected while providing SC services. Such concerns can be addressed by increasing awareness of data security and privacy, as well as transparency within SCE governance.[33] There are also concerns that the interconnectedness of devices could facilitate unauthorized access, potentially leading to physical disruptions and bringing the entire connected infrastructure to a standstill.[9] Furthermore, advancements in technology, such as AI and IoT, have the potential to provide full connectivity and unprecedented improvements to human quality of life within the SCE but also raise challenges regarding security and privacy issues, thereby arguing the need for effective countermeasures.[21]

Another key aspect in the context of SC is the integrity of data, which refers to accuracy and validity.[34,35] The lack of data integrity defeats the purpose of interconnectedness of systems to provide an enhanced quality of services to citizens in an SC environment.[35] Hence, there is a need for SC projects to adopt advanced technologies, such as blockchain and big data frameworks, for processing data emanating from IoT devices. In addition, blockchain can be applied to provide a decentralized framework that records transactions, maintains data integrity, and enhances transaction efficiency through smart contracts.[34] Smart contracts are self-executing agreements coded on blockchain platforms that are generally considered trustworthy due to their transparency, immutability, and automation. They eliminate the need for third-party enforcement and reduce the risk of manipulation or fraud.[36]

Blockchain-based transactions in SCs also ensure data integrity and interoperability.[37] Furthermore, some analysts have recommended shifting to a decentralized big data auditing scheme for SC environments, which are driven by blockchain capabilities that can improve the reliability and stability of the systems, with additional benefits of lower computational costs.[38,39] Such systems not only reduce human interventions but also provide an accurate audit of the performance of AI data-driven analysis.

Effort expectancy is also crucial when exploring the adoption of SCs; it refers to the level of convenience for users when using any information system.[40] Study shows that effort expectancy significantly influences citizens' intention to use SCs.[30] The effort expectancy variable is a crucial component of UTAUT theory, wherein it has been reported that when users find a system convenient, they are more likely to use it regularly.[41,42]

Research on the adoption of AI-powered chatbots for public transport services in an Indian SC showed positive outcomes.[27] They observed that effort expectancy directly influenced the adoption intention of the chatbots, presenting a useful case for a convenient and user-friendly interface in availing daily-used services, such as transportation.[27] A study conducted in Malaysia also reported similar findings regarding the adoption of mobile healthcare applications, where the effort expectancy variable significantly influences the regular use of the mobile application.[43] These findings clearly highlight the need to focus on the effort expectancy variable when designing public interface systems for higher adoption.

Another key factor is facilitating conditions, which refer to the extent to which an individual believes that the technical and organizational infrastructure can support the use of the system.[44] In the context of SCs, facilitating conditions can be enhanced by the use of advanced technologies, such as IoT, which help the administration to effectively process data and provide an interface for service delivery to citizens. Several studies acknowledged the need for a robust technological infrastructure that can mitigate risks to the system while providing efficient service delivery. However, studies conducted from the perspective of technology adoption have reported challenges in the facilitating conditions, considering the dynamic nature of the service delivery and the evolving ecosystem in the context of SCs.[44,45]

These challenges relate to privacy and data security, as well as scalability and interoperability.[45] The role of governance, along with technological infrastructure, has thus emerged as an effective measure of managing the challenges that arise in an SCE.[46] In addition, the behavioral intentions of adopting an information and communication technology (ICT) system play a crucial role in the success of adopting any ICT. In this case, behavioral intentions refer to the strength of any individual's intention to perform a behavior.[47] In the context of SCs, the behavioral intention to adopt services is dependent on various factors, such as ease of use, convenience, assurance of data privacy and security, trust in the system, facilitating conditions, and performance expectancy, among others.[48]

Research conducted in India found that perceived information and service quality influence the behavioral intentions of adoption of an ICT system in an SCE.[49] However, a counterargument is that even users who are aware of the different information systems and possess the requisite skills to use them express concerns regarding the utility, accessibility, security, and efficiency of SC services.[50] The findings are based on interdisciplinary SC research and highlight the need to address these factors to enhance the behavioral intentions of using SC services.

2.3. Addressing security and privacy concerns in SCs

The need to handle data from the perspectives of processing and security is one of the key challenges highlighted in several studies.[36,51,52] Researchers have proposed a new business model that integrates IoT with big data for data processing and analytics, enabling better informed decision-making in SC models.[36] Others have proposed using big data analytics when deciding and creating information technology (IT) infrastructure.[52] This approach ensures that SCs meet the needs of their inhabitants, with integrated systems that encompass smart home, water, and weather sensors, as well as surveillance equipment for data generation, collection, and analysis.[52]

However, evidence on the use of data analytics is often affected by challenges related to data collection and quality, the costs involved in data lifecycle management, as well as data security and privacy.[36] There are legitimate and serious concerns regarding these considerations, including the need to protect SC systems from malicious attacks or illegal access, which compromises individual rights and even the safety of city infrastructure.[36,51] A significant and growing body of research has focused on addressing such information security issues, and there have been various propositions on implementing security measures in an SC environment.

Researchers have mostly focused on the privacy of citizens, data security, and security measures in the interconnected networks.[35,53,54] Some commonly used measures for system security include biometric authentication, facial recognition, and multi-factor authentication.[19,46] While these measures are necessary, they are insufficient in themselves to copper-bottom SCE security in complex systems of interconnected networks. Figure 2 illustrates a comprehensive approach for SC data security and privacy, including SC conceptualization, security requirements, security challenges, privacy challenges, solutions and architectures, and open issues.

It can be seen from Figure 2 that the roadmap offers the benefit of providing an overarching framework, highlighting the different components of the technology ecosystem that require attention to prevent information security attacks, targeting systems and data. An additional layer of security can be imposed by utilizing blockchain technology, which can be integrated with smart devices to provide a secure communication platform.[56] However, it is also important to understand that the exponential rise in computing power brings about fundamental challenges that face the adoption of any system (e.g., financial costs), and there are increasingly critical potential vulnerabilities in increasingly vast systems, which can be exploited with malicious intent. The roadmap displayed in Figure 2 acknowledges the existential issues in this field, including secure data outsourcing, security risk management, and big data processing, all of which are integral parts of the SCE mix that need to be addressed to ensure robust security measures in SCs.[55,56]

2.4. Theoretical framework

The reviewed literature reveals that data privacy, information security, and network security are the main

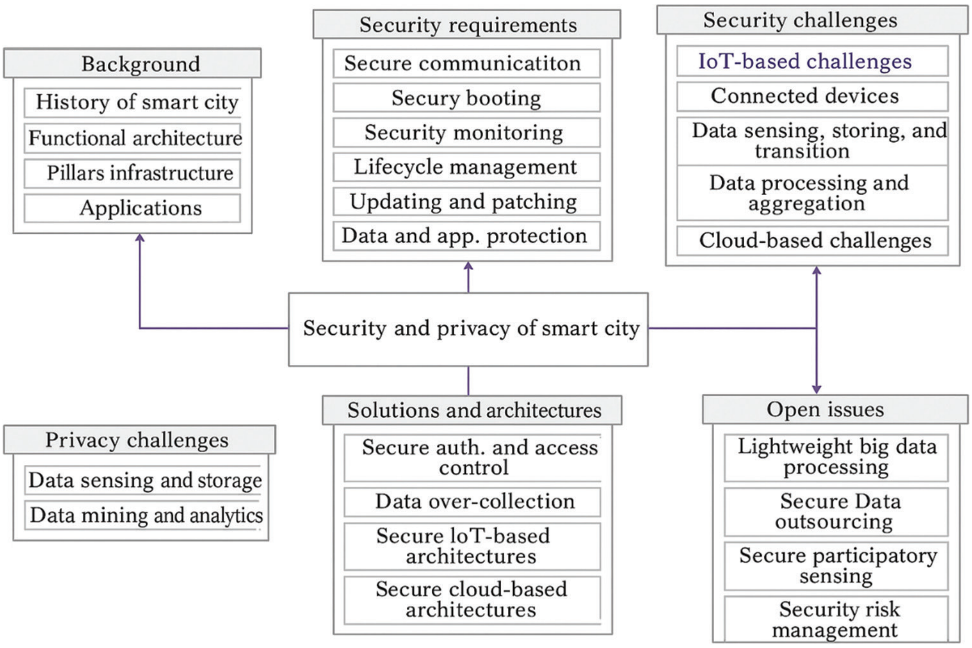

Figure 2. Roadmap for cybersecurity implementation in smart cities[55]
Abbreviations: Auth.: Authentication; IoT: Internet of things.

threats facing the technological ecosystem of SCs.[37,51,55] Specifically, these studies examine several dimensions of these threats, such as unauthorized access to personal data (privacy), system vulnerabilities and malware exposure (information security), and the susceptibility of interconnected communication networks to disruption or interception (network security). Moreover, ICT-related factors, such as effort expectancy, performance expectancy, and facilitating conditions, also play a crucial role in determining the adoption of the SC.[57] These factors are identified as independent variables, and their influence will be studied on the dependent variable, defined here as the willingness to adopt the SC environment. This construct is chosen because it reflects citizens' overall behavioral intention toward accepting and engaging with SC services, which is an outcome commonly used in technology acceptance models (TAMs), such as UTAUT, and supported in recent SC adoption literature.[4,30]

Figure 3 presents the theoretical framework underpinning this study, which integrates both behavioral and technical dimensions to explain citizens' willingness to adopt or perceive SCs. The framework comprises four key constructs: privacy of data, information security, network security, and IT acceptance. Each construct is grounded in technical components relevant to SCEs. The privacy of data refers to the extent to which individuals feel their personal information is protected within SC platforms, encompassing data anonymization techniques, consent management systems, and privacy-preserving

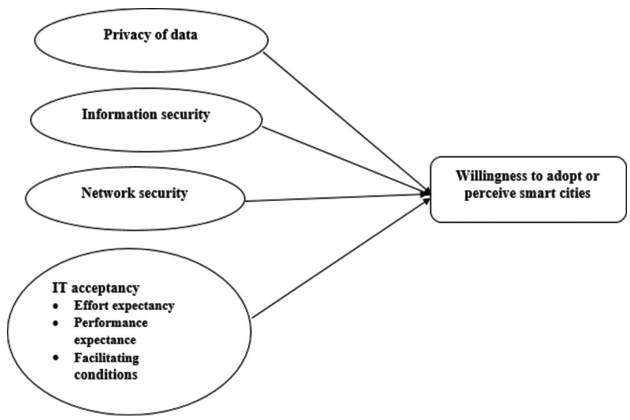

Figure 3. Conceptual framework for the willingness to adopt or perceive smart cities.

analytics that comply with data protection regulations, such as the GDPR.[3,6] Information security addresses the safeguarding of data during collection, storage, and processing through mechanisms, such as encryption algorithms, access control protocols, intrusion detection systems, and secure audit trails. Network security focuses on protecting communication infrastructure, particularly IoT and cloud-based systems, through secure communication protocols, firewalls, virtual private networks, and decentralized trust models, such as blockchain. The final construct, IT acceptance, draws on the UTAUT, incorporating effort expectancy, performance expectancy, and facilitating conditions. These factors relate to the usability and perceived benefits of SC technologies, as well as the availability of technical support and system compatibility.

3. Materials and methods

3.1. Study design

The authors used a survey research strategy to collect data from the recruited participants between May and July 2023. Primary data were collected from two groups of participants: (i) experts experienced in SC projects in Qatar and (ii) general Qatari citizens, defined in this study as adult residents of Qatar, both nationals and long-term expatriates, who live in urban areas and are potential users or beneficiaries of SC services. Unlike the expert group, these citizens were not required to have technical expertise but were expected to be aware of and impacted by urban digital services. An online link was circulated in a Facebook group created specifically to recruit participants for the study. The survey questionnaire comprised three sections. The first section was structured to collect demographic data, which provided information about the general characteristics of the samples included. The second section contained research-specific questions concerning respondents' SC-related data privacy and security concerns. The last section related to the respondents' readiness to adopt SCs. The responses in the second and third sections of the survey questionnaire were designed using five-point Likert scales.

3.2. Instrument

The survey questionnaire was designed to seek responses from the participants in the areas of "actual use of behavior in adopting cybersecurity," "availability of cybersecurity measures," "behavioral intention in adopting cybersecurity," "confidentiality of information," "effort expectancy," "facilitating conditions," "integrity of cybersecurity," "performance expectancy," "resilience of cybersecurity," "safety," and "social influence of cybersecurity." The survey questionnaire was prepared in these areas based on previous studies.[4,57] The broad research parameters selected in this study included three core domains: (i) technological determinants (such as the availability and integrity of cybersecurity systems, and resilience against attacks); (ii) behavioral and psychological factors (including effort expectancy, social influence, and behavioral intention); and (iii) information assurance aspects (such as confidentiality, performance reliability, and perceived safety). The authors selected broad research parameters to accommodate a holistic opinion of the participants regarding various aspects of data security. To gain a more holistic understanding of the data privacy and data security concerns of the respondents, the original survey questionnaire was adapted to be appropriate for the second group of participants—experts experienced working on SC projects, in addition to the original sample of citizens.[58]

3.3. Participant recruitment

The individual respondents appropriate for the study were selected based on specific inclusion criteria to ensure a valid representation of each group. General Qatari citizens were defined as adult residents of Qatar (aged 18 and above) living in urban areas and having at least basic awareness or interaction with SC services, such as digital public platforms, smart transport systems, or municipal applications. These individuals were identified, approached, and recruited through social media groups related to SCs in Qatar. The Facebook groups used for this purpose included "Qatar Living," "Life in Qatar," "Doha Qatar Online Place," "Residents of Qatar//Living in Qatar," "Qatar.com," "Doha Qatar City," "Lusail," and "Lusail Residents Network" (Lusail being Qatar's flagship SC initiative). These groups were selected for their broad and diverse user base, allowing access to a wide range of demographics reflective of the Qatari urban population. The study clearly stated that participation was voluntary, and participants were free to leave the survey or withdraw from the research at any time without providing a reason. For the expert group, the authors used purposive sampling. We contacted professionals with hands-on experience with SC projects in Qatar, particularly in areas such as cybersecurity, ICT development, urban planning, and public infrastructure management. Gatekeepers from relevant companies and agencies facilitated access to these experts. To maintain professionalism and privacy, all communications were carried out through the respondents' personal email addresses outside of working hours.

3.4. Sampling

The study used purposive sampling for the experts and convenience sampling for citizens. This approach was adopted to optimize the participation and selection of qualified respondents for the sample. Purposive and convenience sampling were based on the availability of respondents and the selection of participants with expert knowledge in cybersecurity, although the scope for generalization was limited. This strategy aligns with the principles of mixed-methods research, which often combines qualitative depth and contextual understanding (through purposive sampling) with broader, accessible participation (through convenience sampling), especially during exploratory phases or in studies addressing practical, real-world settings.[59,60] Mixed-methods designs value methodological flexibility and often prioritize contextual relevance over statistical generalizability when exploring complex social or technological phenomena. Nonetheless, this approach suffers from a lack of generalizability of findings to the general population.[60] This research was not aimed at generalizing but rather was focused on a specific aspect (i.e., the influence of data privacy and security concerns on respondents' willingness to adopt SCs in the context of Qatar).

The primary inclusion criteria for the citizen groups were that they should be Qatari adult citizens (aged 18 and above), including residents and non-residents of SCs in the country, who were willing to participate in the online survey. The study collected data from 120 Qatari citizens regarding the impact of their concerns about data privacy and security on their readiness to adopt SCs. Participants in the expert group were subject to additional inclusion criteria of having experience in working on SC projects in Qatar.

3.5. Data analysis

The study collected data from 155 Qatari citizens. The data collected from the general public (hereinafter "public") (n = 120) and experts (n = 35) were analyzed using inferential, parametric, and non-parametric statistics. The authors aimed to establish potential statistically significant differences between the two groups of respondents. To assess group-level tendencies and enable comparison, the authors calculated the mean responses for each group on key variables. While averaging responses in relatively small samples carries the limitation of reduced generalizability, it is widely accepted in social science research as a method to detect central tendencies and significant patterns.[61] Before analysis, the datasets were screened for missing values and outliers, and reliability tests (Cronbach's alpha) were conducted to ensure internal consistency across scale items. The data were then cleaned and standardized using the Statistical Package for the Social Sciences (SPSS version 26, IBM, United States) software to ensure that responses across both groups were comparable. In this study, representativeness was approached through internal consistency within each group and the alignment of demographic distribution (e.g., age, gender, profession) with broader characteristics of the respective populations. For inferential testing, equal variance assumptions were evaluated through Levine's test, and both parametric (independent samples t-tests) and non-parametric methods were applied to validate robustness. Although not statistically representative in a probabilistic sense, the averaged results are analytically useful to highlight comparative differences between the two stakeholder categories. In addition, correlation tests were conducted separately for each group to avoid cross-sample bias and to ensure fair and meaningful comparisons.

4. Results

This section summarizes the results based on the data from 120 citizens and 35 experts. The first part presents data on the demographic characteristics of the participants, followed by the testing of the hypothesis and a discussion of the findings.

4.1. Demographic characteristics of samples

Collected demographic data included participants' age, sex, marital status, number of people in household, number of children in family, prior experience of living in an SC, and status of living in an SC. For the sample group comprising experts, the demographic data collected include age group, sex, marital status, current position in organization, prior experience in SC projects, duration of working on an SC project, and current status of employment in an SC project.

Table 2 shows the responses for the public, indicating relatively even distribution across the categories for demographic characteristics (age, sex, marital status, and family status), apart from the majority being male (60%), married (61%), and not having lived in an SC (81%). While 81% of the public group reported not having lived in SCs, and 78% indicated that they were not currently residing in one, the trustworthiness of the data remains valid due to the nature of the study's objectives. The research was designed not to assess the direct experience of users within a fully developed SC but rather to explore perceptions, attitudes, and concerns regarding the adoption of SC environments, including factors such as data privacy, cybersecurity, and service readiness. Perceived trust, intention to adopt, and awareness of potential benefits and risks are meaningful even in populations not yet embedded in SC contexts, as these perceptions heavily influence future adoption behaviors.[4] Furthermore, Qatar has introduced elements of SC services (e.g., smart transport, digital healthcare, e-government) that citizens interact with even outside formal SC zones, such as Lusail. Thus, although most respondents have not lived in a designated SC, they are nonetheless engaged with smart technologies, making their responses relevant and informative for this study.

The responses of the expert group are shown in Table 3. In contrast to the public group, there was a greater concentration of experts in the age cohort aged 35–45 (49%), followed by the oldest cohort aged 46 and above (34%), and an even sex distribution (with 57% male and 40% female). As with the public group, the majority of experts (63%) were married. The vast majority (91%) had worked directly on SC projects, and 69% were currently working on one, having direct experience in the field. Similar proportions worked as designers (20%), construction workers (29%), project managers (23%),

Table 2. Demographic characteristics of the public group

Question	Options	Frequency	Percentage
What is your age? (years)	18–25	24	20
	26–34	25	21
	35–45	33	28
	46+	38	32
What is your sex?	Male	72	60
	Female	40	33
	Prefer not to say	8	7
What is your marital status?	Single	27	23
	Married	73	61
	Divorced	10	8
	Other	10	8
How many people are there in your household?	1	15	13
	2	14	12
	3	26	22
	>3	65	54
How many children live in your household?	0	33	28
	1	24	20
	2	30	25
	3	7	6
	>3	26	22
Have you ever lived in an SC?	Yes	23	19
	No	97	81
How long have you lived in an SC? (years)	<1	9	8
	1–3	5	4
	4–6	5	4
	>6	4	3
	Have not lived in SC	97	81
Do you currently live in an SC?	Yes	16	13
	No	7	6
	Have not lived in SC	93	78

Abbreviation: SC: Smart city.

and in other managerial positions (29%). Hence, the sample represents a good mix to provide useful insights with respect to the different variables of SCs and citizen readiness to adopt an SCE.

4.2. Statistical test for data analysis

For comparison of the two data sets, an independent sample *t*-test was carried out using SPSS statistical software. This test compares the means of two independent groups to detect any potentially significant difference between them.[62] The null and alternative hypothesis for this test is defined below:

Table 3. Demographic characteristics of the expert group

Question	Options	Frequency	Percentage
What is your age? (years)	18–25	2	6
	26–34	4	11
	35–45	17	49
	46+	12	34
What is your sex?	Male	20	57
	Female	14	40
	Prefer not to say	1	3
What is your marital status?	Single	6	17
	Married	22	63
	Divorced	3	9
	Other	4	11
What is your position in your organization?	Designer	7	20
	Construction worker	10	29
	Project manager	8	23
	Managerial position	10	29
Have you ever worked on an SC project?	Yes	32	91
	No	3	9
How long have you worked on an SC project? (years)	<1	4	11
	1–3	9	26
	4–6	11	31
	>6	8	23
	Have not worked on an SC project	3	9
Do you currently work on an SC project?	Yes	24	69
	No	8	23
	Have not worked on an SC project	3	9

Abbreviation: SC: Smart city.

H_0: The means of the two groups of the public and experts with respect to SC characteristics are not significantly different.

H_1: The means of the two groups of the public and experts with respect to SC characteristics are significantly different.

Considering the above, the output of the independent sample *t*-test is as shown in Table 4. The *t*-test for equality of means shows statistically significant results. This implies that the means of the two groups with respect to the perception of SC characteristics are significantly different. This difference is expected due to the participants' varying levels of exposure and expertise related to SC technologies. This is also evident in the different parameters of the survey questionnaire, i.e., actual use of behavior in adopting privacy and data security in SCs, availability of privacy and data security, behavioral intention in adopting privacy and data security in SCs, confidentiality of privacy and data security, effort expectancy, facilitating conditions, integrity of privacy and data security, performance expectancy, resiliency of privacy and data security, and public readiness to accept SCs. Purposive sampling ensured that only individuals with relevant, hands-on experience in SC projects were included, thereby enhancing the depth and contextual relevance of expert insights. Similarly, the use of convenience sampling for citizens allowed for efficient data collection from a broad and diverse urban population. However, these non-probability sampling methods do not permit statistical generalization to the wider population and are potentially subject to selection bias.[61] For this study, the method was appropriate in exploratory or applied research contexts, where the goal is to compare stakeholder perceptions rather than produce generalizable metrics.

Hence, the null hypothesis is rejected. The differences in the mean are explained based on the argument that the public and experts have different levels of understanding regarding the SCE. The public's perception is primarily derived from personal experience and social communication, such as word of mouth, social media platforms, or public sources.[18] On the other hand, the perception of SCE among experts is derived based on their direct experience of working on SC systems.

A Pearson correlation test was conducted to test the linear association between the different parameters of SCE and citizens' readiness to accept SCs. The correlation test was conducted in two parts, one for the public and the other for experts. This is primarily due to the reasons that the means of perception for the two groups (the public and experts) regarding SC characteristics were found to be significantly different. The null and alternative hypotheses for conducting the correlation test are formulated below:

H_0: There is no significant correlation between the different parameters of SCE and public readiness to accept SCs.

H_1: There is a significant correlation between the different parameters of SCE and public readiness to accept SCs.

The statistical results from the public group are shown in Table 5. It can be observed that all variables representing the different characteristics of SCE from citizens' perspectives display statistically significant results, indicating a positive correlation with their readiness to accept SCs. The observed correlations, in descending order, are performance expectancy (r = 0.842, $p<0.05$), facilitating conditions (r = 0.814, $p<0.05$), confidentiality of privacy and data security (r = 0.794, $p<0.05$), resiliency of privacy and data security (r = 0.792, $p<0.05$), integrity of privacy and data security (r = 0.772, $p<0.05$), effort expectancy (r = 0.759, $p<0.05$), behavioral intention in adopting privacy and data security in SCs (r = 0.750, $p<0.05$), actual use of behavior in adopting privacy and data security in SCs (r = 0.745, $p<0.05$), and availability of privacy and data security (r = 0.714, $p<0.05$). Among these, performance expectancy shows the strongest correlation, suggesting that citizens are more willing to adopt SCs when they perceive clear benefits and efficiency gains. Facilitating conditions also ranked high, indicating that infrastructure and support systems significantly influence acceptance. These findings highlight that citizens' decisions are driven more by perceived utility and available support than by technical or behavioral aspects alone.

The statistical results from the expert group are shown in Table 6. All the variables representing the different

Table 4. Independent sample *t*-test between public and expert groups

Variable	Sig. ($p<0.05$)	Direction of difference
Actual use of behavior	Yes	Experts<public
Availability of privacy and data security	Yes	Experts<public
Behavioral intention	Yes	Experts<public
Confidentiality of privacy and data security	Yes	Experts<public
Effort expectancy	Yes	Experts<public
Facilitating conditions	Yes	Experts<public
Integrity of privacy and data security	Yes	Experts<public
Performance expectancy	Yes	Experts<public
Resiliency of privacy and data security	Yes	Experts<public
Readiness to accept SCs	Yes	Experts<public

Data source: Table A1.
Abbreviations: SCs: Smart cities; Sig.: Significance.

Table 5. Pearson correlation test of the public group

Variable	Correlation with readiness to accept SCs	Significance
Performance expectancy	0.842	$p<0.05$
Facilitating conditions	0.814	$p<0.05$
Confidentiality of privacy and data security	0.794	$p<0.05$
Resiliency of privacy and data security	0.792	$p<0.05$
Integrity of privacy and data security	0.772	$p<0.05$
Effort expectancy	0.759	$p<0.05$
Behavioral intention	0.750	$p<0.05$
Actual use of behavior	0.745	$p<0.05$
Availability of privacy and data security	0.714	$p<0.05$

Data source: Table A2.
Abbreviation: SCs: Smart cities.

characteristics of SCE from the experts' perspective display statistically significant results, indicating a positive correlation with public readiness to accept SCs. The observed correlations, in descending order, are performance expectancy (r = 0.893, p<0.05), confidentiality of privacy and data security (r = 0.891, p<0.05), resiliency of privacy and data security (r = 0.888, p<0.05), integrity of privacy and data security (r = 0.879, p<0.05), effort expectancy (r = 0.876, p<0.05), availability of privacy and data security (r = 0.865, p<0.05), actual use of behavior in adopting privacy and data security in SCs (r = 0.851, p<0.05), facilitating conditions (r = 0.844, p<0.05), and behavioral intention in adopting privacy and data security in SCs (r = 0.836, p<0.05). Performance expectancy remains at the top of the list, showing that experts also emphasize the importance of tangible improvements in service delivery. Interestingly, experts place slightly more importance on confidentiality and resilience of data systems, likely reflecting their deeper understanding of technical vulnerabilities. These insights suggest that while both groups value system performance, experts are more attuned to the foundational role of robust security infrastructure in citizen acceptance.

5. Discussion

The strong correlations demonstrated between the studied variables add support to previous studies. For the performance expectancy variable, a similar study in the United States reported that it had the highest influence on app-use intentions in the context of a service app.[29] A follow-up study also reported the positive influence of the performance expectancy variable on intention to use SC services.[30] These findings indicate that citizens familiar with the solutions offered in an SCE are more likely to adopt and use SC services regularly.

There has been considerable analysis in previous studies of the variables, including confidentiality, privacy, and data security.[8,9,33] These studies highlighted the concerns emanating from full connectivity and large volumes of data collection and analysis, facilitated by AI and intelligent systems, such as IoT. Hence, the findings of this study also concur with the need to redress the privacy and data security issues to enhance public readiness to accept SCs.

Table 6. Pearson correlation test of the expert group

Variable	Correlation with readiness to accept SCs	Significance
Performance expectancy	0.893	p<0.05
Confidentiality of privacy and data security	0.891	p<0.05
Resiliency of privacy and data security	0.888	p<0.05
Integrity of privacy and data security	0.879	p<0.05
Effort expectancy	0.876	p<0.05
Availability of privacy and data security	0.865	p<0.05
Actual use of behavior	0.851	p<0.05
Facilitating conditions	0.844	p<0.05
Behavioral intention	0.836	p<0.05

Data source: Table A3.
Abbreviation: SCs: Smart cities.

For the variable of resiliency of privacy and data security, the findings also affirm previous literature reporting that the interconnectedness of humans with digital devices requires voluminous data exchange, which means that SC systems need to be resilient to protect the privacy of users (i.e., the general public) and to ensure data security continuously.[9] Furthermore, although the literature shows that security and privacy concerns are common and fundamental in the context of SC environments,[33] there is a need for robust monitoring mechanisms to ensure resiliency of privacy and data security, which in turn enhances trust and public readiness to accept SCs. Hence, the findings of this study also concur with the need for resilient privacy and data security to enhance public acceptance of SCs.

The strong and positive correlation between the variable of integrity of privacy and data security is also closely related to the variables of privacy and data security, as well as the variable of confidentiality of privacy and data security, wherein strong support has been observed in literature with respect to influence on public readiness to accept SCs.[18,21,47,62] This is based on the axiomatic assumption that the public expects their data to be accurate when availing themselves of public services (e.g., medical health records). Prior research has also highlighted the use of advanced technologies, such as blockchain, to maintain data integrity in an SCE, enhancing trust and confidence among the residents of SCs.[35,37,58] In the context of Qatar, this concept is gaining traction, with several projects, such as Lusail SC and the Ministry of Communications and IT, promoting blockchain-based digital identity systems, smart healthcare platforms, and secure data-sharing protocols. These developments indicate a clear trend toward integrating advanced technologies as part of Qatar's National Vision 2030. However, full-scale implementation remains in progress, requiring continued policy alignment, technical capacity-building, and public engagement to ensure effective adoption.

Hence, the findings of this study also concur with previous research in demonstrating that higher integrity of privacy and data security leads to enhanced readiness among the public to accept the SC environment. For the variable of effort expectancy, it is observed that there is a strong correlation with public readiness to accept SCs for both the public and experts. This is also consistent with existing literature that reported the effort expectancy significantly influences citizens' intention to use SCs.[30] The strong correlation can be explained based on UTAUT, wherein users find a system convenient, they are more likely to use the system regularly.[22,46]

The strong correlation between the variable of facilitating conditions of public readiness to accept SCs is explained based on the argument that a robust technological architecture and infrastructure are necessary to support the services in SCs. Moreover, the advancements in technology also offer the scalability of services with ease, thereby ensuring that the technology infrastructure supports the citizen-centric services in SCE. These findings are also consistent with academic literature, which reports that robust technological infrastructure and governance enhance public participation in the SCE, thereby enabling an easy and efficient delivery of services by governments.[45,46]

Finally, for the variable of behavioral intention in adopting privacy and data security in SCs and the variable of actual use of behavior in adopting privacy and data security in SCs, it is observed that a strong correlation is demonstrated with public readiness to accept SCs for both the public and experts. This is because when the public understands the need for privacy and data security and trusts the ecosystem regarding privacy and data security measures, they are more likely to use the services in an SCE. These findings are also consistent with those in previous studies, which pointed out that the behavioral intention to adopt services is dependent on various factors, such as ease of use, convenience, assurance of data privacy and security, trust in the system, facilitating conditions, and performance expectancy.[48,49] In the public group, behavioral intention showed a correlation coefficient of $r = 0.750$ ($p<0.05$), and actual use of behavior showed $r = 0.745$ ($p<0.05$), indicating strong, statistically significant relationships with readiness to accept SCs. In the expert group, the same variables also revealed strong positive correlations of $r = 0.836$ and $r = 0.851$, respectively (both $p<0.05$). Hence, although the two groups are significantly different, the statistical results confirm a strong and positive correlation between the variables of SCs and public readiness to accept SCs.

6. Conclusion

6.1. Main outcomes

In the coming years, at varying paces in different global and regional contexts, the majority of current urban populations will live in SC environments. The use of technology in providing public services has become a common norm for government and corporate entities. However, the longstanding challenges of data security and privacy remain prevalent, concerning service users and providers. In this regard, this research focused on the effect of data privacy and data security issues on the public's willingness to adopt the SC environment. To achieve the research objectives, a critical review of previous academic literature was conducted regarding the interconnection between data privacy and security issues, as well as the adoption of SCs, key factors of SC adoption, and how security and privacy concerns are currently addressed in the SC context.

Based on the reviewed literature, this study developed a theoretical framework conceptualized to investigate perceptions of SC adoption variables for two representative samples, the "public" and "expert" groups. The findings revealed that the two samples differ in their responses, as observed from the output of the independent sample *t*-test. However, a strong positive correlation is observed between all variables of SC adoption, i.e., performance expectancy, facilitating conditions, confidentiality of privacy and data security, resiliency of privacy and data security, integrity of privacy and data security, effort expectancy, of behavioral intention in adopting privacy and data security in SCs, actual use of behavior in adopting privacy and data security in SCs, availability of privacy and data security, and public readiness to accept SCs.

The findings present useful insights into the importance of information security in an SC environment. Since the majority of systems are interconnected, it is imperative to set up strong administrative and governance control, which can mitigate the risk of vulnerabilities in an SC environment. Hence, some recommendations can be made based on this study for governmental authorities looking to increase public acceptance of SCs in Qatar and similar contexts.

First, concerns regarding privacy and data security need to be addressed both for the existing SCE paradigm and during the conceptualization of new SC models. For this purpose, previous studies[34,37] have suggested using advanced technologies, such as blockchain, big data, and IoT, to address network security, privacy, and data confidentiality. In Qatar, such implementation could build upon existing frameworks, such as the National Cybersecurity Strategy and Lusail SC's pilot initiatives in digital ID and data governance.[14] Practical steps include adopting permissioned blockchain systems for public service records (e.g., smart health or education) and creating a centralized trust authority under the Ministry of Communications and IT.

Second, the systems should be scalable to ensure public availability of the services. Prior research has suggested using cloud services to handle scalability and sustain system performance when managing large volumes of data.[2,24,31] Since the SC environment spans multiple services, such as healthcare, transportation, and connectivity, there must be minimal downtime and enhanced service continuity. In the Qatar context, integrating scalable cloud infrastructure (e.g., through Qatar Cloud, Microsoft Azure Qatar Region) into government and municipal platforms would address performance bottlenecks while ensuring compliance with local data residency laws.

Third, the basic functionalities of services, such as performance expectations and effort expectations, must be adequately addressed when designing both the front end and the back end of SCE systems. This entails active stakeholder consultation and participation from the design stage onward, with continuous evaluation of deployed systems. The development of a Qatar-specific TAM could guide policymakers in measuring key predictors of adoption, such as perceived usefulness, trust, and ease of use, based on national user behavior studies. Such a model could be institutionalized by bodies like the Qatar Digital Government initiative.

Finally, the government should be aware of the factors inhibiting the adoption of SC services. This can be achieved through public education campaigns that increase trust in SC systems, thereby contributing to a positive behavioral intention toward using SC services regularly. Several initiatives, such as the "Digital Qatar" literacy programs and smart citizen apps, should be expanded to enhance transparency, raise cybersecurity awareness, and demystify SC technologies for ordinary residents. These efforts, combined with responsive feedback mechanisms, can bridge the gap between policy design and public trust.

6.2. Limitations

While this study has presented useful insights into data privacy and security in an SC environment, it was also conducted within a limited scope in the context of SCs in Qatar. The focus is also limited to data privacy and security and does not encompass a wider range of variables that potentially influence people's willingness to live in SC environments. Moreover, the data analysis, while suited to meeting the objectives of the current research (i.e., exploring stakeholder views), offers limited in-depth insights concerning important SC-related issues. This study has several limitations, including a small expert sample (n = 35) and potential sampling bias from Facebook-based citizen recruitment. The adapted survey lacked validation in the Qatari context, and parametric tests assumed equal variances without verification. Pearson's correlation indicates association but not causality. In addition, key UTAUT constructs, including social influence and habit, were excluded, limiting theoretical depth. Future research should address these concerns using longitudinal designs and broader model applications.

6.3. Suggestions

This study found clear and consistent relationships between cybersecurity-related factors and the willingness of both the public and experts to adopt SC systems in Qatar. Performance expectancy, data confidentiality, and system resiliency emerged as the most influential factors for both groups, with experts placing greater emphasis on data integrity and technical infrastructure. The analysis also showed meaningful differences in perception between the two groups, underlining the need for tailored strategies in SC planning and implementation. Future research should broaden the range of variables considered in SC adoption, with particular attention to models, such as TAM, and a complete use of the UTAUT framework, including dimensions like social influence and habit. It is also important to validate survey tools in the local context through pilot testing. Expanding the sample to include multiple cities and more diverse participants, and adopting longitudinal or experimental designs, would allow for a deeper understanding of how privacy and security concerns shape public adoption over time. These steps would strengthen both the theoretical and practical contributions of future work in this area.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: All authors
Formal analysis: Dana Ahmad Al-Ali
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Writing–review & editing: All authors

Ethics approval and consent to participate

Informed consent was obtained from all subjects involved in the study. All procedures were performed in compliance with relevant laws and institutional guidelines and have been approved by the appropriate institutional committee: Research Ethics Committee of Brunel University London (Reference number: 38065-LR-Jul/2022-40874-2; date of approval: August 4, 2022).

Consent for publication

Informed consent for publication of anonymized participant data was obtained from all participants.

Availability of data

The research data are available at https://figshare.com/articles/journal_contribution/Untitled_It_b_Data_Privacy_and_Security_Concerns_and_Readiness_to_Accept_Smart_Cities_Empirical_Evidence_from_Qatar_b_em/25764780 (accessed on January 22, 2025).

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Appendices

Table A1. Independent sample *t*-test

EV	Levine's test for equality of variances		*t*-test for equality of means					95% CID	
	F	Sig.	*t*	df	S2T	MD	SED	Lower	Upper
Actual use of behavior in adopting privacy and data security in SCs									
Ad.	0.664	0.417	−2.570	153.000	0.011	−0.527	0.205	−0.933	−0.122
NAd.			−2.751	61.676	0.008	−0.527	0.192	−0.910	−0.144
Availability of privacy and data security									
Ad.	2.856	0.093	−3.106	153.000	0.002	−0.642	0.207	−1.050	−0.234
NAd.			−3.509	68.061	0.001	−0.642	0.183	−1.006	−0.277
Behavioral intention in adopting privacy and data security in SCs									
Ad.	0.784	0.377	−2.732	153.000	0.007	−0.568	0.208	−0.979	−0.157
NAd.			−2.842	58.833	0.006	−0.568	0.200	−0.968	−0.168
Confidentiality of privacy and data security									
Ad.	0.070	0.791	−3.042	153.000	0.003	−0.631	0.207	−1.041	−0.221
NAd.			−3.055	55.735	0.003	−0.631	0.207	−1.045	−0.217
Effort expectancy									
Ad.	0.135	0.714	−2.670	153.000	0.008	−0.570	0.214	−0.992	−0.148
NAd.			−2.708	56.548	0.009	−0.570	0.211	−0.992	−0.148
Facilitating conditions									
Ad.	0.807	0.370	−2.325	153.000	0.021	−0.473	0.204	−0.875	−0.071
NAd.			−2.441	59.742	0.018	−0.473	0.194	−0.861	−0.085
Integrity of privacy and data security									
Ad.	0.656	0.419	−2.717	153.000	0.007	−0.560	0.206	−0.967	−0.153
NAd.			−2.819	58.600	0.007	−0.560	0.199	−0.957	−0.162
Performance expectancy									
Ad.	1.246	0.266	−2.843	153.000	0.005	−0.604	0.212	−1.024	−0.184
NAd.			−2.958	58.857	0.004	−0.604	0.204	−1.013	−0.196
Resiliency of privacy and data security									
Ad.	0.044	0.833	−3.243	153.000	0.001	−0.661	0.204	−1.063	−0.258
NAd.			−3.273	56.133	0.002	−0.661	0.202	−1.065	−0.256
Public readiness to accept SCs									
Ad.	11.615	0.001	−3.132	153.000	0.002	−0.649	0.207	−1.058	−0.240
NAd.			−3.712	75.033	0.000	−0.649	0.175	−0.997	−0.301

Abbreviations: Ad.: Assumed; CID: Confidence interval of the difference; df: Degree of freedom; EV: Equal variances; MD: Mean difference; NAd.: Not assumed; S2T: Significance (2-tailed); SCs: Smart cities; SED: Standard error difference.

Table A2. Pearson correlation test of the public group

Variables	1	2	3	4	5	6	7	8	9	10
1. Actual use of behavior in adopting privacy and data security in SCs	1	0.822**	0.832**	0.861**	0.817**	0.853**	0.832**	0.822**	0.840**	0.745**
2. Availability of privacy and data security	0.822**	1	0.895**	0.874**	0.834**	0.850**	0.820**	0.837**	0.800**	0.714**
3. Behavioral intention in adopting privacy and data security in SCs	0.832**	0.895**	1	0.926**	0.875**	0.886**	0.821**	0.855**	0.800**	0.750**
4. Confidentiality of privacy and data security	0.861**	0.874**	0.926**	1	0.909**	0.926**	0.873**	0.888**	0.885**	0.794**
5. Effort expectancy	0.817**	0.834**	0.875**	0.909**	1	0.910**	0.852**	0.858**	0.807**	0.759**
6. Facilitating conditions	0.853**	0.850**	0.886**	0.926**	0.910**	1	0.870**	0.920**	0.886**	0.814**
7. Integrity of privacy and data security	0.832**	0.820**	0.821**	0.873**	0.852**	0.870**	1	0.872**	0.876**	0.772**
8. Performance expectancy	0.822**	0.837**	0.855**	0.888**	0.858**	0.920**	0.872**	1	0.893**	0.842**
9. Resiliency of privacy and data security	0.840**	0.800**	0.800**	0.885**	0.807**	0.886**	0.876**	0.893**	1	0.792**
10. Public readiness to accept SCs	0.745**	0.714**	0.750**	0.794**	0.759**	0.814**	0.772**	0.842**	0.792**	1

Note: **Correlation is significant at the 0.01 level (2-tailed).
Abbreviation: SCs: Smart cities.

Table A3. Pearson correlation test of the expert group

Variables	1	2	3	4	5	6	7	8	9	10
1. Actual use of behavior	1	0.922**	0.886**	0.919**	0.937**	0.880**	0.940**	0.902**	0.910**	0.851**
2. Availability of privacy and data security	0.922**	1	0.881**	0.901**	0.896**	0.863**	0.912**	0.877**	0.916**	0.865**
3. Behavioral intention	0.886**	0.881**	1	0.929**	0.925**	0.926**	0.944**	0.890**	0.920**	0.836**
4. Confidentiality of privacy and data security	0.919**	0.901**	0.929**	1	0.934**	0.895**	0.952**	0.902**	0.914**	0.891**
5. Effort expectancy	0.937**	0.896**	0.925**	0.934**	1	0.932**	0.957**	0.927**	0.934**	0.876**
6. Facilitating conditions	0.880**	0.863**	0.926**	0.895**	0.932**	1	0.938**	0.904**	0.918**	0.844**
7. Integrity of privacy and data security	0.940**	0.912**	0.944**	0.952**	0.957**	0.938**	1	0.934**	0.960**	0.879**
8. Performance expectancy	0.902**	0.877**	0.890**	0.902**	0.927**	0.904**	0.934**	1	0.954**	0.893**
9. Resiliency of privacy and data security	0.910**	0.916**	0.920**	0.914**	0.934**	0.918**	0.960**	0.954**	1	0.888**
10. Public readiness to accept SCs	0.851**	0.865**	0.836**	0.891**	0.876**	0.844**	0.879**	0.893**	0.888**	1

Note: **Correlation is significant at the 0.01 level (2-tailed).
Abbreviation: SCs: Smart cities.

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Design of vibro-impact dampers with different optimized parameters affecting the system dynamic behavior

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Abstract

The problem of controlling and mitigating vibrations of the main structure is very important. The use of passive control devices is one solution to this problem. To ensure high efficiency of these devices, their parameters must be optimized. Many authors have addressed the problem of selecting the optimal design for such dampers, but many issues remain unresolved. This paper examines the influence of various optimal designs of the asymmetric single-sided vibro-impact non-linear energy sinks (SSVI NESs), that is, vibro-impact dampers, on system dynamics and damper efficiency in mitigating unwanted vibrations of the main structure. Nine damper designs with different masses and other optimized parameters are considered. These designs exhibit similarly high efficiency but display complex and distinct dynamic behaviors. We show that many damper designs can achieve comparable high performance. Therefore, the results of optimization procedures—which, moreover, allow a considerable degree of arbitrariness in their execution—can be ambiguous. SSVI NESs consistently display complex asymmetrical dynamics with alternating periodic modes and irregular, particularly chaotic, modes across different excitation force frequencies. Although the dynamic behavior of each optimally designed damper varies, this complexity does not affect the damper efficiency, which remains relatively stable.

Keywords: Optimal design; Vibro-impact damper; Efficiency; Mitigation; Non-linear energy sink

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1. Introduction

Over the years, scientists and engineers have been striving to find ways and tools to mitigate the unwanted vibrations in many engineering structures. One such method is passive vibration control. As a means of passive control, the tuned mass dampers (TMDs) have been developed and put into practice to suppress vibrations in well-known building structures.[1,2] Non-linear energy sinks (NESs) have been proposed as an advancement over TMDs.[3-5] NESs are coupled to the main structure through a non-linear connection, while TMDs are attached through a linear connection. NESs dissipate part of the main structure's energy due to essential system non-linearity, thereby reducing vibrations.

Over the past 2 decades, the study of NESs has become widespread in the global academic literature.[6,7] Lin *et al.*,[8] for example, described types of strong non-linearities and four types of NESs that have gained prominence. Among these, the vibro-impact (VI) NES—also referred to as a VI damper—is regarded as one of the most effective devices for damping vibrations of the main structure.[9] VI NES's ability to reduce resonant response amplitudes is crucial for practical applications.[10] Numerous articles have been devoted to studying their performance.[11-13]

One recent study analyzes the response of VI systems under periodic and random excitations using an efficient approach.[14] These systems demonstrate complex non-linear phenomena, such as multistability, chaotic motion, and grazing events. The paper also discusses the impact modeling method.

Li *et al.*[15] examined the effectiveness of the VI NES when a beam is subjected to permanent and transient loads. They concluded that vibration reduction depends on the clearance size, mass ratio, and location and is almost independent of the damping mechanism. In a separate study, Weidemann *et al.*[16] described the contact using the Hertzian contact law and determined the effective values of the elastic modulus E and contact radius R. Li *et al.*[17] investigated a double-sided NES coupled to a two-story primary structure (PS) under impulsive loading. They optimized the linear stiffness and viscous damping of the non-smooth NES for different clearance values. In a study by Gong *et al.*,[18] the chaotic dynamics of a VI system with three degrees of freedom under periodic excitation were examined both numerically and experimentally. They simulated impacts using the non-linear contact force based on the Hertz contact model between a sphere and a plane.

Meanwhile, Wang *et al.*[19] considered a double-sided NES coupled to a PS under periodic excitation. The mass ratio was very small (0.87%). The damping coefficient was calculated in an unusual way, based on the masses and the material restitution coefficient. They studied the influence of contact stiffness and clearance on system response and emphasized the need to develop an optimization method to select these parameters for better performance. They believe that the longest impact duration provides the most effective response regime and should be considered when selecting an optimized NES design.

Optimizing NES parameters is an essential and critical procedure. It should assist in selecting an optimal damper design that provides the best attenuation of the main structure's vibrations. Multiple-parameter optimization exhibits a striking synergistic effect.[20,21] Several articles have proposed their own optimization algorithms to solve these problems.[22-26] Various programs on the MATLAB platform implement different optimization algorithms. The "surf" function provides a three-dimensional graph showing the ranges of the two parameters for which the objective function reaches its minimal value. However, this graph is plotted with fixed values of other parameters and changes appearance when those values are altered. Local minima of the objective function are found using the "fminsearch" and "fmincon" functions. The "ga" function finds the minimum of the objective function using a genetic algorithm.[27] In the optimization process, the choice of the objective function and the setting of its calculation parameters play an important role. However, optimization procedures do not and cannot yield a single unambiguous result. This is because many different sets of damper parameters can provide equally effective mitigation of the main structure's vibrations. However, the system dynamics may differ significantly depending on the specific VI damper used. In this paper, we show the varying system dynamics when single-sided VI NESs (SSVI NESs) of different optimized designs are coupled to the main structure. Thus, based on the results of the optimization procedure and considering engineering considerations related to damper parameters, the designer must make the final decision regarding the optimal damper design.

Accordingly, the objectives of this article are as follows:

(i) To show that SSVI NESs with different optimal designs provide practically the same mitigation of the main structure's vibrations and demonstrate sufficiently high efficiency;

(ii) To demonstrate the different system dynamics that result when VI NESs of different optimized designs are coupled to the main structure;

(iii) To illustrate the areas of non-linearity with both bilateral and unilateral impacts for different dampers with optimal designs.

2. Mathematical model of the VI system

A mechanical VI system with two degrees of freedom, consisting of two bodies, is considered. Various aspects of this model's dynamic behavior have been studied in our previous works,[20,21] but a brief description is repeated here for completeness. The parameters of the PS are as follows: A large mass m_1, linear stiffness k_1, and damping coefficient c_1. The parameters of the damper are: A small mass m_2, linear stiffness k_2 and damping coefficient c_2, where $m_2 < m_1$. During the system's motion, the VI damper repeatedly strikes both the obstacle and the PS directly, as shown below. These impacts introduce strong non-linearity into the system and contribute to the reduction of the PS's energy. The VI system (PS–damper), illustrated schematically in Figure 1, has been presented in numerous studies[1,5,12] as a conceptual model of an SSVI NES. In this

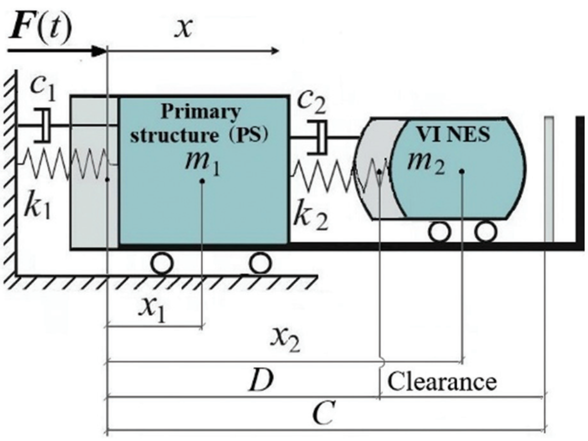

Figure 1. Schematic of the vibro-impact (VI) system with a primary structure and a single-sided VI non-linear energy sinks

paper, we primarily focus on the concept of clearance, which is an important parameter in the damper's configuration and will be discussed frequently. As shown in Figure 1, the clearance is defined as the distance C–D.

The PS has the following parameters:

m_1 = 1,000 kg, k_1 = 3.95×10^4 N/m, c_1 = 452 N·s/m, E_1=E_3 = 2.1×10^{11} N/m^2, ν_1=ν_3 = 0.3.

In this paper, we study the system's dynamical behavior under the action of a harmonic force:

$F(t) = P\,cos(\omega t+\varphi_0)$, P = 800 N. Its period is $T = 2\pi/\omega$.

We focus on modeling repeated impacts. In studying the dynamics of a VI system, the impact rule, that is, the modeling of impacts plays an important role. This topic continues to be discussed in the literature.[28-32] There are two basic models: (i) The instantaneous impact model (most commonly used in NES dynamics, though not always), where impacts are treated as instantaneous. At the moment of impact, the coordinates of the colliding bodies are equal, and their velocities change abruptly, governed by the Newtonian coefficient of restitution. (ii) The duration impact model, which considers the duration of impact and allows local body deformations of the colliding bodies. In this model, this impact is represented by a contact force acting only during the impact. This force is discontinuous and can be either linear or non-linear. In his quasi-static contact theory, Hertz proposed modeling this force as non-linear:[33,34]

$$F_{con}(z) = K[z(t)]^{3/2} \qquad \text{(I)}$$

The first model simulates rigid impact reasonably well, while the Hertzian model simulates both rigid and soft impacts effectively. It can be considered "a more realistic model of the impact process."[35] Therefore, in all our works, we model impacts using the non-linear interactive contact force *Fcon* (z) as described in Equation I.

The impact is not instantaneous; it has a finite duration. In Equation I, z represents the rapprochement of the colliding bodies in the contact zone due to local deformation, as allowed by Hertz's theory. The rapprochements z_1 and z_2 differ for the impacts between the damper and the PS, and between the damper and the obstacle, respectively.

The conditions for impacts to occur are as follows:

$x_1 \geq x_2$, i.e., $x_1 - x_2 \geq 0$ (the damper hits the PS directly);

$x_2 \geq x_1 + C$, i.e., $x_2 - x_1 - C \geq 0$ (the damper hits the obstacle).

The rapprochements of the colliding bodies as a result of these impacts are defined as:

$z_1 = x_1 - x_2$ (when the damper hits the PS directly);

$z_2 = x_2 - x_1 - C$ (when the damper hits the obstacle).

The coefficient K incorporates both mechanical and geometrical characteristics of the contacting surfaces and differs depending on which surfaces are colliding, as shown below.

When the damper hits the PS directly:

$$K_1 = \frac{4}{3}\frac{q_1}{(\delta_1+\delta_2)\sqrt{A_1+B_1}}$$

When the damper hits the obstacle:

$$K_2 = \frac{4}{3}\frac{q_2}{(\delta_3+\delta_4)\sqrt{A_2+B_2}}$$

$$\delta_1 = \frac{1-\nu_1^2}{E_1\pi}, \quad \delta_2 = \frac{1-\nu_2^2}{E_2\pi}, \quad \delta_3 = \frac{1-\nu_3^2}{E_3\pi}, \quad \delta_4 = \frac{1-\nu_4^2}{E_4\pi} \qquad \text{(II)}$$

The mechanical characteristics of all colliding surfaces include Young's modulus of elasticity E_1, E_2, $E3$, and E_4 and Poisson's ratios ν_1, ν_2, ν_3, ν_4. Parameters A and B are defined by the geometry of the colliding surfaces: A_1, B_1 describe the PS collision surface and the left surface of the SSVI NES; A_1, B_2 describe the right surface of the SSVI NES and the obstacle surface. According to the table in Goldsmith's[34] work, for a sphere-plane collision, A_1=B_1=1/2R_1, A_2=B_2=1/2R_2. Assuming large spherical radii R_1=R_2=1 m, we set: A_1=B_1=A_2=B_2=0.5 m^{-1}. If the ratio A_1/B_1=A_2/B_2=1, then from,[34] q_1=q_2=0.319.

This modeling approach enables the study of how both mechanical and geometric characteristics of contact surfaces influence system response and damper efficiency. In particular, it allows analysis of impact softness by varying elasticity moduli to simulate softer or harder surface materials. For this purpose, we optimized E_2 and E_4, the elasticity moduli of the damper surfaces to find values that yield the best mitigation of PS vibrations.[36]

The differential equations governing the system's motion are written as follows:

$$m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 - c_2(\dot{x}_2 - \dot{x}_1) - k_2(x_2 - x_1 - D) = \\ = F(t) - H(z_1)F_{con}(z_1) + H(z_2)F_{con}(z_2) \\ m_2\ddot{x}_2 + c_2(\dot{x}_2 - \dot{x}_1) + k_2(x_2 - x_1 - D) = \\ = H(z_1)F_{con}(z_1) - H(z_2)F_{con}(z_2) \tag{III}$$

with initial conditions at $t = 0$:

$$x_1(0) = 0, x_2(0) = D, \dot{x}_1(0) = \dot{x}_2(0) = 0, \varphi_0 = 0 \tag{IV}$$

The Heaviside step function $H(z) = \begin{cases} 1, & z \geq 0 \\ 0, & z < 0 \end{cases}$ "activates" the non-linear contact force upon impact and "deactivates" it when there is no impact.

The system described by Equation III is strongly non-linear and discontinuous, making it a stiff system of ordinary differential equations (ODEs). To solve it, we use the MATLAB variable-step solver "ode23s," which adapts the step size that becomes very small during impacts. This allows us to determine with sufficient accuracy the instant when the Heaviside function becomes equal to unity, that is, in our problem, the bodies' collision begins.

The dampers are designed to mitigate the PS vibrations, that is, to reduce its total mechanical energy. The well-known formula describing this energy is:

$$E_{1total}(t) = E_{1kinetic}(t) + E_{1poten}(t) = \left[m_1\dot{x}_1(t)^2 + k_1x_1(t)^2\right]/2 \tag{V}$$

The maximum value of this energy is used as the objective function when determining the optimal damper parameters. The specific parameters selected for its calculation are discussed in detail in the following section.

3. Dynamical behavior of dampers with different designs

The selection of the optimal design for SSVI NES is a mandatory procedure aimed at finding damper parameters that ensure the best mitigation of the PS vibrations, that is, the maximum possible reduction of its energy. For this purpose, optimization procedures were performed using standard MATLAB tools, namely, the "surf," "fminsearch," and "fmincon" functions.

The maximum total energy of the PS, E_1max, was chosen as the objective function, calculated at a near-resonant frequency ω=6.3 rad/s. However, the optimization procedures do not and cannot provide unambiguous results, because different damper parameter sets can yield similar efficiency, that is, a similar reduction in the PS energy; many such sets can be found. Lu *et al.*[3] also noted: "The non-linear stiffness properties have a significant influence on control effectiveness, and they can be implemented in numerous scenarios with plenty of configuration parameters." We present nine different "scenarios with plenty of configuration parameters."

Optimization procedures performed with some damper parameters emphatically showed that heavier dampers reduce the PS energy more effectively. With these procedures, optimization of the damper mass m_2 did not make sense. In a previous study, Saeed *et al.*[37] also did not seek an optimized mass value but calculated the objective function for each selected mass separately. Therefore, we believe that for each pre-selected damper mass, the optimization of the other parameters should be performed separately. We selected three different damper masses and analyzed their efficiency and the system's dynamic behavior for these dampers.

When simulating repeated impacts by the Hertz's contact force (Equation I), all its parameters become part of the motion equations (Equation III); in particular, Young's modulus of elasticity is included in the coefficient K (Equation II). The optimal values of the parameters in the motion equations should provide the minimum of the objective function (Equation V), that is, achieve the best reduction of the maximum PS energy. This problem is solved by optimization procedures. The MATLAB platform function "fminsearch," which we used for parameter optimization, allowed simultaneous optimization of several parameters, including Young's moduli. Young's moduli characterize the mechanical properties of a material and vary for different materials. Optimization procedures have shown that smaller values of Young's moduli for the damper surfaces' material E_2 and E_4 provide greater efficiency.[21] Lower Young's moduli correspond to softer materials and hence softer impacts with longer duration.

This is similar to recommendations by certain studies[38,39] to choose a smaller value of the Newtonian restitution coefficient when modeling impact as instantaneous, where the velocity jump at impact is expressed through this coefficient. Therefore, for all dampers, we set:

$E_2 = 2.21\times10^7$ N/m^2, $E_4 = 2.05\times10^7$ N/m^2, $\nu_2=\nu_4 = 0.4$.

3.1. VI dampers with m_2 = 20 kg

The mass of this lightweight damper is 2% of the PS mass. After performing optimization procedures, we selected three different sets of its parameters (Table 1).

Attention should be paid to the parameters of dampers $V_{20\text{-}2}$ and $V_{20\text{-}3}$. The damping coefficient c_2 is more than twice as small compared to that of $V_{20\text{-}1}$; the clearance (C–D) has taken on a non-standard value, becoming excessively large.

The maximum PS energy as a function of the excitation force frequency when PS is coupled to three SSVI NESs of different optimal designs with $m_2 = 20$ kg is shown in Figure 2.

Figure 2 illustrates the different system dynamics for these three dampers. Each damper significantly reduces the resonant peak and slightly shifts it toward lower frequencies. The $V_{20\text{-}2}$ and $V_{20\text{-}3}$ dampers reduce the resonant peak more effectively, despite having a much lower damping coefficient c_2 and a large, non-standard clearance (C–D) compared to $V_{20\text{-}1}$. Figure 3 and Table 2 show the variations in system motion for these cases. Bilateral impacts on both the PS and the obstacle occur within a narrow frequency range, bounded by the dashed vertical lines and shaded in pink. Outside of this range, only impacts on the PS occur (no impacts on the obstacle); this region is shaded beige. The $V_{20\text{-}1}$ damper functions as a linear damper without any impacts at both low and high excitation force frequencies, where the periodic mode T,0,0 is realized. We denote an nT-periodic regime with m damper impacts on the PS and k impacts on the obstacle per cycle as nT,m,k. For example, $2T$,2,1 is a $2T$-periodic mode with two impacts on the PS and one impact on the obstacle per cycle. Here, T is the period of the exciting force.

Table 1. Parameters of the damper optimal designs with m_2=20 kg

Variant	k_2 (N/m)	c_2 (N·s/m)	D (m)	C (m)	C–D (m)
$V_{20\text{-}1}$	120	140	0.060	0.360	0.300
$V_{20\text{-}2}$	215	61.0	0.029	0.673	0.642
$V_{20\text{-}3}$	115	64.1	0.030	0.673	0.643

Table 2. Modes realized in different excitation force frequency ranges for a system with different dampers of optimal design (m_2=20 kg)

Variant	Area		
	Left beige	Pink	Right beige
$V_{20\text{-}1}$	$2T$,1,0	T,1,1	$2T$,1,0 $3T$,1,0
$V_{20\text{-}2}$	T,1,0	$2T$,2,1	T,1,0 $2T$,2,0 $2T$,1,0
$V_{20\text{-}3}$	T,1,0	T,1,1 Irregular AM	$2T$,1,0

Abbreviation: AM: Amplitude-modulated mode.

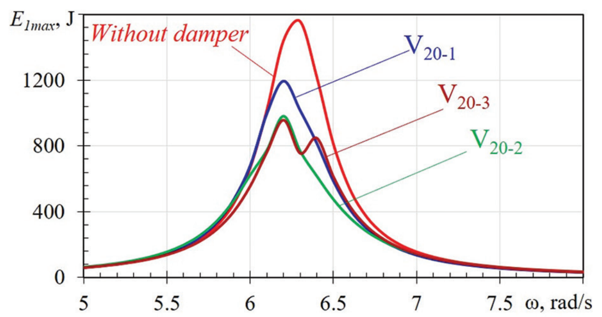

Figure 2. Maximum energy of the primary structure coupled to three single-sided vibro-impact non-linear energy sinks of different optimal designs with m_2=20 kg, as a function of the exciting force frequency

Figure 3 demonstrates narrow regions of bilateral impacts (on both the PS and the obstacle) for all three dampers. The regions of unilateral, direct impacts on the PS only are wider. However, the width of these non-linear zones does not determine the damper's efficiency. According to the theory of targeted energy transfer, it is the system's non-linearity that allows the NES to extract energy from the PS.

Table 2 shows that the realized periodic regimes differ for each damper. Only one of the realized modes is not periodic: An irregular amplitude-modulated mode, which occurs at the excitation force frequency ω=6.4 rad/s when the $V_{20\text{-}3}$ damper is coupled to the PS. The characteristics of a similar mode are illustrated further in Figure 4.

Table 2 clearly demonstrates the realization of different motion regimes when dampers of similar efficiency are coupled to the PS. An alternation of modes with different periodicity (T, $2T$, and $3T$) and different numbers of impacts per cycle, both directly on the PS and on the obstacle, is observed. However, despite the complex and varied dynamics across the three dampers, their performance remains consistent, as shown in Figure 2.

Thus, it is evident that three dampers with the same mass but different optimized parameters can effectively

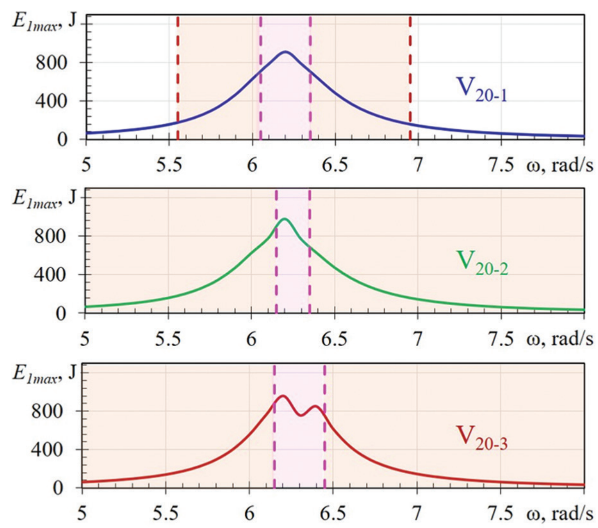

Figure 3. Areas of non-linearity in the system motion when the primary structure is coupled with three different optimally designed dampers with m_2 = 20 kg

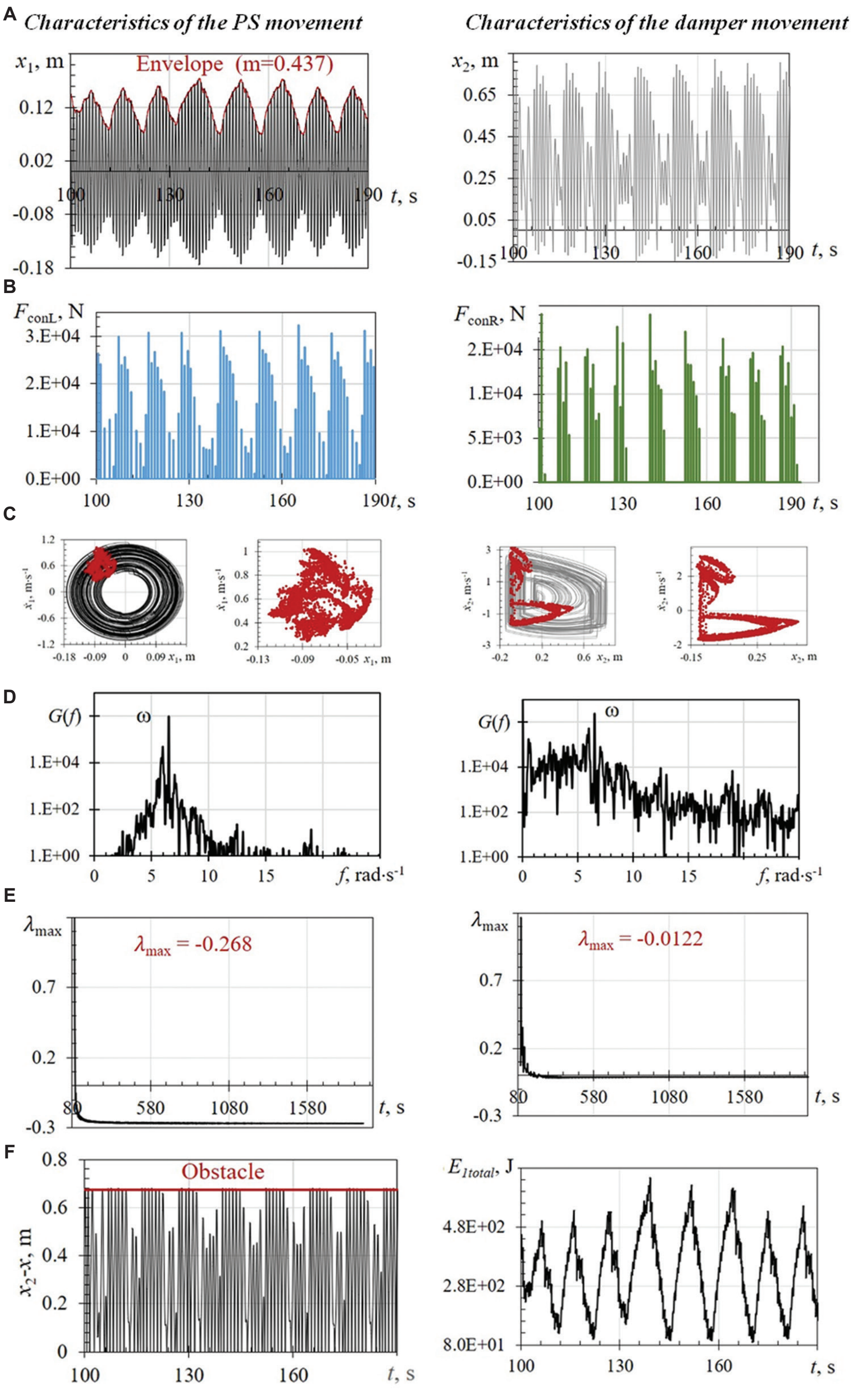

Figure 4. Characteristics of the irregular amplitude-modulated mode at ω = 6.5 rad/s. (A) Time histories of the displacements. (B) Contact impact forces when the damper hits the primary structure (PS) directly on the left (in blue) and the obstacle on the right (in green). (C) Phase trajectories with Poincaré maps in red. (D) Fourier spectra on a logarithmic scale. (E) Lyapunov exponents. (F) Relative displacements of the damper (left) and the total energy of the PS (right).

mitigate the vibrations of the PS by reducing its maximum total energy, while exhibiting significantly different dynamic behaviors.

3.2. VI damper with mass $m_2 = 40$ kg

The mass of this lightweight damper is 4% of the PS mass. After performing optimization procedures, we selected three different sets of parameters (Table 3).

Table 3 shows that the trend of a significant increase in clearance (C–D) and a decrease in the damping coefficient c_2, observed in lighter dampers, persists in the heavier ones as well. Notably, our subsequent studies have confirmed this trend for lighter SSVI NESs.[40] Dampers with such non-standard optimized parameters provide good mitigation of PS vibrations, which is evident in Figure 5 for the $V_{40\text{-}3}$ variant damper.

The maximum PS energy as a function of the excitation force frequency for three SSVI NESs of different optimal designs with $m_2 = 40$ kg is shown in Figure 5.

The graphs in Figure 5 are similar to those in Figure 2, although the VI dampers differ in mass and other parameters. Each damper significantly reduces the resonant peak and shifts it toward lower frequencies. The shift is more pronounced than in Figure 2. Dampers $V_{40\text{-}2}$ and $V_{40\text{-}3}$ reduce the resonance peak more strongly. Compared to the $V_{40\text{-}1}$ damper, they have lower stiffness k_2, a lower damping coefficient c_2, and a larger clearance (C–D). The curves of the maximum PS energy reveal different performance characteristics for these three dampers. The $V_{40\text{-}1}$ damper produces only one resonant peak. By shifting it to the left, it significantly reduces the PS energy at higher frequencies but increases it at lower frequencies. In contrast, dampers $V_{40\text{-}2}$ and $V_{40\text{-}3}$ produce two resonant peaks and reduce PS energy across the entire frequency range. These dampers also outperform those with $m_2 = 20$ kg in Figure 2. In general, optimization programs tend to favor larger damper masses for better mitigation of PS vibrations. However, the scientific literature often indicates that the VI NES mass should be small, about 1% of the PS mass. For this reason, we investigated the performance of a lighter damper with a 2% mass ratio and demonstrated good efficiency when some of its parameters are allowed to take non-standard values.

Figure 6 and Table 4 show the variation of the system motion for these cases.

The pink zones in the middle of Figure 6, representing regions of bilateral damper impacts (on both the PS and the obstacle), are similar to those in Figure 3. The beige areas for dampers $V_{40\text{-}2}$ and $V_{40\text{-}3}$ also match those in Figure 3, corresponding to zones where only direct impacts on the PS occur. The key difference lies in the presence of gray zones adjacent to the pink areas for the $V_{40\text{-}1}$ damper. In these frequency ranges, impacts occur only on the obstacle, with no direct contact with the PS. Outside these ranges, the $V_{40\text{-}1}$ and $V_{40\text{-}2}$ dampers operate as linear dampers, exhibiting shockless oscillations. The system undergoes periodic motion with period T, where T is the period of the exciting force, and no impacts occur. Such motion is denoted as T,0,0. As with the dampers in Section 3.1, the width of the non-linearity zones does not affect damper efficiency, as shown in Figure 5.

Table 3. Parameters of the damper optimal designs with m_2=40 kg

Variant	k_2 (N/m)	c_2 (N·s/m)	D (m)	C (m)	C–D (m)
$V_{40\text{-}1}$	1,550	644.0	0.100	0.124	0.024
$V_{40\text{-}2}$	215	232.0	0.060	0.360	0.300
$V_{40\text{-}3}$	215	64.1	0.030	0.673	0.643

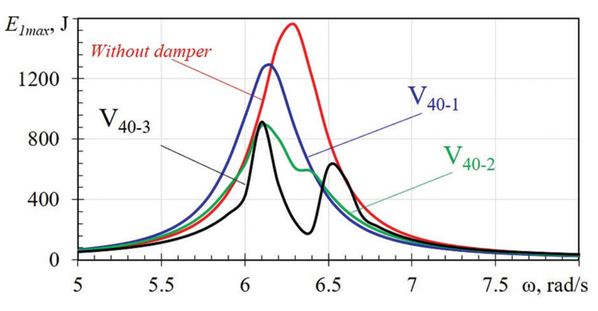

Figure 5. Maximum energy of the primary structure coupled to three single-sided vibro-impact non-linear energy sinks of different optimal designs with $m_2 = 40$ kg as a function of the exciting force frequency

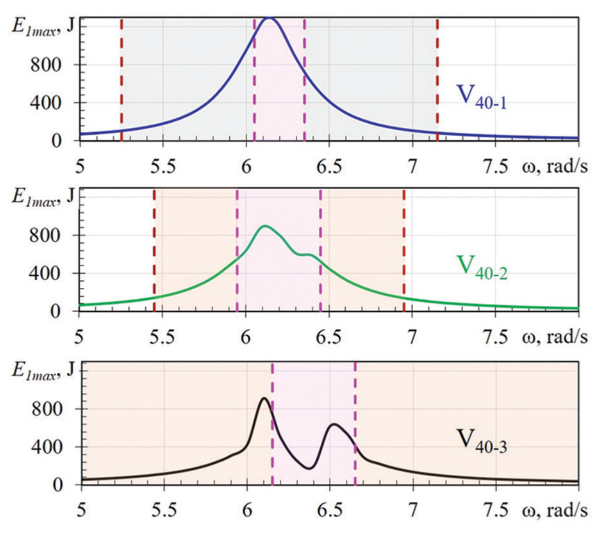

Figure 6. Areas of non-linearity in the system motion when the primary structure is coupled to three different dampers of optimal design with $m_2 = 40$ kg

Table 4. Modes realized in different frequency ranges for a system with different dampers of optimal design with m_2=40 kg

Variant	Area		
	Left	Pink	Right
V_{40-1}	Gray T,0,1 T,0,2	T,1,2	Gray T,0,2 T,0,1
V_{40-2}	Beige 2T,1,0	3T,2,1 T,1,1 Chaotic	Beige 2T,1,0 Chaotic 3T,1,0
V_{40-3}	Beige T,1,0 2T,0,1	T,1,1 Irregular AM	Beige 2T,1,0 3T,1,0

Abbreviation: AM: Amplitude-modulated mode.

Table 4 clearly exhibits that the system demonstrates periodic motion at almost all excitation force frequencies. Only occasionally, at some frequencies of the exciting force does the system display irregular behaviour. Figure 4 provides the detailed characteristics of an irregular amplitude-modulated mode realized at excitation frequency ω=6.5 rad/s when the V_{40-3} damper is coupled to the PS.

Table 4 demonstrates a more complex and rich system dynamics compared to Table 2. In addition to the alternation of periodic motion with different periodicities and different numbers of impacts per cycle, chaotic and amplitude-modulated motion can also be observed. However, even in this case, such complex dynamics also do not deteriorate the damper's efficiency.

The characteristics shown in Figure 4 are typical of an irregular amplitude-modulated mode. Figure 4A shows time histories for the PS and the damper; the modulation envelope is shown in red in this Figure. The modulation coefficient (depth of the modulation) is m = 0.437. Figure 4B demonstrates the contact forces during damper impacts on the PS directly in blue (left) and on the obstacle in green (right). The phase trajectories in the form of tangles and the Poincaré maps in the form of smears are characteristic of chaotic motion (Figure 4C). Broad, continuous spectra (Figure 4D) are also indicative of chaotic motion. However, the Lyapunov exponents (Figure 4E) are small but not positive, as they should be for a truly chaotic regime. Therefore, we refer to this regime only as an irregular amplitude-modulated mode. The relative damper displacements (Figure 4F, left) show impacts on the PS directly when $(x_1–x_2)$ = 0, and on the obstacle when $(x_2–x_1)$=C = 0.673 m. Figure 4F, right presents the total PS energy as a function of time.

Table 5. Parameters of the damper optimal designs with m_2=60 kg

Variant	k_2 (N/m)	c_2 (N·s/m)	D (m)	C (m)	$C–D$ (m)
V_{60-1}	198	538	0.000	0.0498	0.0498
V_{60-2}	115	232	0.060	0.3600	0.3000
V_{60-3}	315	232	0.060	0.3600	0.3000

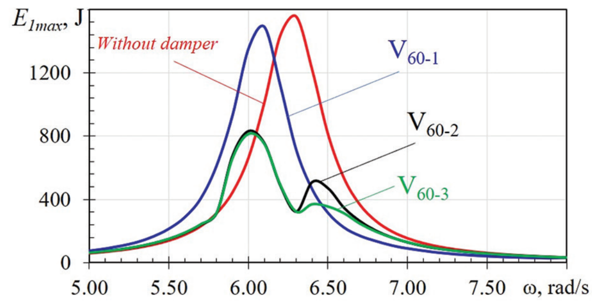

Figure 7. Maximum energy of the primary structure coupled to three single-sided vibro-impact non-linear energy sinks of different optimal designs with m_2=60 kg as a function of the excitation force frequency

Thus, the three dampers with m_2 = 40 kg, and the various other parameters exhibit motion patterns similar to those observed for the dampers with m_2 = 20 kg. They effectively mitigate PS vibrations by reducing the maximum total energy of the PS. Bilateral damper impacts occur over relatively narrow frequency ranges, while in wider frequency ranges, impacts occur either only on the PS directly or only on the obstacle. At low and high frequencies, the system with the V_{40-1} and V_{40-2} dampers moves periodically without any impacts, and the dampers operate as linear ones.

3.3. VI damper with m_2 = 60 kg

The mass of this damper is 6% of the PS mass. After performing optimization procedures, we selected different sets of its parameters (Table 5).

Table 5 shows that the optimized parameters for the heavier damper are quite standard; the clearance does not reach excessively large values.

The maximum PS energy as a function of the excitation force for three SSVI NESs of different optimal designs with m_2 = 60 kg is depicted in Figure 7.

The graphs in Figure 7 are similar to those in Figures 2 and 5, although the VI dampers have different masses and other parameters. Each of these dampers reduces the resonant peak and shifts it toward lower frequencies. The shift is larger than in Figures 2 and 5. The V_{60-2} and V_{60-3} dampers reduce the resonance peak more effectively. Compared to the V_{60-1} damper, these dampers have different stiffness values k_2, lower damping coefficients c_2, and larger clearances (C–D). The curves of the maximum PS energy demonstrate similarly different performance among the three dampers, as seen in Figure 5. The V_{60-1} damper produces only one resonant peak. By shifting this peak to the left, it significantly reduces the PS energy at higher frequencies but increases it at lower ones. In contrast, the V_{60-2} and V_{60-3} dampers produce two resonant peaks and modify the PS energy differently across various frequency ranges.

Figure 8 and Table 6 show the variation in system motion for these cases.

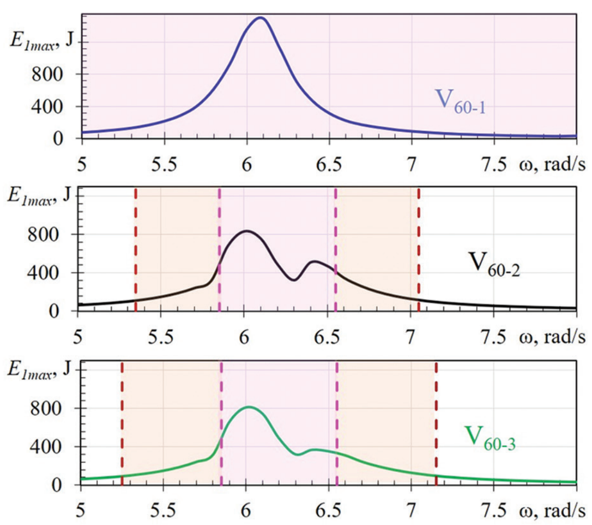

Figure 8. Areas of non-linearity in the system motion when the primary structure is coupled to three different dampers of optimal design with m_2=60 kg

Table 6. Modes realized in different areas of the frequency ranges for a system with different dampers of optimal design, with m_2=60 kg

Variant	Area		
	Left	Pink	Right
V_{60-1}	Pink T,1,1 2T,3,2 T,2,2 3T,7,6	T,4,4 T,3,3 T,2,2 Chaotic	Pink T,2,1 T,1,1 Chaotic
V_{60-2}	Beige 4T,1,0 Chaotic 6T,2,0 3T,1,0	T,1,1 Irregular AM	Beige 4T,1,0 Chaotic
V_{60-3}	Beige 2T,0,1	T,1,1 Irregular AM Chaotic	Beige 2T,1,0 3T,1,0

Abbreviation: AM: Amplitude-modulated mode.

These graphs differ from those in Figures 2 and 5 in that the pink areas are wider. For the V_{60-1} variant damper, the pink area spans the entire frequency range, indicating bilateral damper impacts, both directly on the PS and on the obstacle, across this range. In the beige areas, only impacts on the PS occur. Outside of these ranges, at low and high frequencies, the dampers of V_{60-2} and V_{60-3} variants operate as linear dampers, performing periodic, shockless oscillations denoted as T,0,0. These graphs once again demonstrate that the width of non-linearity zones, and particularly the zones of bilateral impacts, does not necessarily suggest the damper's efficiency.

Table 6 demonstrates complex and rich system dynamics, including chaotic and amplitude-modulated regimes. For the V_{60-1} damper, which provides a zone of bilateral impacts over the entire frequency range, modes with a large number of impacts occur. However, as in previous cases, these complex dynamics do not affect the damper's efficiency.

Thus, the three dampers with m_2 = 60 kg and various other parameters, when coupled to the PS, demonstrate a motion pattern generally similar to those of the previous cases, despite some differences. They effectively mitigate PS vibrations quite well, reducing the maximum total energy of the PS. Bilateral damper impacts occur over wider frequency ranges compared to previous versions. In some frequency ranges, there are only direct impacts on the PS. At low and high frequencies, the system with the V_{60-2} and V_{60-3} dampers also moves periodically without any impacts, where the damper operates as a linear device.

4. Brief discussion

The consideration of nine variants of the optimal design for the SSVI NESs with different masses showed that the dampers of all variants effectively mitigate the PS vibrations. However, different variants of the optimal design have their own features, noted in Sections 3.1, 3.2, and 3.3. The study showed that neither the narrowness nor the width of the non-linearity areas, nor the complex dynamics that occur in a system with attached SSVI NESs, determines the damper's efficiency. Only the graphs of the maximum PS energy provide insight into the energy behavior and reduction. The presence of many different optimal SSVI NES designs, providing similar reductions in PS energy, makes it difficult to choose a final option. In addition, the implementation of optimization procedures using MATLAB tools has no specific order, allows for great arbitrariness, and requires experience and skill from the performer. In a previous study, Kang *et al.*[6(p1)] state: "There is no exact method to simplify the design of the multiparameter non-linear energy sinks." Each optimal damper design found must be tested. Therefore, the final decision on the selection of the optimal SSVI NES design for real-world applications should be made by the design engineer based on the results of optimization and testing, as well as other engineering considerations.

5. Conclusion

In this paper, we studied the dynamics of the strongly nonlinear VI system "PS–SSVI NES." Nine variants of SSVI NESs with optimal designs were considered. They exhibited different masses and other optimized parameters. The main results of the study can be summarized as follows:

(i) All variants of the dampers with optimal design showed similarly high efficiency in reducing the vibrations of the PS. A clear representation of this is provided by graphs demonstrating the behavior and reduction of the maximum PS energy;

(ii) The system with attached SSVI NESs demonstrated complex dynamics and both narrow and wide nonlinearity zones, which do not affect the damper's efficiency;

(iii) The similarity in performance and dynamics of these different dampers clearly proves the existence of multiple optimal damper designs that provide a similar effect in mitigating PS vibrations. This is precisely why optimization procedures do not and cannot yield unambiguous results; in addition, the optimization process using MATLAB tools allows for a large amount of arbitrariness. Therefore, each selected optimal damper design should be tested.

The obtained results indicate certain difficulties in using the SSVI NESs in practical engineering problems related to the selection of a suitable optimal damper design. Moreover, the damper mass should be selected in advance, and all other parameters should be optimized for this selected mass. The scientific literature proposes choosing a small SSVI NES mass, but the optimization programs show that larger masses provide better results. Our research demonstrated that a small SSVI NES mass provides relatively high damper efficiency, but some optimized damper parameters acquired non-standard, unusual values. This conclusion was confirmed in the course of our further studies but requires confirmation in cases involving changes in different structural parameters, such as PS stiffness, PS damping, and external load intensity.

Future studies should also compare the performance of the SSVI NES and the TMD. It is believed that one of the main advantages of the NES over the TMD is its ability to preserve tuning, that is, having the optimized parameters, it maintains behavior and efficiency even when structural parameters change. We intend to study this problem in detail.

The studies were conducted under the action of periodic external load on the VI system. There is an opinion that the effectiveness of VI NESs is most evident when the system is exposed to transient loads, such as impulsive, explosive, and seismic. In this regard, we intend to repeat the studies of the SSVI and double-sided VI NESs under blast loading.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: Petro Lizunov, Olga Pogorelova
Formal analysis: Olga Pogorelova, Tetyana Postnikova
Investigation: Tetyana Postnikova
Methodology: Olga Pogorelova
Writing – original draft: Olga Pogorelova
Writing – review & editing: Olga Pogorelova, Tetyana Postnikova

Ethics approval and consent to participate

Not applicable.

Consent for publication

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Availability of data

Not applicable.

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A novel approach of quality assessment of potatoes using artificial neural network

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Abstract

A novel approach for quality assessment of potatoes using an artificial neural network (ANN) technique is developed and integrated with thermal imaging system to analyze the decay of tissues in potatoes. The merger of ANN with acquired thermal images leads to increased system efficiency, accuracy, reliability, and speed. A sample of 480 thermal images of potatoes was generated for training and testing the dataset. Categorization of potatoes as healthy or defective is performed based on seven critical parameters, such as standard deviation, energy, entropy, skewness, kurtosis, means, and variance. A classifier based on ANN is employed, incorporating two hidden layers with 200 neurons in the first layer and 50 neurons in the second layer. The input layer size is feature-dependent, while the output layer employs two neurons for binary classification. Among the seven features evaluated individually, entropy and energy achieved the best results, with classification accuracies of 79.81% and 81.27%, respectively. The highest overall performance, 94.89% accuracy with 455 correctly classified samples, was obtained by combining all features except variance. It is observed that integrating thermal imaging with ANNs is a promising approach for quality assessment. Selecting appropriate features is crucial for optimizing the classification model.

Keywords: Quality assessment of agricultural products; Artificial neural network; Smart assessment technique; Thermal imaging; Feature extraction; Image processing

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1. Introduction

Ensuring the quality of fruits and vegetables is critical for the agricultural industries, as it directly influences productivity, profitability, and consumer safety. Quality assessment typically considers parameters such as nutritional value, shape, ripeness, and texture, which determine whether the product is categorized as healthy or defective. However, achieving reliable grading in practice remains challenging because of the wide variability in products and the risk of hidden defects that are not visible to the naked eye.[1] Traditional approaches to quality assessment rely heavily on manual inspection. While simple and low-cost, these methods are labor-intensive, time-consuming, and prone to inconsistency across evaluators. Moreover, they often fail to detect early-stage or internal tissue defects, which can lead to post-harvest losses and reduced market value. These limitations underscore the need for automated, objective, and rapid evaluation techniques.[1]

In recent years, the integration of artificial intelligence (AI) with advanced imaging technologies has transformed agricultural quality assessment. Techniques such as visible, near-infrared, hyperspectral, and thermal imaging, when combined with machine learning models, have achieved higher accuracy and reliability in detecting defects.[2] Machine learning and deep learning methods, including artificial neural networks (ANNs), convolutional neural networks (CNNs), support vector machines (SVMs), and decision trees, have been widely applied to automate classification and enhance detection performance.[3,4]

Among these imaging modalities, thermal imaging has emerged as a promising non-destructive tool. Unlike visible or hyperspectral methods that depend on controlled lighting or extensive datasets, thermal imaging is independent of ambient illumination and is capable of capturing temperature variations linked to physiological changes.[5,6] Each object emits electromagnetic radiation above absolute temperature, primarily in the infrared spectrum. Thermal cameras are equipped with sensors sensitive to specific infrared wavelengths. These sensors capture the emitted radiation and convert it into an equivalent heat map representing the temperature distribution of the object. The amount of thermal radiation emitted by an object is governed by the Stefan–Boltzmann law.[7] given by Equation I:

$$E = \sigma T^4 \quad \text{(I)}$$

where:
E = Energy radiated by the object under consideration
σ = Boltzmann's constant, 5.67×10^{-8} W.m^{-2}·K^{-4}
T = Absolute temperature in Kelvin

Thermal imaging is preferred over hyperspectral imaging (HSI) in applications where there is a risk of tissue contamination due to physical touch, a lack of dependency on ambient illumination, or an object having low contrast or a dark color. This makes it particularly effective in detecting bruises, decay, or disease-related tissue alterations.[8-10] Furthermore, it avoids the risk of tissue contamination associated with contact-based sensing, offering a safe and rapid alternative for food quality monitoring. The present study leverages these advantages to propose a thermal imaging-based ANN framework for potato quality assessment. Potatoes are a staple crop worldwide and highly susceptible to fungal, bacterial, and viral infections such as Rhizoctonia canker,[2] potato wart,[11], early blight,[12] blackleg,[13] and ring rot.[14] These diseases often cause tissue decay that develops internally before becoming visible externally, making early detection vital for maintaining quality and marketability.

In this work, thermal images of potatoes were acquired under controlled conditions, and seven statistical and texture-based features—skewness, kurtosis, variance, mean, energy, standard deviation, and entropy—were extracted to quantify tissue decay. These features served as inputs to a two-hidden-layer ANN classifier designed to categorize potatoes as either healthy or defective. The methodology emphasizes both the performance of individual features and their combinations in driving accurate classification outcomes. The main contributions of this study include demonstrating the effectiveness of thermal imaging as a noninvasive tool for potato quality assessment, developing a feature-driven ANN framework that balances accuracy with computational efficiency,[15] and evaluating the role of individual features and their combinations in enhancing classification reliability.[7]

The current paper consists of six sections: Section 1 provides the introduction, problem statement, and motivation behind this study. Section 2 reviews related work on imaging and AI-based quality assessment of agricultural products. Section 3 details the materials, methods, and experimental setup used in this study. Section 4 presents and discusses the results of the ANN-based classification model. Section 5 concludes with the main findings, with future directions outlined in section 6.

2. Literature review

Visible imaging systems, also referred to as visible near infrared (VNIR), for the analysis of the quality of agricultural products have been employed in previous works.[16-19] However, the work presented in these articles has single defect detection limitations in the fruits. Furthermore, a similar sensing device was employed for the analysis of different categories of defects present in fruits belonging to citrus family.[20] Several researchers have used HSI technique for the identification of bruise and defects. Research on classification and defect detection in apples was implemented using machine learning-based classification models, including linear discriminant analysis (LDA),[21] SVM,[22] and neural networks.[23] Some other defect detection related research using HSI technique includes infection due microbes in oranges,[24] as well as bruise[25] and skin defects[26] in pears.

VNIR and HSI-based techniques performed admirably, resulting in higher accuracy and different classification parameters. Although these techniques have several drawbacks, these drawbacks include VNIR performance deterioration in poorly illuminated areas, or high computational resources and a large dataset for HSI-based imaging techniques. Due to these factors, these imaging techniques are not suitable for deployment for real-time applications for quality assessment. During the last decade, the thermal imaging technique has gained approval from the research fraternity toward the quality assessment process.[8-10]. In different post-harvest methods, the effectiveness of thermal imaging is assessed by Pathmanaban *et al.*[5] It discusses about various packaging and storage condition to increase the shelf life of agricultural products. It provides fast, large-scale quality assessment of agricultural products, producing an enhanced quality control process.[27] Changes in temperature variation are an important indicator toward early detection of defects, bruises, and disease. It enables timely intervention for preventing further deterioration of the agricultural products.

Both statistical methods and neural network models have been widely examined for defect detection and classification tasks. Authors have employed statistical methods such as analysis of variance, multivariate analysis of variance, multiple regression models, and Pearson correlation analysis (PCA) for detection of defects in blueberries[28] and classification of apples on the basis of bruise depth.[29] Optimization of the bruise detection model for pears was achieved by employing lock-in thermography.[30] Pulse phase thermography and HSI-based techniques were utilized for early bruise detection in apples.[22] In this research, the classification between healthy and defective apples was performed using PCA and minimum noise function (MNF). Furthermore, the result validation was performed using LDA, MNF, and SVM.

To improve fruit and vegetable classification accuracy, researchers used a variety of machine learning algorithms, including LDA, SVM, decision trees, random forests, and K-nearest neighbors, as well as neural network models like ANN, CNN, autoencoders, and generative adversarial networks.[4] Deep learning neural networks are also employed, providing an effective classification model.[3] However, the requirement of a larger and more enrich database is required to achieve better performance, making it computationally more complex. Detection of bruises in apples has been performed using thermal imaging techniques.[31] In this research, the authors studied the heat and cold images of tissue bruising in apples and monitored the bruise as a gradient of temperature. Texture-based features were employed along with statistical analytical tools in another research for classifying apples into different classes.[32] Peach fruit deterioration has been examined by using thermal imaging system.[33] Six distinct time-varying thermal images were captured over a 56-h period. To assess the bruising of peach, a temperature gradient was observed. Pre-trained CNN-based classification model, LeNet, was employed to classify bruises in pears.[34] In this article, a dataset consisting of 4371 images in the thermal spectrum was acquired sample of 300 pears.

3. Materials and methods

This section outlines the methodology used in this study. Potatoes were obtained from the local market, and their thermal images were captured using a thermal scanner to generate the sample space. This sample space was then divided into training and testing datasets. Thermal images in the training set were converted to grayscale, and seven key features were extracted to quantify the quality of potatoes. In this study, tissue decay serves as the assessment parameter. Based on extracted features, ANN classifier is able to categorize potatoes as either healthy or defective. The ANN model generates a probabilistic distribution to classify each potato accordingly. The proposed methodology is illustrated in Figure 1.

3.1. Hardware and software

Thermal scanner, TiS45, is used to acquire thermal images from the samples of potatoes. The scanner is able to capture the thermal radiations form the object irrespective of the ambient illumination. The acquired thermographs are equivalent to the temperature variation of the object. The thermal scanner with the operating temperature ranging between +50°C to −10°C, pixel resolution of 160×120 pixels, and a spectral range of 7500–14000 nm. Ambient temperature range of 30–35°C was ensured during image acquisition. The emissivity of the thermal scanner was manually set to 0.95 to match the emissivity of the potato surface, ensuring that the recorded thermal profiles accurately reflected tissue temperature variations. This value aligns with reported emissivity characteristics of biological materials. Python simulating tool was employed for training and testing of the classification model. The implementation was performed in Python using widely adopted scientific libraries: NumPy and Scikit-learn for feature extraction and pre-processing, TensorFlow for ANN model development, and Pandas with Matplotlib for data management and visualization. The simulating tool was exercised on the online platform of Google Colab Pro. This platform provided with specifications, including an A100 GPU by Nvidia comprising 16 GB of RAM and 32 GB of main memory.

3.2. Thermal imaging system

The thermal imaging system shown in Figure 2 was used to acquire thermographs of both healthy and defective potatoes. It employs pulse phase thermography, a non-destructive infrared technique in which a short pulse of hot air is applied to the sample and the subsequent cooling response is captured. Converting this response into the frequency domain enhances contrast between regions with different thermal properties. Since defective potato tissues dissipate heat differently from healthy ones, pulse

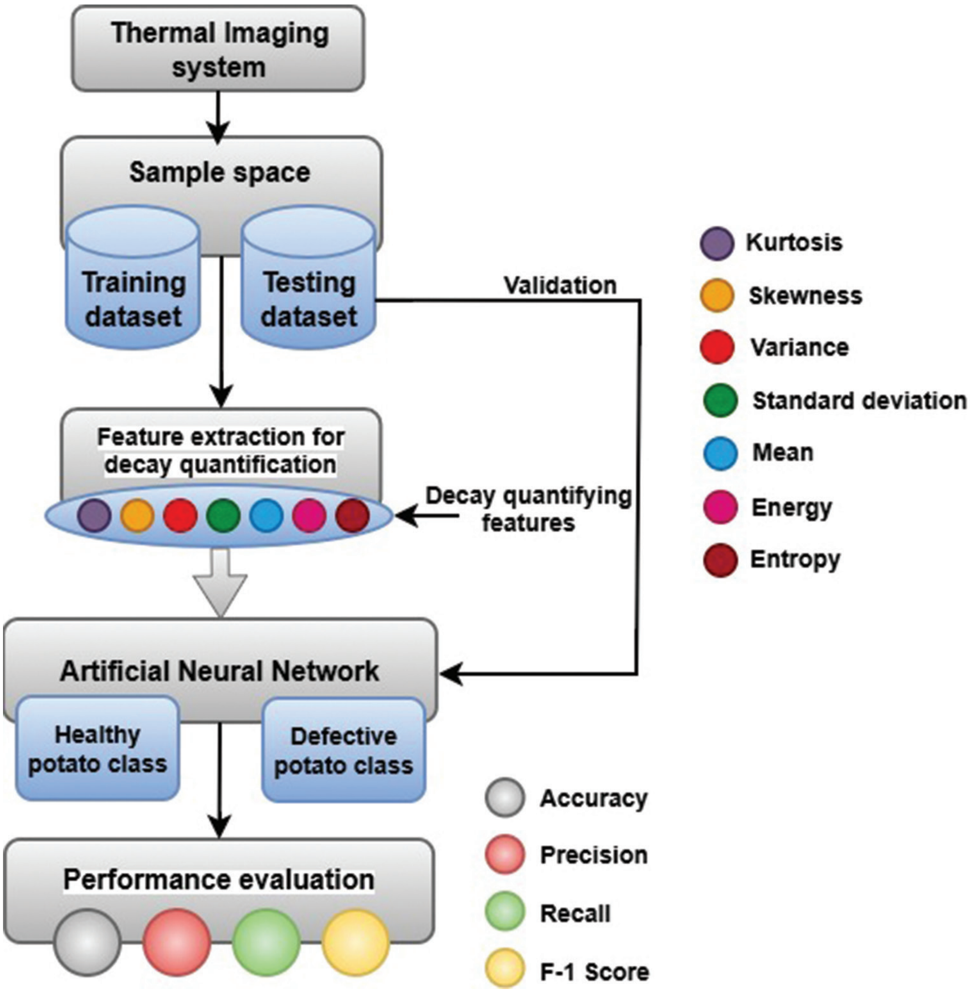


Figure 1. Flow diagram of proposed methodology

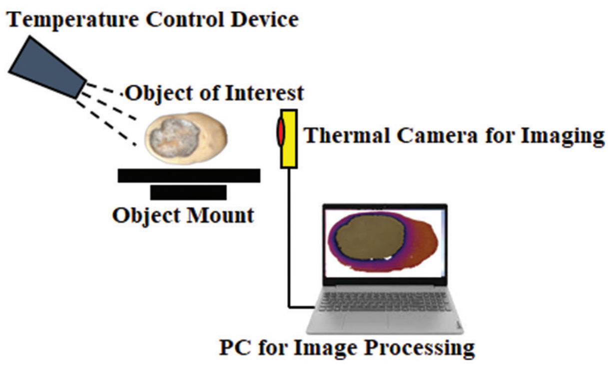


Figure 2. Thermal imaging system

phase thermography can reveal internal defects and early decay that are not visible on the surface. Its non-contact nature, independence from ambient lighting, and ability to detect subsurface anomalies make it highly suitable for agricultural quality assessment.

These thermographs were stored in a memory mounted on the processing system. A distance of 15 cm was maintained between the scanner lens and the object.

3.3. Dataset development

The dataset developed for this study included two separate classes of potatoes: Healthy and defective, based on the tissue decay as the assessment parameter. Potatoes were sourced from a local market to capture natural variability in shape, size, and surface conditions. Both healthy and defective samples were included, with tissue decay occurring progressively under natural storage conditions. As shown in Figure 2, samples of potatoes were placed on the mount, and by using thermal scanner, a total of 480 thermal images were acquired. From these 480 thermal images, 250 thermal images categorized as class of defective potato quality, and 230 thermal images categorized as class of healthy potato quality. The defective potato quality was quantified on the basis of potato surface tissue decay over a period of time. The entire dataset was divided into training and testing subsets in a 5:1 ratio, with 400 thermal images used to train the classification model and the remaining 80 images reserved for testing. Table 1 shows the division of all the samples into the training and testing dataset. It also shows the number of samples acquired for healthy and defective potatoes. Several representative samples from the sample space are shown in Figure 3.

3.4. Features for quantifying assessment parameters

Thermal images acquired and stored in the previous section to develop the dataset are converted from RGB channel to grayscale to reduce the dimension, leading to reduced computational complexity of the classification model. Decay of the tissues as captured by the thermal scanner is considered the parameter for assessing potato quality. The parameters which are used to assess the quality of potato are the decay of the surface tissues as measured by the thermal scanner. To quantify the decay, seven features are used, including skewness, kurtosis, variance, mean, energy, standard deviation, and entropy. These features were chosen because they represent a balanced combination of first-order statistical measures (mean, variance, standard deviation), higher-order statistical measures (skewness, kurtosis), and texture/energy-based measures (entropy, energy). Together, they provide a comprehensive description of the distribution and variability in thermal intensity values, which is essential for detecting subtle differences between healthy and decayed tissues. Furthermore, these features are determined for each image and used by the ANN-based classification model.

Table 1. Dataset classification

Quality of potatoes	Total samples	Training dataset	Testing dataset
Defective	250	209	41
Healthy	230	191	39
Total dataset	480	400	80

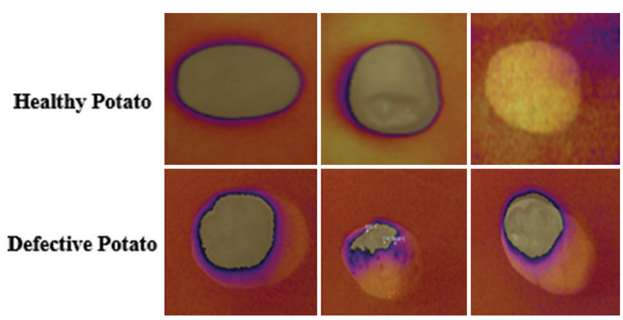


Figure 3. Representative samples

3.5. ANN clasifier

In this research, ANN-based classification model is developed to segregate potatoes on the basis of decay degree into two distinct classes: Healthy and defective. The motivation of employing ANN-based classification model is its low latency and increased system efficiency. As discussed in the previous section, seven features are identified to quantify the decay of the surface tissues of potatoes for quality assessment. In Figure 4, the architecture of ANN-based classification model is shown, where the first layer, the input layer, has seven neurons. Each neuron receives a single feature value for each image from the dataset. These features are represented from X1 through X7 in Figure 5. The second layer, as shown in the architecture, is the hidden layer with two dense layers with 200 and 50 neurons, where all the computation of the classification model is performed. For the linear functionality of ReLU activation function, it is used for each node of the hidden layers. The third layer is the output layer generating the final probabilistic distribution. Another model tuning functionality employed is the dropout function, which optimizes the number of neurons in each hidden layer and their interconnections. The weight adjustment of neurons is performed iteratively

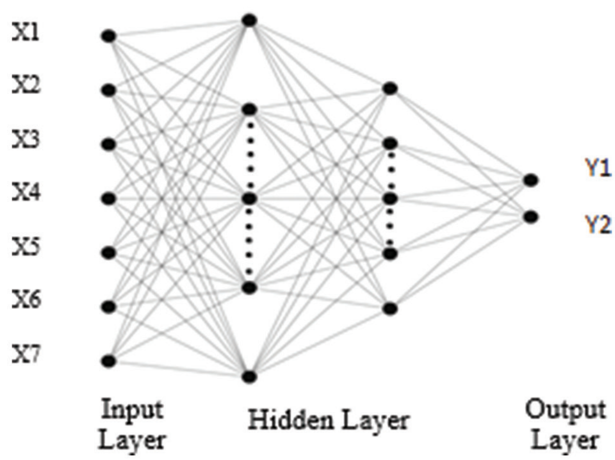


Figure 4. Architecture of artificial neural network

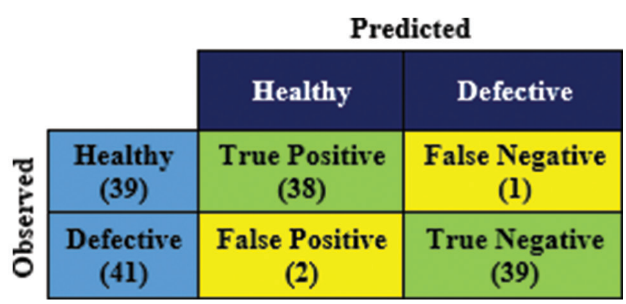


Figure 5. Confusion matrix of the classification model

using the adaptive filtering of feedback to generate the respective output.

The adaptive nature of the network updates weights by minimizing the error, which is evaluated in terms of accuracy and loss metrics, thereby optimizing the model for classification tasks. Two neurons form the output layer enabled by the Softmax activation function.[35]

To optimize the model, the weights of the neurons need to be adaptively updated after each epoch. The updating of neuron weight is mathematically represented by Equation II. In the proposed classification architecture Adam optimizer has been employed. It evaluates expectation (first moment) and the variance (second moment) of the targeted value using gradient of the given function. Using these two values and a learning rate of 0.001, the error function is evaluated. The present value of the weight of the neuron is adjusted to provide the updated weight of the neuron using this error function, as shown in the equation. For optimization, the system is iterated for 30 epochs.

$$\omega(t) = \omega(t-i) - \alpha \frac{\hat{m}(t)}{\sqrt{\hat{v}(t)+\epsilon}}; \quad 1 \le i \le k \qquad \text{(II)}$$

where
$\omega(t)$ = Adjusted weighted coefficient
i = Total training cycles
k = Maximum training cycles allowed
α = Step size for weight update
$\hat{m}(t)$ = Corrected first moment estimate
$\hat{v}(t)$ = Corrected second moment estimate
ϵ = Parameter to avoid division by zero

Evaluation of error between the actual value and the predicted value is computed using the forward propagation method. The weight of the neuron is convolved with all the inputs from the previous layers. The result of the operation is then summed with the bias weight of the architecture. On this value, the ReLU activation function is applied, generating the output of the current neuron. Mathematically, this is represented by Equation III:

$$\textit{Neuron output: } y_i = \emptyset(\sum x_i w_i) + b_i \qquad \text{(III)}$$

where:
y_i = Neuron output
$\emptyset$ = Activation function of the neuron
b_i = Neuron initializing bias
x_i = Input to the current layer of the hidden layer

For comparing the predicted and actual values, binary cross-entropy function is used.

3.6. Performance evaluation parameters

A confusion matrix, consisting of four key outcomes includes true positives (TP), where the model correctly predicts the positive class; true negatives (TN), where the model correctly identifies the negative class; false positives (FP), where a negative instance is incorrectly classified as positive; and false negatives (FN), where a positive instance is incorrectly classified as negative, are employed to evaluate the overall performance of a model. These parameters are then used to compute the performance of the proposed model. The performance evaluation parameters for different classification models are compared to obtain the optimum model for quality assessment of potatoes based on decay of tissues. The performance evaluation parameters used in this study are:

(i) Accuracy. It evaluates the models ability of correct classification and is mathematically given as:

$$\text{Accuracy} = \frac{\text{TN} + \text{TP}}{\text{Total predictions}} \qquad \text{(IV)}$$

(ii) Precision: The precision parameter determines the FP rate. The higher the value of this parameter, the lower the FP rate, which indicates the reliability of the classification model. Mathematically, precision is expressed as:

$$\text{Precision} = \frac{\text{TP}}{\text{TP} + \text{FP}} \qquad \text{(V)}$$

(iii) Recall: The recall parameter is also known as the sensitivity of the classification model. It indicates an FN rate. The higher the recall, the lower the FN rate, indicating that it is a good classification model. Mathematically, recall is expressed as:

$$\text{Recall} = \frac{\text{TP}}{\text{TP} + \text{FN}} \qquad \text{(VI)}$$

(iv) F1-Score: It quantifies performance by computing the harmonic mean between precision and recall. For obtained values between zero and one, the performance is best to poor.

$$\text{F1} - \text{Score} = 2^*\left(\frac{\text{Precision}^*\text{Recall}}{\text{Precision} + \text{Recall}}\right) \qquad \text{(VII)}$$

4. Results

This section outlines the algorithm underpinning our proposed methodology for classifying potato quality based on tissue decay. Smart quality assessment model based on seven statistical features from thermally generated images is proposed for the segregation of potatoes as healthy or defective. Thermal images are pre-processed by converting them from RGB channel to grayscale to reduce the dimensionality while preserving thermal patterns. The extracted features, including standard deviation, energy, entropy, skewness, kurtosis, mean, and variance, are normalized to prevent one feature from outweighing others while ensuring consistency. These normalized features serve as an input to an ANN-based classifier, which outputs a probabilistic distribution, indicating whether each potato sample is healthy or defective. A two-hidden-layer ANN model (200 and 50 neurons) with a Softmax output layer is employed for classification. Initially, individual features are considered to analyze their performance. Subsequently, these features are combined, and their performance is determined. For the evaluation of the performance of the model, parameters such as accuracy, recall, precision, and F1-score are evaluated. The best-performing features and combinations are determined based on these evaluations, providing a robust framework for thermal-based quality assessment. This approach leverages thermal imaging and ANN to effectively assess potato quality, aligning with similar methodologies in agricultural quality assessment.

Algorithm 1.

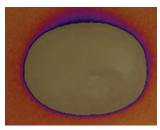
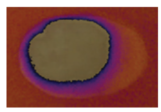
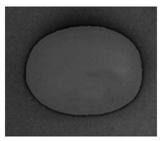
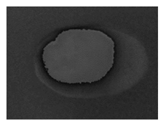
```
Input → Corpus of thermal images
Output → Classification Predictions
Corpus = Set of all thermal images

for image in Corpus do
  gray_img = rgb_to_gray (image)
  K = kurtosis (gray_image)
  S = skewness (gray_image)
  M = mean (gray_image)
  V = variance (gray_image)
  SD = standard_deviation (gray_image)
  SE = shannon_entropy (gray_image)
  E = energy (gray_image)

  Feature_Vector = [K, S, M, V, SD, SE, E]
  Img_features = Img_feature.append (Feature_Vector)
end

Scaled_feature = Min_Max_Scalling (Img_feature)

# Stage 1: Evaluate Individual Features
for features in Scaled_features do
  Model = load_ANN_Model()
  Prediction = ANN_Model (feature)
  Evaluate (Prediction) → Accuracy, Precision, Recall, F1-Score
end

# Stage 2: Evaluate Combination of Features
for feature_combinations in feature_combination (scaled_features) do
  Model = load_ANN_Model()
  Prediction = ANN_Model (feature_combination)
  Evaluate (Prediction) → Accuracy, Precision, Recall, F1-Score
end

Select best individual feature and feature combination based on
performance

End
```

The algorithm 1 proposes the outline for a systematic approach for segregating healthy potatoes from defective potatoes. This classification is performed by quantifying the tissue decay of potatoes for which seven features are considered. These features are extracted from the acquired thermal images of potatoes. Each thermal image is converted into its respective grayscale from which these seven features are extracted. Since the numerical representations of these features are skewed, using Min-Max scaling, the features are normalized to generate a feature map. For classification, two phases are considered. In the first phase, each feature is considered individually to determine their classifying significance. In the second phase, their combined effect is considered for classification purpose.

4.1. Simulation results

Table 2 shows the demonstrative outcome of the proposed simulation framework in a sequential manner. Stage 1 is the acquisition of the thermal image from the potato, and stage 2 is its conversion from RGB channel to grayscale channel. Stages 3 and 4 present the extracted and normalized extracted values of the feature to quantify

Table 2. Demonstrative outcomes of the proposed simulation framework

Stage	Healthy	Defective
Stage 1: Image acquisition		
Stage 2: RGB to grayscale conversion		
Stage 3: Image features	K 5.98840351 S −1.76220199 M 11.59286264 SD 81.5141566 SE 4.38183408 E 5.53889269	K 2.023527 S−1.4894787 M 18.00129207 SD 83.53689846 SE 5.74982747 E 2.81695787
Stage 4: Scaling of features	K−0.58828428 S−1.56893667 M−1.48091018 SD−0.08037347 SE−0.82732362 E−0.70364438	K−0.83755939 S−1.42365514 M−0.09562881 SD 0.14799461 SE 1.09261631 E−0.85029113
Stage 5: Probabilistic distribution	$\begin{bmatrix} 0.992961 \\ 0.0070382 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0.00001513 \\ 99.9984860 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$
Stage 6: Output of the model	Healthy potato	Defective potato

the decay of potato. In stage 3, it is observed that the value of standard deviation is very high as compared to other parameters. This high value will influence the decision-making more strongly. To remove such significant impact of one feature over other features, the values obtained in stage 3 are normalized to generate the values and shown in stage 4. The values are normalized between −1 and 1. Stage 5 shows the probabilistic distribution of the classification model classifying the samples to either healthy or defective classes respectively. Stage 6 shows output of the algorithm.

4.2. Confusion matrix

Figure 6 illustrates the confusion matrix for the testing dataset, detailing the classification outcomes of the model in terms of TP, TN, FP, and FN. In this context, healthy potatoes are considered the positive class, and defective potatoes are the negative class. The structure of the obtained confusion matrix is shown in Figure 5.

In the testing dataset, 39 samples were of healthy quality and 41 samples were of defective quality. In this study, healthy quality is considered true value, while defective quality is considered false value. For the healthy quality of potatoes, 38 were accurately classified as true values, and only 1 sample was wrongly classified as defective quality. Furthermore, for defective quality, out of 41 samples, 39 samples were accurately classified as true values, and remaining 2 samples were classified as false values. These results indicate that the model has a high accuracy in correctly classifying both healthy and defective potatoes, with minimal misclassifications.

4.3. System performance for individual features

In this section, a discussion on achieved results is presented considering the decay quantifying features individually. Table 3 showcases the performance of the ANN-based classification model. When individual features were used as inputs, the model's input layer composed of a single neuron. On complete training, the testing accuracy varied depending on the feature analysis. Specifically, the energy and entropy features yielded testing accuracies of 81.36% and 79.83%, respectively. In contrast, features such as variance and kurtosis resulted in lower testing accuracies of 53.14% and 58.17%, respectively. The testing accuracies for other features assessing potato quality decay fell between these values.

To make a more robust understanding toward the performance of each feature in quantifying the assessing parameters toward classifying potatoes as defective or healthy, three more parameters were considered, including Precision, recall, and F1-score. Table 4 shows the observed values for these parameters. Utilizing the energy feature, the model achieved a precision of 88% for defective potatoes, with recall values of 88% for healthy samples and 77% for defective ones. Importantly, the F1-scores obtained from the energy and entropy features ranked among the highest across all evaluated metrics. In contrast, the variance feature demonstrated weak performance, yielding only 51% precision for defective potatoes, 47% recall for healthy samples, and an overall F1-score of 54%. Similarly, the kurtosis feature performed slightly better than variance but still fell short of acceptable standards. From the discussion of values observed in Tables 3 and 4 for assessing the performance of the classification model,

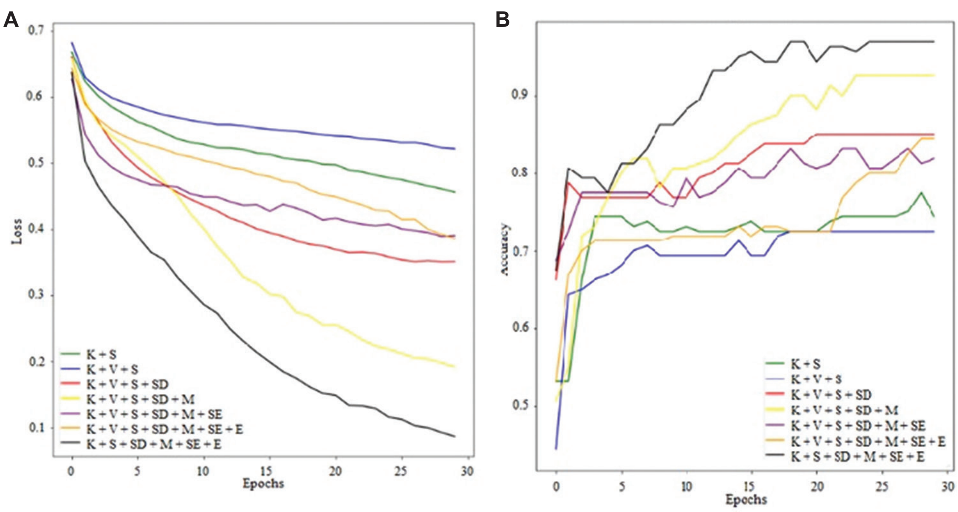


Figure 6. Performance curves showing accuracy versus epochs (A) and loss percentage versus epochs (B)
Abbreviations: E: Energy; K: Kurtosis; M: Mean; S: Skewness; SD: Standard deviation; SE: Entropy; V: Variance.

variance and kurtosis feature quantified the decay with the lest contribution toward the development of a better classification model for assessing the quality of potato.

4.4. Ensemble feature-based model performance

Impact of the combination of features toward assessing the quality of potatoes is presented in this section. In Table 5, a combination of features and their respective accuracy and loss percentage is presented. It is observed from Table 5 that with increasing features as an input to the classification model to quantify the decay as the assessing parameter—the accuracy of the model—improves. Furthermore, it is also noted that the variance feature does not improve the model performance. Instead, it reduces the accuracy of the ANN-based classification model. The testing accuracy achieved for only kurtosis and skewness as decay quantifying feature was 79.65%. On adding variance to these two features as an input, the testing accuracy dropped to 61.34%. However, further addition of features effectively increased the testing accuracy of the ANN-based classification model.

Furthermore, when the classifier was trained using a combination of these decay-quantifying features as input, it achieved a testing accuracy of 87.29%. Through previous observations in this study, variance reduces the classifier performance. Therefore, another simulation was performed where all the features were considered except variance. The testing accuracy achieved for this model increased drastically to 94.89%. According to these results, it was concluded that the performance of the classification model does not only depends on the number of variables used as an input to the model but also on the significance of that variable, which plays an important role in determining the performance.

The impact of number of epochs on the accuracy and loss percentage for different combinations of features is shown in Figure 6. It is observed that when the variance feature is removed from the ensemble of features, the performance of the model is higher as compared to other combinations. This figure shows the variation of loss percentage in panel A and accuracy percentage in panel B as a function of number of epochs. In Figure 6A, in general, as the number of epochs is increased, the loss percentage of the classification model reduces. In this figure, as the more number of features are used as an input for the quality assessment of potatoes, the gradient of decrease of loss percentage of the classification model increases. The gradient for the combination of six features is highest, as shown by the declining curve represented by the black curve. In Figure 6B, the increase in the accuracy for the quality assessment of the classifier is presented. In this figure, the value of accuracy increases as more features are used as an input to the classification model. For the set consisting of six features, excluding the variance, the rate of increase of accuracy, as the number of epochs increases, is higher, as shown by the black curve in the graph.

To better understand the impact of combination of features, three other performance evaluation parameters are discussed in this section. These parameters: precision,

Table 3. Performance of individual features

Feature	Accuracy (%)		
	Training	Validation	Testing
Kurtosis	67.8	60.03	58.17
Skewness	74.9	77.53	78.23
Variance	52.53	50.17	53.14
Mean	69.48	62.57	64.49
Standard deviation	66.37	72.47	70.89
Entropy	76.95	82.57	79.83
Energy	71.39	80.43	81.36

Table 4. Classification report of individually considered feature

Feature	Classwise classification report					
	Precision		Recall		F1-Score	
	Healthy	Defective	Healthy	Defective	Healthy	Defective
Kurtosis	0.89	0.53	0.31	0.94	0.44	0.70
Skewness	0.98	0.69	0.64	0.99	0.75	0.82
Variance	0.81	0.51	0.47	0.98	0.54	0.68
Mean	0.97	0.57	0.33	0.99	0.46	0.73
Standard deviation	0.81	0.64	0.74	0.67	0.79	0.64
Entropy	0.99	0.77	0.63	0.99	0.74	0.85
Energy	0.83	0.88	0.88	0.77	0.82	0.83

Table 5. Model performance accuracy for combination of features

Feature	Dataset	Accuracy (%)	Training loss
K+S	Training	74.37	0.45
	Validation	82.49	
	Testing	79.65	
K+S+V	Training	72.5	0.51
	Validation	57.49	
	Testing	61.34	
K+S+V+M	Training	85	0.34
	Validation	87.5	
	Testing	88.4	
K+S+V+M+SD	Training	92.5	0.18
	Validation	87.5	
	Testing	84.38	
K+S+V+M+SD+SE	Training	83.74	0.38
	Validation	89.99	
	Testing	91.26	
K+S+V+M+SD+SE+E	Training	84.37	0.37
	Validation	89.99	
	Testing	87.29	
K+S+M+SD+SE+E	Training	97.5	0.08
	Validation	95.99	
	Testing	94.89	

Abbreviations: E: Energy; K: Kurtosis; M: Mean; S: Skewness; SD: Standard deviation; SE: Entropy; V: Variance.

recall, and F1-score. The observed values for these parameters are presented in Table 6. In general, as the number of features used as input to the classification model increases, so does the precision parameter, which quantifies the decay of the potato for quality assessment. This pattern, however, breaks down in the second case when the variance feature is combined with kurtosis and skewness. The value of precision is reduced before increasing again. When variance was added to the model, the value dropped from 88% to 52% before increasing to 83% and then increasing further as the number of inputs increased. Furthermore, when all the features are considered, except variance, the increase in the value of precision is very significant. A similar pattern can be observed for recall and F1-score parameter. When variance is considered, the value of recall and F1-score is 83% and 64%, respectively. The values for both of these parameters increase further with increasing the number of input to the classification model. Moreover, the performance value increases substantially when the variance feature is excluded from the feature combination.

In comparison with traditional manual inspection, which is often subjective and struggles to identify internal or early-stage defects, the proposed system demonstrates a significant improvement in accuracy and reliability. Earlier automated approaches using visible or HSI combined with statistical classifiers have reported accuracies in the range of 80–90%, but these methods typically require large datasets, controlled lighting conditions, and higher computational costs. By contrast, our thermal imaging-based ANN framework achieved an accuracy of 94.89%, offering a more robust alternative with reduced dependence on external illumination and smaller training datasets. This indicates that the proposed method not only surpasses manual inspection but also provides a more practical and scalable solution compared to other automated imaging techniques for potato quality assessment.

Table 6. Classification results for feature ensemble

Ensemble features	Precision	Recall	F1-score	Class
K+S	0.88	0.74	0.80	Defective
	0.79	0.90	0.84	Healthy
K+S+V	0.52	0.83	0.64	Defective
	0.73	0.36	0.48	Healthy
K+S+V+SD	0.83	0.98	0.91	Defective
	1.00	0.67	0.80	Healthy
K+S+V+SD+M	0.92	0.88	0.90	Defective
	0.81	0.87	0.84	Healthy
K+S+V+SD+M+SE	0.84	0.97	0.91	Defective
	1.00	0.79	0.88	Healthy
K+S+V+SD+M+SE+E	0.84	0.94	0.89	Defective
	0.95	0.87	0.91	Healthy
K+S+SD+M+SE+E	0.92	0.98	0.96	Defective
	1.00	0.88	0.94	Healthy

Abbreviations: E: Energy; K: Kurtosis; M: Mean; S: Skewness; SD: Standard deviation; SE: Entropy; V: Variance.

Although the present study evaluates potatoes individually, the proposed system can be adapted for multiple-sample detection. By capturing thermal images of batches on a conveyor system and segmenting individual potatoes within each frame, simultaneous analysis is achievable. Given the low computational cost of feature extraction and ANN inference, such an extension would enable faster, real-time grading suitable for industrial settings. Moreover, the framework can be extended to process multiple potatoes simultaneously through batch imaging and segmentation, enabling scalable deployment in industrial grading lines.

5. Conclusion

This study demonstrates the potential of integrating thermal imaging with ANNs to create a reliable, non-invasive framework for potato quality assessment. Beyond achieving high classification accuracy, the key contribution lies in showing that a carefully chosen set of statistical and texture-based features can capture subtle thermal variations linked to tissue decay, enabling early detection of defects that are difficult to identify visually. The proposed system addresses major shortcomings of manual inspection and complex hyperspectral methods by offering a solution that is faster, more consistent, and less dependent on costly equipment or controlled lighting environments.

From a practical standpoint, the approach can be readily adapted to post-harvest grading, storage monitoring, and supply chain management, where rapid and objective decision-making is critical to reducing losses and improving market value. The methodology also provides a foundation for scaling similar thermal–AI systems to other crops, thereby supporting precision agriculture and sustainable food management practices. Overall, the work reinforces the value of combining thermal imaging with lightweight AI models to deliver practical, scalable, and industry-ready solutions for agricultural product quality assessment. By combining low-cost thermal imaging with efficient neural network models, this work offers a practical pathway for real-time, scalable, and non-invasive quality assessment of potatoes and other perishable crops in agricultural supply chains.

6. Future work

Technology is ever-evolving phenomenon, and with their advancement, the quality assessment models for agricultural products can be made more robust, scalable, accurate, and automated using AI-supported technology. The results obtained in this study can be further improved by improving on various variables used to achieve the goal of this study. One such variable is the sample size. By enriching the sample size and using the augmentation techniques, the dataset generated can be more versatile making the training of the classification model more advanced. This may lead to accurate classification even with noisy data when deployed in real-world situation. Another aspect where the performance can be improved is by fusing multiple classification models. This may remove the drawbacks of any particular model and leveraging the strength to develop a more holistic model, which can be scaled to different aspects of quality grading of agricultural products. Integrating these enhancements with other non-destructive testing methods, including electronic nose and spectroscopy, will provide better analysis toward a more comprehensive understanding the quality assessment of agricultural products. Finally, using the concept of transfer learning and multi-task learning, the assessment model will be able to provide more accurate assessment across diverse datasets.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

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Ethics approval and consent to participate

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Availability of data

Data used in this work are available from the corresponding author on reasonable request.

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ARTICLE

Investment projects in extractive industries: The role of engineer-to-order machinery

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Abstract

Investment decisions in extractive industries increasingly depend on the technological configuration of engineer-to-order (ETO) machinery. This study explores the role of ETO projects in reshaping investment logic within extractive industries. To strengthen conceptual framing, we explicitly distinguished between primary and secondary ETO within the multi-project investment structure. Special attention was given to secondary ETO—the adaptation of standardized equipment to specific geological conditions—which emerges as a critical component of multi-project investment strategies. We clarified that the novelty of the approach lies in treating secondary ETO as an embedded, corrective investment rather than a standalone engineering decision. In addition, we quantitatively assessed the impact of ETO-related expenditures within multi-project investment, using the net present value indicator. This study introduced a model that comprises both the base serial equipment and a custom ETO component, enabling the achievement of the designed performance parameters. To analyze sensitivity, we employed the Box–Wilson experimental design method. Results showed that ETO costs had no significant influence on the response function (i.e., the production volume required to reach breakeven), whereas the most critical factors were the marginal revenue and the project duration. Theoretically, this study reconceptualizes ETO not as an isolated manufacturing decision but as a functional component within broader investment planning. These results reinforce the conceptual distinction between primary and secondary ETO by demonstrating that corrective engineering adaptations embedded in multi-project structures do not alter the financial breakeven logic.

Keywords: Engineer-to-order; Mechanical engineering; Large companies; Investment; Multi-project; Extractive industries

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1. Introduction

The tightening of sustainable development requirements at the global level has led to a reduction in coal use while providing a powerful impetus to the increase in metal ore extraction. Global extraction of raw metallic ores has risen nearly fourfold, from 2.7 billion tons in 1970 to almost 9.4 billion tons in 2022.[1] However, intensive coal mining has persisted in some countries. For example, the United States (U.S.) coal industry produced 585.5 million tons in 2023, including 133 million tons from 34 U.S. longwall faces.[2] Core natural resources (CNR)'s Bailey Complex in Pennsylvania remains the leading longwall complex with 10.8 million tons in 2024, followed by CNR's Enlow Fork Complex (9.2 million tons) in Pennsylvania, and American Consolidated Natural Resources's Marshall County mine (9 million tons) in West Virginia. In contrast, China, which produced 4.76 billion tons of coal in 2024, has more than 1,700 small mines extracting up to 300,000 tons of coal annually. Some companies, while closing small- and medium-sized coal mines with a production capacity below 600,000 tons, are transforming and expanding large mines to increase production capacities.[3]

The extraction of mineral resources, including coal and metal ores, depends heavily on the geological and mining conditions of a deposit. This poses high risks in terms of investment project implementation, with meeting planned production targets being a key challenge. Organizational aspects further complicate the situation. A testimony from an expert regarding a project at the American mine—The Longview mine—located near Volga, West Virginia, is as follows:

> The biggest change we are seeing is the mining industry adjusting to multiple original equipment manufacturers (OEMs) being involved in a longwall build. The major OEMs in the longwall space are no longer manufacturing their own equipment… We have been planning for our longwall since breaking ground on the project. With the departure of Joy and Cat from the roof support market, we then looked at other manufacturers. We decided to partner with Famur [Poland] because they had in-house design capability… The Longview mine will be the first new longwall constructed in this new era, bringing together a Joy shearer, Famur shields with Hauhinco Bergbautechnik (HBT) electro-hydraulics, and an Armoured Face Conveyor from Longwall Associates.[4(p23)]

The company HBT, previously known as Hauhinco, acquired Cat's longwall mining equipment business and renamed the entity. The new name in a way resembles that of a predecessor OEM, Deutsche Bergbautechnik, which was acquired by Bucyrus before Bucyrus itself was acquired by Cat.

Thus, in the era of globalization, mining must be based on the principles of customization, which implies manufacturing products tailored to client orders. Since the late 1990s, this phenomenon has been recognized in the scientific literature under the term engineer-to-order (ETO). Its defining motto is often cited as the idiom "No Run of the Mill," signifying exceptionality and non-standardization.[5]

This institutional consolidation in mining equipment supply created a structural environment in which secondary ETO became not merely a corrective action but also an embedded mechanism for restoring functional adequacy after standardized procurement. In the academic literature, the ETO approach is predominantly associated with primary projects.[5,6] In industries that require complex engineering solutions—such as mechanical engineering, aerospace, and oil and gas—ETO serves as a means to meet non-standard demand.[7-9] According to recent reviews, digital technologies and cloud-based manufacturing (manufacturing-as-a-service) have significantly improved ETO efficiency in developed economies,[10] but custom design services remain expensive.

Typically, ETO remains the domain of small and medium-sized enterprises, which possess the organizational flexibility and agility to quickly reallocate resources.[6,9] Scientific works on the production strategies of such companies mainly concern primary projects;[11,12] however, in the extractive industries, this pattern is shifting: ETO is increasingly concentrated in large integrated holdings with combined engineering, manufacturing, and service capacities.[13,14] The Case Boxes 1 and 2 illustrate this situation. To understand this contradiction, one must distinguish between primary ETO projects (creating unique equipment) and secondary ETO projects (modifying existing serial equipment to achieve target performance under specific operating conditions).

The ongoing tension between the drive for standardization in mining equipment and the necessity to adapt to specific geological conditions leads to the emergence of so-called secondary ETO projects.[15] These occur after the acquisition of standard equipment, once its inadequacy under operating conditions becomes evident. Despite its practical relevance, this phenomenon remains largely unexplored in terms of economic efficiency.

The situation with ETO in the mining sector theoretically falls within the real options approach; however, this primarily applies to primary projects. In contrast, secondary ETOs operate as forced corrective investments—projects implemented almost in emergency mode to address defective situations.[16] It is evident that the nature of secondary ETOs renders the extensive research on Project Portfolio Selection and Scheduling redundant, as the situation itself eliminates the need to choose which projects to develop.[17]

Secondary ETO projects do not concern cases where serial equipment or technologies are unavailable (unique developments). Their mission is far more prosaic—to eliminate the negative effects caused by the application of serial equipment. For example, a coal shearer with standard auger cutting drums may fail to achieve the planned load on the longwall due to specific geological features of the coal seam within a site. This threatens the economic efficiency of the entire investment project. To remedy the situation, the coal company must order the design and manufacture of customized augers. This constitutes a typical example of a secondary ETO project. It is reasonable to regard secondary ETOs as design modifications that do not alter the underlying production technologies but differ from the serial model by more than 10–15% of their components.

However, when dealing with local engineering adaptations for specific conditions, it is worth recalling the parable circulated in 1928 by Wiers.[18] The story of the skilled mechanic who was called into a factory because a certain machine had stopped and would not run. When the job was completed, the mechanic sent in a bill for USD 200.00 for only a few minutes' work. This charge impressed the president as being excessive, so he ordered the bill sent back to be itemized. Upon its return, it read this way, "Turning one bolt, USD 1.00; knowing which bolt to turn, USD 199.00."[18(p10)]

Therefore, secondary ETO, especially in the field of mining machinery manufacturing, can be considered an extension of the make-to-order practice.[19]

Secondary ETO is particularly significant in the context of mining investment projects. When purchased equipment fails to meet planned productivity due to mismatches with site conditions, an additional project becomes necessary. This changes the nature of investment: instead of a single-project scenario, a multi-project configuration emerges—a bundle of interrelated initiatives, in which ETO serves as a corrective mechanism for inadequacies in standardized solutions.

In the context of a portfolio model with resource and temporal constraints, the development of the aforementioned multi-project configuration for modernizing a coal shearer unfolds in the following sequence:
(i) Development by the coal company of a basic investment project to equip the mining face with a standard mechanized complex
(ii) Procurement of serial equipment and implementation of the base investment project
(iii) Gaining negative operational experience at the mining face
(iv) Commissioning by the coal company of an ETO project from the supplier to correct the negative effects
(v) Development of the ETO project and manufacture of modified equipment
(vi) Implementation of the modified equipment by the coal company.

In the project management literature, there has been substantial development of multi-project management approaches.[20-22] and resource portfolio balancing techniques.[23,24] However, applying these frameworks to the unique context of the mining sector—characterized by dominant buyers, centralized procurement, and high geological-operational risk—requires additional adaptation.

Particularly notable are studies on the institutional structure in the industry. For example, it has been shown that in Germany, Poland, and Ukraine, government subsidies for coal mining led to the formation of clientelist structures, in which mining companies acted as patrons for large mechanical engineering firms.[16] This has created a new logic of interdependencies. Therefore, there is a pressing need to develop models that incorporate ETO as an integral part of multi-project investment logic in the extractive industries. Contemporary academic literature provides limited conceptual support for such configurations, thereby underlining the relevance of this study. In confirmation, it is appropriate to mention a previous study[25] that assessed the effectiveness of the primary ETO project using the net present value (NPV) method, namely the primary one.

Therefore, the purpose of this study is to develop and demonstrate an approach to analytically assessing the statistical significance of the impact of projects with ETO of secondary type on the overall effectiveness of multi-project investment, justifying its relevance.

2. Methods

The methodological framework of this study was built upon an interdisciplinary approach that combines elements of organizational design, production engineering, and innovation economics. The focus lay on ETO manufacturing in the mining machinery sector, which involves customized product development in response to specific client requirements.

This is a hybrid study, combining theoretical generalization with experimental modeling aimed at evaluating the economic efficiency of investment decisions in mining machinery and related extractive industries. The study also employed qualitative methods, including case studies of specific ETO projects implemented by companies operating in the heavy machinery segment. The methodological tools included:
(i) An adapted method for evaluating the economic efficiency of investment projects under conditions of individualized design (ETO);
(ii) Mathematical modeling and statistical techniques, particularly multifactorial experimental design, which allows for analysis of the interrelations

between technological parameters, production system configuration, and financial outcomes;

(iii) Techno-economic analysis of prototype characteristics and system behavior simulation under various scenarios.

The experimental research was conducted using a digital model of the production environment, approximated to real-world conditions of extractive enterprises. Special attention was paid to assessing the sensitivity of economic outcomes to changes in individual variables (investment volumes, project duration, cost of capital, market conditions, etc.). The theoretical assumptions were validated through comparisons with practical case data and industry-specific information.

2.1. Methodology for evaluating multi-project investment efficiency with ETO components

The methodology for evaluating the efficiency of multi-project investment—including ETO components—relied on the calculation of NPV. Unlike the above-mentioned work,[25] we proceed from the conditions of breakeven in multi-project investment. The NPV of a project investment is defined by the equation:

$$NPV = -Inv + \sum_{0}^{T} \frac{TR_t - TC_t}{(1+r)^t} \quad (1)$$

Where Inv is the total investment costs, TR_t is the total revenues in year t, TC_t is the total costs in year t, T is the total project duration, and R is the cost of capital (discount rate). A project is considered efficient if NPV ≥ 0.

Among two alternative projects, the one with the higher NPV is more efficient. If NPV is equal to 0, the project is at breakeven: investment equals the sum of discounted cash flows over the project's lifecycle.

To determine the breakeven threshold, the annuity formula is used:

$$NPV = 0 \Leftrightarrow CF_t = \frac{Inv}{\sum_0^T \frac{1}{(1+r)^t}} \quad (2)$$

Where CF_t is the constant annual cash flow. Total revenues and costs depend on production volume:

$$TR_t = pQ;\ TC_t = cQ \quad (3)$$

Where p is the unit price (revenue per unit sold), c is the unit cost (direct cost per unit), and Q is the annual production volume.

Thus, the annual cash flow can be expressed as:

$$CF_t = (p-c)Q = \pi Q \quad (4)$$

Where π is equal to $p-c$ (marginal revenue per unit). The minimum production volume required for breakeven is:

$$Q \geq \frac{CF_t}{\pi} \quad (5)$$

Because secondary ETO aims to restore planned productivity rather than change strategic investment scale, the required production volume at breakeven (Q) provides a more economically meaningful response variable than NPV.

The uniqueness of this approach lies in incorporating a custom-designed ETO component into the project structure. This element—typically a redesigned or modified part—makes it possible to achieve a target production level Q that would not be attainable with standard equipment alone. In this case, a single-project scenario becomes a multi-project configuration. The total investment becomes:

$$Inv = Inv_{Base} + Inv_{ETO} \quad (6)$$

Where Inv_{base} is the investment in base equipment and Inv_{ETO} is the investment in ETO design and manufacturing.

Multi-project efficiency depends on ETO cost, implementation time, cost of capital, and the marginal revenue of the produced output. The four selected variables—investment, project duration, cost of capital, and marginal revenue—correspond directly to canonical drivers of investment project performance and therefore capture the essential financial logic of ETO within a multi-project configuration. This formulation explicitly embeds ETO within the investment decision-making process, treating it as an endogenous mechanism rather than an exogenous cost shock.

2.2. Statistical analysis

Using a fractional factorial design enables us to represent the multi-project structure where secondary ETO acts as an incremental corrective investment embedded into a larger capital system.

The Box–Wilson experiment, also known as central composite design and response surface methodology, is a type of response surface methodology used to optimize processes by identifying the relationships between independent variables (factors) and a dependent variable (response).[26] The research method we applied has been sufficiently refined in solving problems that, unlike typical applications of the method, do not belong to the engineering domain.[27-29]

We used the Box–Wilson method to test the null hypothesis (H_0), which states that the response function

(Q) is not significantly influenced by the factor "total investment volume." We considered four factors, one of which was investment with an ETO project and without a project, varied them according to a certain plan, and established the statistical significance of the influence of these variables on the Q.

2.3. Variable selection and justification

Independent variables (research factors) included:

- x_1: Total investment volume (Inv; including ETO)
- x_2: Project duration (T)
- x_3: Discount rate (r)
- x_4: Marginal revenue per unit (π)

Each factor varied across a continuous range; however, for analysis, all variables were standardized to a normalized scale, from −1 to +1, regardless of their units.

2.4. Experimental design

A fractional factorial experiment of the type 2^{4-1} was used, which reduces the number of required runs from 16 to 8 without losing interpretive value. Table 1 shows the design matrix. Each row corresponds to one experiment. For example, in Experiment 3:

- x_1 (investment) was set at its lower level (no ETO, $Inv_{ETO} = 0$)
- x_2 (project duration) was at its upper level
- x_3 (cost of capital) was at its lower level
- x_4 (π) was at its upper level.

2.5. Model setup and response function

The formal Q (required production volume) is modeled as:

$$Q = f(x_1, x_2, x_3, x_4) \quad (7)$$

All factors were standardized within the range [−1; +1].

2.6. Baseline data and assumptions

We considered a small-scale (up to 10 million U.S. dollars [USD]) investment project. These are capital investments sufficient to equip a mechanized complex of a coal mine face in Poland, Ukraine, and China. In the U.S. and Australia, practicing projects of this kind may require larger-scale investments. Table 2 presents the ranges of variation. According to mining equipment suppliers, the investment cost of equipping the longwall is approximately 8 million USD (with $Inv_{ETO} = 1$ million USD) or 7 million USD (without ETO, $Inv_{ETO} = 0$).

Table 1. Fractional factorial experiment matrix of the type 2^{4-1}

Experiment number	x_1	x_2	x_3	x_4
1	−1	−1	−1	−1
2	1	−1	−1	1
3	−1	1	−1	1
4	1	1	−1	−1
5	−1	−1	1	1
6	1	−1	1	−1
7	−1	1	1	−1
8	1	1	1	1

3. Results

The case of customized augers for a coal shearer served as the operational anchor connecting the statistical model in this study with a real-world example of secondary ETO implementation. The analysis was anchored in an illustrative industrial configuration involving equipping a coal mine's longwall. The system included powered roof supports, a scraper conveyor, and a shearer-loader. To reach the planned production capacity, the mine must commission an ETO project from the mining equipment supplier. The goal of this ETO project was to develop and manufacture a custom set of augers to replace the standard components.

The variation of factors according to the matrix yielded results for Q (Table 3). The Q values ranged from 0.131 Mt (Experiment 3, most favorable case) to 0.476 Mt (Experiment 6, least favorable case). In the

Table 2. Investment project parameters

Factors	Normalized scale	Parameters
x_1 (million USD)	+1	8
	−1	7
x_2 (years)	+1	5
	−1	3
x_3 (%)	+1	12
	−1	4
x_4 (USD/t)	+1	12
	−1	7

Table 3. Numerical results of experimental simulation

Experiment number	Result (Q; Mt)
1	0.360
2	0.240
3	0.131
4	0.257
5	0.243
6	0.476
7	0.277
8	0.185

first case, factors x_2 and x_4 were at upper levels; in the latter, they were at lower levels. The resulting regression equation is:

$$Q = 0.271+0.018x_1-0.059x_2+0.024x_3-0.071x_4 \quad (8)$$

From the regression, we obtained an R of 0.979, R^2 of 0.958, adjusted R^2 of 0.902, $F(4,3)$ of 17.160, $p<0.021$, and standard error of 0.332. Negative coefficients for x_2 and x_4 indicate that increasing these factors reduces Q.

The H_0 is a statistical assumption that there is no significant relationship between the two studied variables. The p-value indicates the probability that the H_0 is true. If $p \le \alpha$, the H_0 is rejected. In frequentist statistics, the α-level (also known as the significance level) represents the probability of rejecting the H_0 when it is true. The results of testing the statistical significance of the relationships between variables x_i and the Q, obtained using Statistica for Windows, are presented in Table 4.

Regarding the sensitivity of the Q to factor variation, the H_0 assumed no significant relationship between total investment volume (including ETO) and the Q. The calculated p-value (0.218, which is >0.05) with a t-statistic of 1.555 supported the validity of H_0. Out of the four studied factors, only two—x_2 (project duration) and x_4 (marginal revenue π)—exhibited a statistically significant impact on the Q. The strongest influence arose from x_4, as shown by its largest standardized regression coefficient. Although the sample size was limited, the obtained results were consistent with the absence of significant effects, making a type II error unlikely at the current scale.

Factor x_1 (investment, including ETO) did not exhibit a statistically significant influence on the outcome. The results presented in the Pareto chart (Figure 1) confirmed H_0: investment in ETO does not significantly affect the economic performance of the multi-project. A simplified regression using only statistically significant variables yields:

$$Q = 0.271-0.059x_2-0.071x_4 \quad (9)$$

Table 4. Regression summary for dependent variable *Q*

Parameter	b constant	Standard error of b	t (3)	*p*-value
Intercept	0.271	0.012	23.109	<0.0001
x_1	0.018	0.012	1.556	0.218
x_2	−0.059	0.012	−4.998	0.015
x_3	0.024	0.012	2.053	0.132
x_4	−0.071	0.012	−6.085	0.009

Where we obtained an R of 0.930, R^2 of 0.866, adjusted R^2 of 0.812, $F(2,5)$ of 16.089, $p<0.007$, and a standard error of 0.046.

4. Discussion

The finding that ETO-related investment did not significantly affect Q aligns with the theoretical nature of secondary ETO: unlike primary ETO, where design flexibility can generate real options value, secondary ETO merely corrects mismatches produced by standardized procurement. Its economic role is stabilizing rather than value-creating. This finding has important implications for investment planning in the extractive industries, where high capital intensity and uncertainty in both market and geological conditions create elevated risk.

The absence of a significant influence from ETO-related expenses implies their neutral role in the overall economic performance of a multi-project investment. In practical terms, this means that mining companies can initiate ETO projects in response to technical shortcomings of standard equipment without a substantial risk of losing profitability. ETO thus acts as an adaptation mechanism that enhances flexibility and resilience in investment strategies under volatile conditions.

The most powerful influence on economic outcomes arose from π (marginal revenue)—the difference between product price and unit cost. This factor reflects both market conditions and internal operational efficiency. The main investment risks in the mining sector are therefore linked not to engineering costs, but to price fluctuations and geological variability.

In real practice, π is a volatile indicator. For example, according to global coking coal market data,[30] extraction

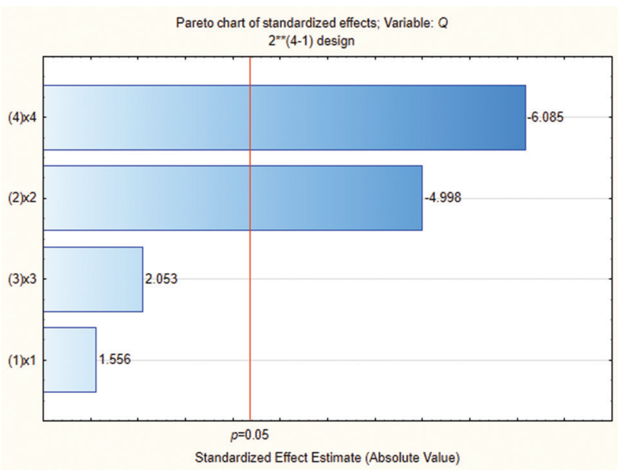

Figure 1. Pareto chart of standardized effects
Abbreviations: DV: Dependent variable; MS: Mean square.

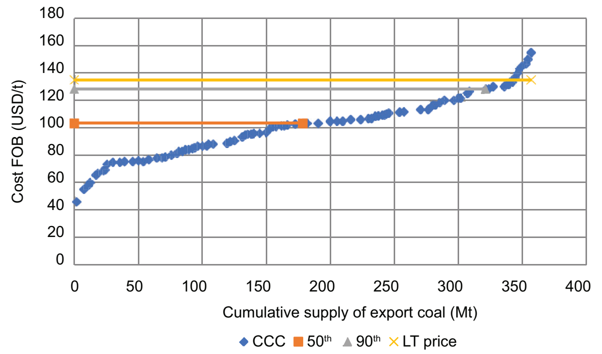

Figure 2. Cumulative cost curve using the example of world coking coal export
Abbreviations: FOB: Free on board; LT: Long term.

costs vary considerably (Figure 2). Given that π (marginal revenue) is the strongest determinant of Q, the variability of global cost structures—illustrated by the cumulative cost curve—directly affects investment risk: the production cost for 50% of cumulative global shipments is $103/ton; for 90%, it is $128/ton; and the average long-term contract price is $135/ton. This means that the marginal income at the 90% threshold is just $7/ton.

The second most significant factor is project duration. The longer the equipment remains in service, the more time is available for amortizing the investment, reducing financial pressure per unit of output. This finding emphasizes the importance of maintaining technical service infrastructure and upgradeability, enabling long life cycles for industrial assets.

While the cost of capital and investment volume (including ETO) were not statistically significant in this case, this does not mean that they are unimportant. These variables remain strategically critical, especially under conditions of limited access to financing. Their lack of significance in this model likely reflects strong compensatory effects from other factors.

In summary, secondary ETO projects, when incorporated as components in a broader multi-project investment, serve as effective tools for correcting deficiencies in base equipment without reducing the overall financial viability of the initiative. This structure is particularly valuable in markets where equipment is procured centrally but operated under high-risk conditions—e.g., geological, technical, and economic. In such contexts, a multi-project configuration with embedded ETO enables more controllable and stable investment outcomes.

The demand for secondary ETO projects becomes especially relevant in standardized procurement environments, where centralized design decisions may lead to the repetition of flawed solutions that prove ineffective in specific operating conditions. Therefore, a critical research task is to develop methods for the early prediction of ETO requirements—even during the procurement phase for serial equipment.

Case Box 1. Decline of Germany's custom-oriented mining equipment sector

During the peak period of Germany's coal industry, a dense ecosystem of mining equipment manufacturers emerged. Strong, localized ties between engineering firms and specific coal mines enabled near-instant customization, effectively eliminating the need for formal ETO procedures. Mechanization tools were developed in close coordination with end users, ensuring seamless operational integration.

However, the gradual closure of coal mines and the broader decline in coal production led to widespread restructuring in the equipment manufacturing sector. Many small firms either closed down or were absorbed by larger industrial groups. This process dismantled the highly responsive and flexible supply network that had previously existed.

Even historically recognized brands—such as Haus Herr und Söhne, once a respected name in coal mining equipment—failed to survive this structural transformation. The consolidation of manufacturing capacity under a few dominant players reduced the availability of hyper-customized solutions and increased reliance on standardized product lines. As a result, the role of ETO re-emerged, but within a fundamentally different industrial and institutional context.[20]

The novelty of this study lies in viewing ETO not as an isolated manufacturing decision but as a functional element of multi-project investment logic in the extractive industries. This reframing opens a new research agenda: the development of models for integrating ETO into investment portfolio management, risk allocation, and budgeting strategies within complex capital initiatives.

5. Limitations

The authors acknowledge the schematic nature of the project investment analysis presented, for example, by using a simplified annuity model of annual cash flow. In reality, cash flows vary significantly over time. Questions remain about the feasibility of ETO projects for loss-making mines and the impact of ETO under different market and geological conditions. Notably, this constitutes

Case Box 2. Industrial clientelism in mining equipment manufacturing (Germany–Ukraine–Poland)[20]

A seminal example of vertically integrated ETO dynamics comes from Germany in the mid-1990s. The non-state mining conglomerate Rheinische Aktiengesellschaft für Braunkohlenbergbau und Brikettfabrikation (RAG)—operating exclusively on public subsidies—established control over mining equipment supply by acquiring key manufacturing firms through its subsidiary Deutsche Bergbau-Technik GmbH (DBT). In 1995, DBT consolidated ownership of three major companies: Halbach & Braun Maschinenfabrik (conveyors), Hermann Heintzmann Maschinenfabrik (roof supports), and Westfalia Becorit (plow systems and supports). This consolidation effectively internalized machinery design and adaptation within the RAG investment cycle, transforming external ETO from a market transaction into an intra-conglomerate engineering response.

This industrial integration enabled German coal operations to reduce internal costs and generate export profits from standardized yet adaptive equipment. RAG's monopolization of the domestic equipment market preceded its emergence as a national mining monopsonist, setting a model for similar structures in Eastern Europe.

In Ukraine, a comparable structure appeared in the early 2000s, when the Ministry of Coal Industry oversaw the creation of Ukrvuglemash—a trade-industrial holding that centralized equipment procurement and manufacturing under direct budgetary control.

In Poland, the attempt to replicate German consolidation initially favored the Famur holding. However, this was later offset by the creation of the ZZM–Kopex Group, illustrating competing tendencies within a subsidized coal economy.

Although DBT was eventually sold to the U.S.-based Bucyrus International, the organizational logic of clientelized engineering integration has persisted—and arguably shaped global standards of control over secondary ETO execution.

a broad research field in which this study only traces the first furrow.

The greatest structural limitation, however, lies in the rigidity of ETO itself in a monopolized mining equipment market. These findings should not be overgeneralized to primary ETO or large-scale capital redesigns, where engineering changes may carry strategic value rather than neutral financial impact. The Case Box 3 illustrates this paradoxical situation.

Case Box 3. "ETO for designers of ETO"—A recursive irony

In 1933, American novelist Nathanael West published Miss Lonelyhearts, a short novel about a young journalist who writes an advice column+ under that pseudonym.[31] The column becomes so successful that other newspapers begin replicating it. Eventually, the protagonist considers launching The Miss Lonelyhearts of Miss Lonelyhearts—a meta-column offering advice to advice-columnists.

This recursive twist mirrors a current paradox in the world of mining equipment: a domain where ETO exists to solve non-standard engineering challenges—yet standardization itself frequently fails, particularly when centralized procurement enforces uniformity across highly diverse geological realities.

As a result, OEMs and engineering teams tasked with executing ETO projects increasingly find themselves in need of second-order adaptations—custom solutions for their own custom solutions. It is as if the time has come to launch ETO for the designers of ETO.

6. Conclusion

The key contributions of this study include (i) introducing the category of secondary ETO projects in mining machinery, (ii) demonstrating through statistical analysis that their costs are not significant for small-scale projects (below 10 million USD), and (iii) highlighting implications for the broader practice of investment planning under geological uncertainty. These clarifications strengthen both the theoretical framing and the practical relevance of the study. The novelty of this study lies in viewing ETO not as an isolated manufacturing decision but as a functional element of multi-project investment logic in the extractive industries. This reframing opens a new research agenda: the development of models for integrating ETO into investment portfolio management, risk allocation, and budgeting strategies within complex capital initiatives. By embedding secondary ETO within the logic of multi-project investment, the study reframes engineering adaptation as a structured risk-management tool rather than an ad hoc technical intervention.

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Conflict of interest

The authors declare that they have no competing interests.

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ARTICLE

Smart safety: From regulation to innovation—rethinking jockey safety vests through design-led wearable technology

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Abstract

User-centered design addresses end users' needs to ensure effective product deployment. Unlike previous methods, this process focuses on addressing technology-related issues without considering ethical or sociocultural factors. As a result, radical product innovation continues to capture the interest of design scholars and experts. Contemporary advancements in technology and materials have significantly influenced the development of personal protective equipment (PPE) in sports, with a growing emphasis on enhancing athletes' well-being. Within equestrian disciplines, PPE such as safety vests for jockeys plays a critical role in mitigating physical risk. While prior research has examined the physiological, cognitive, and performance-related aspects of horse riding, a notable gap remains in understanding how the design of jockeys' PPE can effectively reduce the severity of sustained injuries. This study investigates the current limitations and future potential of jockey safety vests through the lens of material innovation, wearable technology, and design regulation. Drawing on a case study within the Australian regulatory context, this research identifies a critical tension between safety standards and innovation, suggesting that rigid compliance frameworks may inadvertently hinder the evolution of high-performance protective equipment. The study proposes a design-led approach to rethinking jockey vests as intelligent wearable systems—incorporating flexible sensors and smart materials—to enhance injury prevention, improve post-accident outcomes, and offer actionable data for both medical professionals and insurers. The study advocates for a shift toward more dynamic product standards that support design experimentation and user-centered innovation in sports PPE, thereby serving as a foundational step for future research and applications.

Keywords: User-centered design; Design thinking; Personal protective equipment; Design; Design innovation; Sports product design

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1. Introduction

In the pursuit of optimizing athletic performance and minimizing injury risk, sports scientists continually explore emerging technologies, data-driven platforms, advanced materials, and therapeutic innovations. Within this context, the design of health-related products has increasingly emphasized the application of user-centered design (UCD) and human-centered design (HCD) methodologies. These approaches foreground the designer's responsibility to engage deeply with users' values, needs, and evolving conditions. As such, designers play a pivotal role in translating user insights into meaningful innovations that respond to the dynamic landscape of sports health and safety. Currently, interactive systems developed for work, education, and recreation fall under the broad category of HCD systems. Numerous international enterprises increasingly recognize the importance of innovation in maintaining continuity and thriving in the market. Specifically, innovation is essential for improving product performance and delivering customer benefits; as a result, designers play a pivotal, yet sometimes underappreciated, role in creating and implementing innovations in response to changing user needs and demands. Despite several calls and efforts to precisely define secondary and tertiary users through UCD methodologies, this aspect remains insufficiently addressed.[1-4] Co-design and participatory design methodologies have gained widespread traction across diverse sectors, including business, health care, government, and education, due to their capacity to foster inclusive, context-sensitive innovation. These approaches emphasize collaboration between designers and stakeholders, positioning users not merely as recipients of design outcomes but as active contributors throughout the design process. Their growing adoption reflects a broader shift toward democratizing design, whereby the lived experiences, insights, and aspirations of end users inform and shape design decisions. This participatory ethos enhances relevance, usability, and acceptance of design solutions and underscores the strategic value of stakeholder engagement in addressing complex societal challenges.[5-7] While established models and design principles for engaging diverse, multidimensional stakeholder groups remain limited, co-design is increasingly acknowledged as a foundational methodology for addressing complex, transdisciplinary challenges.[8]

Human lifestyles and habits have changed significantly since the coronavirus disease 2019 epidemic; in particular, healthcare systems have been increasingly compelled to deliver services within home environments.[9] As a result, technology has become increasingly important in meeting these demands and enhancing safety and quality of life for patients and caregivers alike. Wearable health technologies and activity trackers have grown in popularity, supporting the premise that the data they generate may enable medical practitioners to provide higher-quality care. The integration of Internet of Things (IoT) technologies, the miniaturization of wearable sensors, and advances in computational capabilities have collectively transformed contemporary medical care. These developments enable real-time monitoring, personalized diagnostics, and data-driven interventions, offering unprecedented precision and responsiveness in both clinical and preventive health contexts. As sensor technologies become increasingly compact and powerful, their application in healthcare continues to expand, supporting remote patient management, rehabilitation, and performance optimization with greater efficiency and accessibility.[10,11] The proliferation of wearable technologies has enabled the real-time collection of extensive biomechanical, physiological, and biochemical data from athletes. However, despite the availability of these advanced tools, the precise relationship between the data they generate and actual injury risk remains poorly understood.[12] This disconnect presents a challenge for designers and sports scientists alike, as it limits the translation of raw sensor outputs into meaningful insights that can inform the design of protective equipment, training protocols, and health interventions. Addressing this gap requires interdisciplinary research to establish validated frameworks linking sensor-derived metrics to specific health outcomes. Such frameworks would enhance the relevance of wearable technologies in sports contexts and support the development of more targeted and effective personal protective equipment (PPE). By aligning technological capabilities with evidence-based indicators of athlete well-being, designers can better respond to the nuanced demands of high-impact sports and contribute to safer, more informed athletic environments.

PPE remains the primary means of ensuring athlete safety during sports participation, and wearable technology has increasingly demonstrated its potential in sports for early injury prevention. Sports involve varying degrees of risk, whether in contact activities (e.g., football) or individual pursuits (e.g., cycling), and accidents may occur unexpectedly. Each sport presents distinct hazards, and athletes rely on PPE to minimize injury risk while maintaining optimal performance. Helmets, padding, and guards are not optional but essential for preventing catastrophic injury.[13] To date, safety gear has been rigorously engineered to address worst-case circumstances while maintaining performance and comfort. The implementation of appropriate safety measures significantly reduces injury risk, with different sports requiring tailored protective solutions that reflect their unique dynamics and potential hazards. Properly fitted helmets for cycling, hockey, or motorcycling, for example, can be lifesaving in the event of an accident, whereas inadequate protection may result in severe injuries, including concussions and traumatic brain injury.[14-19] The enforcement of reliable and well-designed protective equipment is increasingly recognized as a proactive strategy for injury prevention.

Notably, evidence suggests that a significant proportion of sports-related injuries among young athletes could be prevented through the consistent use of appropriate protective gear.[13] Beyond regulatory compliance, ongoing research highlights how design innovation and the integration of advanced materials have contributed to protective solutions that enhance safety while addressing athletes' evolving performance and comfort needs.[3,20]

Indeed, to protect athletes' safety during sports participation, researchers in this field continually explore novel technologies, data platforms, and therapeutic approaches that can help athletes perform at their peak while reducing injury risk. Even though this approach is typically more technology-driven than user-driven, it remains critical to promote the design and development of unique, tailored solutions that can be applied across as many sports as possible. Given its widespread popularity and the high incidence of injury associated with the sport, thoroughbred horse racing was selected as the focal activity for this investigation. Despite its demanding nature and the inherent risks faced by jockeys, innovation in PPE within this domain remains limited. This observation highlights a critical gap in the design and development of safety gear for high-impact sports, where the integration of advanced materials and UCD principles could significantly enhance protection and performance. In addition, there is limited information available regarding the design of jockey safety vests and the basic data underpinning their standards. Due to time constraints and geographic limitations, the author focused this research on Australian jockeys' safety vests. Consequently, this study examined the design of a specific safety device from a designer's perspective. Notably, there is a lack of specialized literature addressing the design of safety vests for jockeys, particularly in relation to their integration with emerging technologies. This gap presents an opportunity for innovation, as the incorporation of wearable devices and IoT systems into equestrian safety gear holds significant potential to overcome user-related barriers. Such integration could enhance functionality, improve real-time monitoring, and support adaptive protection strategies, ultimately contributing to safer and more responsive equipment tailored to the unique demands of thoroughbred horse racing.

The Australian thoroughbred horse racing industry currently shows a limited capacity to evaluate jockeys' safety vests.[21-24] Issues related to ergonomics and flexibility may be addressed through the development of differentiated designs for female and male jockeys, as well as through the introduction of innovative materials. The ongoing inadequacy of safety vests currently used in Australian thoroughbred racing underscores the urgent need for continuous innovation in protective equipment design. This need is further amplified by the increasing integration of wearable technologies in sports, which offer enhanced functionality, adaptability, and UCD potential.[3] Jockeys operate under uniquely demanding conditions—racing at speeds exceeding 60 km/h atop large, powerful animals—while simultaneously managing both their own and their horses' performance.[25] Compounding these challenges are strict weight regulations, which often necessitate extreme weight-control practices that may adversely affect physiological and cognitive function, as well as overall health and performance.[26] Unlike athletes in other disciplines, jockeys must maintain peak physical condition and minimal body weight year-round, with no off-season for recovery or recalibration.[27] Collectively, these factors highlight the critical importance of advancing PPE design to better support the safety, health, and performance of jockeys.

Globally, professional thoroughbred horse racing is a highly competitive, hazardous, and popular sport in which jockeys participate in a large number of races per year. In response, Australia mandated the use of safety vests for riders in 1998, with the aim of reducing jockey injuries. Nonetheless, the restrictive nature of Australian product standards—many of which have been revised infrequently over recent decades—has constrained both radical and incremental innovation. While the growing adoption of wearable technologies across other sporting disciplines (driven by their enhanced functionality and design adaptability) underscores the need for continued innovation in protective equipment, this momentum has yet to meaningfully extend to jockey safety gear. The absence of comparable advancements in this field highlights a critical opportunity for new design interventions that leverage emerging technologies to address the unique demands and risks associated with thoroughbred horse racing. Accordingly, this study presents findings from the author's initial Australian study involving jockeys and related medical professionals, aimed at understanding how safety vests might incorporate wearable technologies and advanced materials to support injury mitigation strategies. As a qualitative ethnographic study conducted from a designer's point of view, the data gathered informed a call for revisions to existing standards and the application of a newly proposed conceptual framework intended to guide the design of a wearable technology-enabled safety vest. To address users' needs, the author adopted a problem-solving design approach, emphasizing the significance of user-driven product development and highlighting how, in some cases, existing product standards may impede innovation.

1.1. A risky profession: A brief overview of thoroughbred horse racing and its risks

In the highly competitive landscape of contemporary sports, athletes continually seek performance-enhancing advantages through the strategic selection of equipment. The integration of advanced technologies into PPE and sport-specific gear has become central to this pursuit. From speed-optimizing running shoes and precision-engineered golf clubs to sensor-embedded basketballs and intelligent soccer balls that are capable of tracking performance metrics, equipment design now plays a pivotal role in shaping athletic outcomes. These innovations not only support physical performance but also reflect the evolving intersection of design, data, and user experience in sports contexts. Sports vary considerably in their characteristics and associated risks. Athletes may be exposed to hazards arising from the playing environment (e.g., obstacles or barriers) or from interactions with other competitors. During high-impact incidents, athletes may experience forces sufficient to cause fractures, permanent injury, or even death. The use of appropriate PPE can therefore decrease the risk and severity of injury. Common forms of sports PPE include equipment designed to protect against impact forces, e.g., helmets, knee or elbow pads, and body protectors. Selecting suitable PPE is essential, as different types of sports are tested under varying conditions. Although PPE cannot entirely eliminate the risks of sports, it plays a vital role in safeguarding athletes' health in both recreational and competitive contexts.[28-30]

Following a general consideration of high-impact sports and the role of PPE design in injury reduction, the author identified a clear need for focused research in the field of thoroughbred horse racing. Today, horse racing is a major global enterprise with a long history, including documented horse competitions dating back to the Roman Empire. Historically, horses have relied on their innate agility and speed to evade threats, traits that remain deeply embedded in their behavior. Despite extensive training and domestication, these characteristics contribute to their beauty and power while also rendering them inherently unpredictable, especially in high-pressure environments. Consequently, being a jockey remains a perilous profession. Empirical research demonstrates that sudden and unpredictable movements in ridden horse behavior, such as spinning, leaping, or abrupt halts, pose significant risks not only during high-speed racing but also during transitional activities such as warm-ups. These incidents can lead to rider destabilization and injury regardless of the training or experience level of either the horse or the jockey.[31] Racecourse environments further compound these risks, as external stimuli such as changing weather conditions, vibrations, and sounds produced by built structures or signage may startle horses. When unmitigated, such design-related factors can directly compromise rider safety. Whether competing on a country track or at a large metropolitan meeting, jockeys are primarily focused on crossing the finish line first, race after race. While jockeys are aware of the dangers inherent in their profession, they often accept that their career may end abruptly as a result of a serious fall. Moreover, repeated success and the associated adrenaline may compel jockeys to remount quickly after injury, perpetuating cycles of physical risk and vulnerability.[32] As former jockey Brian Rouse observed, thoroughbred racing can be likened to "driving a car with no brakes. If you make a mistake, you cannot rectify it in one stride."[32(p288)]

In response to the high incidence of injuries in thoroughbred racing, the Australian Racing Board (ARB) introduced mandatory safety standards in 1998, requiring all jockeys—regardless of gender—to wear protective vests compliant with ARB 1.1998 and the European Standard EN 13158.[33(p69)] These regulations represented a major step toward establishing safety protocols in the sport. The mandated vest designs specifically focus on protecting vulnerable anatomical regions, including the rib cage, abdomen, and spine, during both training and racing. An example of an approved vest used in Racing Australia (RA) is shown in Figure 1.

Currently, RA recognizes the following safety vests as approved: (i) Hows Racesafe; (ii) Ozvest; (iii) Racelite Pro; (iv) Vipa; (v) Vipa 1; (vi) USG Flexi Race; and (vii) Airowear Swift. In addition, the following Level 2 safety vests are approved: Vipa II, and the following Level 3 safety vests are approved: Vipa III.[33(p69)] Despite their crucial role in injury prevention, the standards governing jockey safety vests in Australia have

Figure 1. The Racelite jockeys' safety vest.[32]

undergone little revision over recent decades. These limited updates have neither delivered significant benefits to users nor enabled the incorporation of new technologies such as smart textiles or embedded sensors, thereby leaving wearers exposed to potentially preventable risks.[34,35] Concurrently, the increasing number of female jockeys highlights the need for ergonomically responsive designs that accommodate diverse body types and performance needs.[36] It is also important to note that safety vests and helmets are regulated under separate standards by different organizations, which may result in inconsistencies in protection and design coherence across essential safety equipment.[33] Previous research examining the type and frequency of jockey injuries has called for more effective safety vest designs.[37,38] This is crucial given that, in the event of a fall, jockeys most commonly experience soft-tissue injuries and/or fractures, particularly to the following regions:

> "lower limb injuries (range, 18–25%), followed by injuries to the face, head, and neck (range, 16–21%); shoulder (range, 17–18%); upper limb (15%); and back (range, 9–14%)."[39(p1)]

To adopt a holistic approach, the author investigated the design of jockeys' safety vests worn in Australia by first examining how users engage with existing models—both in terms of their on-track performance and in relation to other wearable equipment such as helmets or silk tops. As users ultimately determine the effectiveness of a product, their understanding and needs are central to the design process. Within this framework, design thinking provides continuity from problem identification to ideation, and, ultimately, solution development. Accordingly, the study focused on safety vests, their primary users (jockeys and associated medical professionals), and the Australian product standards that shape, and at times constrain, the trajectory of design innovation.

In the context of Australian flat racing, injury rates among jockeys remain alarmingly high. Over one-third of the nation's 860 professional jockeys require medical attention annually due to race-related incidents, with approximately 40% experiencing falls that result in an average absence from competition of 5 weeks. These interruptions affect not only physical recovery but also financial stability, particularly for jockeys without comprehensive insurance coverage, placing additional strain on their families.[40] Longitudinal data reveal that 89% of jockeys have sustained at least one medically significant fall, with many experiencing long-term or permanent disability. Falls occur at a rate of 0.45/100 rides and may result in severe or fatal outcomes.[41] In response to these risks, every race meeting is attended by medical teams comprising doctors, ambulance officers, and critical care nurses, who follow each race in dedicated trackside vehicles to provide immediate intervention.[42-44] Against this backdrop, the author's study represents a pioneering effort to engage both jockeys and medical professionals in a user-driven exploration of safety vest design. Employing a research-through-design methodology, the study sought to generate insights through iterative design practice, emphasizing co-creation and contextual responsiveness. The findings suggest that current safety vests fall short of providing adequate protection and that the integration of advanced technologies—such as smart textiles and embedded sensors—could significantly contribute to reducing injury severity and recovery time.[3]

1.2. Available knowledge of safety vest standards

Jockeys' safety vests are specifically engineered to shield the rib cage and portions of the abdomen to reduce the risk of severe injury during falls or collisions. The regulatory foundations for these garments can be traced to the United Kingdom (UK), where, since 2001, jockeys have been required to wear protective equipment compliant with the European Standard EN 13158.[45] This standard established performance benchmarks for impact absorption, coverage, and durability, thereby formalizing the integration of safety vests into professional horse racing. From a design-thinking perspective, such regulations serve a dual role: They safeguard minimum safety requirements while simultaneously constraining opportunities for innovation. Designers must therefore balance regulatory compliance with creative exploration, negotiating the tension between meeting prescribed performance criteria and addressing the evolving needs of jockeys in terms of comfort, ergonomics, and integration with other racing apparel. In this way, the vest exemplifies how product design in high-risk sports is shaped at the intersection of human experience, material technology, and regulatory governance.

To contextualize the Australian standards for jockey safety vests, which are largely derived from UK ones, the author developed a concise overview of their historical and technical evolution. These standards have their roots in the UK, where the European Standard EN 13158 was developed.[45] In the UK, equestrian safety has been shaped through collaborative efforts between the Shoe and Allied Trades Research Association (SATRA) and the British Equestrian Trade Association (BETA). The BETA standard, first introduced in 1991 with input from medical experts, represented a significant advancement in protective garment design. Subsequent updates introduced more rigorous impact testing protocols and incorporated a dedicated protective zone for the C7 vertebra, located at the base of the cervical spine, reflecting increased sensitivity to anatomical vulnerabilities.[46] BETA standards align with the European norm EN 13158:2009 and mandate annual retesting of garments by certified laboratories, such as those operated by SATRA, to ensure material integrity and consistent performance.[45,47] These requirements have directly influenced manufacturing practices, particularly in zipper design and the structural configuration of center-back panels, which must remain continuous and meet specific dimensional criteria. As a result, contemporary safety vests often feature modular foam paneling with strategically placed gaps to optimize shock absorption while maintaining compliance. Importantly, the UK framework incorporates participatory governance, with rider representatives holding voting rights on both the BETA Body Protector General Committee and the BETA Standard Committee. This inclusive approach contrasts with the Australian system, where comparable stakeholder engagement in standard-setting processes is largely absent. The UK model thus offers a compelling example of how user-informed regulation can foster more responsive and contextually attuned design outcomes in high-risk sports.

In 2018, BETA released a revised version of its safety standard, formally adopting it as the new benchmark for equestrian body protection. This update reflects ongoing efforts to align protective equipment with evolving safety requirements and industry best practices. All criteria of the relevant European standard (such as EN 13158) are satisfied by the 2018 Body Protector Standard.[45,47] Notably, this revision applies broadly to "body protectors" and is not specific to jockeys. BETA has stated that the level of protection provided by the 2009 and 2018 versions is equivalent in terms of performance. However, from January 2024, several disciplines and rider organizations will no longer recognize the 2009 version, which ceased production at the end of 2018. BETA withdrew approval of the earlier standard due to the advanced age of some garments still in use—up to 13 years old—and because regulations must apply uniformly to all clothing bearing the same certification label. The BETA standard outlines precise criteria for shock absorption, delineates the anatomical regions requiring protection, and mandates minimum spacing between internal foam panels to ensure safety.[45,47] Moreover, shoulder protectors are now governed by a dedicated BETA standard. Research on falls during eventing competitions (though not specific to jockeys) suggests that shoulder protection can minimize the risk of collarbone fractures by up to 80%. BETA further recommends that body protectors be replaced every 3–5 years, depending on usage frequency and garment care.[45,47] The impact-absorbing capacity of foam materials may deteriorate over time, particularly after repeated falls, potentially compromising future protective performance.

In Australia, RA introduced dedicated safety vest regulations in 1996, developed in collaboration with Human Impact Engineering. These criteria were mostly based on the SATRA standard.[46] Climatic differences between Australia and the UK were a primary motivation for developing the Australian standard ARB 1.1998. While much of SATRA's original language was retained,[46] adaptations were introduced to accommodate Australia's warmer climate. As noted by Gibson, because "the water retention requirement was deleted and the temperature specified for hot weather testing was reduced from 50°C to 40°C."[46(p7)] In addition, because jockeys often adopt a crouched posture during races, Gibson recommended lowering the upper back section of the vests to create more space between the vests and helmet when in this position.[46,48] Consequently, ARB 1.1998 received certification from Standards Australia in 1998.

At present, two safety vest standards are recognized in Australian thoroughbred racing: ARB 1.1998 and the European standard EN 13158.[34(p69)] In July 2014, RA formally discontinued the SATRA standard but retained ARB 1.1998, which had originally been derived from SATRA's framework. A key distinction between these standards is the omission of the narrow bar impactor test, a critical assessment included in both SATRA and EN 13158, from the ARB standard. This omission highlights a potential opportunity for design advancement, as explored in this study, by revealing areas where current testing protocols may be insufficient to ensure optimal protection. In contrast, EN 13158 fully integrates the technical components of the BETA standards, offering a more comprehensive and rigorous approach to safety validation. Further differences exist in the minimum padding areas required by SATRA/ARB standards compared to those mandated by EN standards. Moreover, the thickness and materials utilized in current jockey safety vests do not account for the integration of sensors or advanced materials. A principal barrier to such innovation lies in the Australian standards, which have undergone minimal revision since their introduction. This stagnation creates a cyclical constraint on innovation. Even when jockeys compete internationally, they are required to wear the authorized equipment of the host country. While jockeys seek optimal balance between comfort and protection, Australian regulatory frameworks remain anchored to the ARB 1.1998 standard—aligned with the European EN 13158 specification established nearly three decades ago—thereby constraining contemporary design innovation and technological advancement in protective equipment.

2. State of the art

Recent advancements in sports PPE have increasingly incorporated smart materials, sensor technologies, and biomimetic design principles to enhance performance, safety, and the user experience. In disciplines such as cycling, football, and motorsports, wearable devices are now routinely used to monitor physiological data and to support injury prevention. However, the thoroughbred racing industry has yet to fully adopt these innovations, particularly in the design of jockeys' safety vests. Existing standards remain largely static and do not reflect the potential of emerging technologies or the nuanced needs of diverse user groups. While prior studies have explored the integration of advanced materials and data analytics in sports medicine, few have addressed the unique ergonomic and regulatory challenges faced by jockeys. This study builds on these developments by proposing a UCD approach, guided by the author's proposed dependency-based user experience (D-UX) framework, to reimagine safety vests as smart, responsive systems aligned with both medical and performance requirements.

2.1. Summary of the literature review

The literature on PPE in high-impact sports reveals a growing emphasis on innovation, particularly through the integration of smart materials, wearable technologies, and UCD approaches. In disciplines such as motorsport, cycling, and alpine skiing, iterative design processes have led to significant improvements in injury mitigation.[49-55] These advancements are often supported by evolving international standards, such as EN 1078 and FIA 8856-2018, which guide the development of helmets, body armor, and sensor-enabled gear. Recent developments in sports technology highlight the growing role of wearable sensors in enhancing both safety and performance monitoring. Devices such as accelerometers, inertial measurement units, and heart-rate monitors are increasingly used to track biomechanical and physiological parameters in real time.[56] These systems can detect impact forces that exceed concussion thresholds, monitor indicators of physiological stress, and provide early warnings for conditions such as heat exhaustion and fatigue.[57,58]

Despite these developments, the design and regulation of jockeys' safety vests remain notably under-researched. Studies indicate that jockeys experience disproportionately high rates of concussion, spinal trauma, and long-term disability.[3] However, the standards governing their protective equipment, such as EN 13158 and ASTM F1937, have remained largely unchanged for decades.[58-63] This stagnation has hindered the adoption of lighter, more flexible materials and wearable technologies that could enhance safety, comfort, and personalized injury monitoring.

The thoroughbred racing industry presents unique challenges. Jockeys experience frequent falls at speeds exceeding 60 km/h, often resulting in severe injuries.[64] Unlike athletes in other sports, jockeys maintain peak physical condition year-round due to the absence of an off-season, placing additional demands on their PPE. Although safety vests are mandatory, their design has not kept pace with technological advancements or ergonomic needs. Existing standards tend to prescribe fixed design features rather than functional outcomes and may inadvertently limit the diversity of available technologies, products, services, and processes on the market.[59,60-62] As a result, jockeys—particularly in Australia—often rely on a narrow range of standardized products. Thermal discomfort and restricted mobility are commonly reported issues, suggesting a need for more flexible, breathable, and responsive materials. HCD and user experience design (UXD) approaches, which emphasize iterative prototyping, ergonomic testing, and user feedback, have been proposed as means of improving the usability of jockeys' PPE.[65] However, in regulated sports environments, designers must navigate complex stakeholder requirements, balancing athlete needs with compliance obligations.

Overall, the literature underscores a critical gap in the design and standardization of jockeys' safety vests, particularly in Australia. While the sport contributes significantly to national and global economies, the protective equipment used by jockeys remains outdated and inconsistently regulated. Much of the reporting and advocacy for safety improvements originates from non-academic sources. Based on these findings, the author has consistently emphasized the need for prototype development and the integration of smart technologies into jockeys' safety vests. While such advancements present significant opportunities, they also pose challenges. Effective implementation requires careful consideration of sensor placement, material compatibility, and ergonomic factors to ensure accurate data collection without compromising protective performance or user comfort.

3. Materials and methods

The author began with the intention of clarifying how the term "design" is understood within usability-focused research. Over the years, the noun "design" has been the subject of numerous attempts to establish a standardized definition.[66] However, it remains a dynamic concept, closely linked to product development processes and esthetics. Although the author engaged with only a small portion of the Australian jockey population, the insights gathered were sufficiently significant to warrant further research in this field. Because no illness was directly implicated, this study does not fall within the scope of epidemiological research. Instead, it adopts a qualitative, user-centered approach to explore the lived experiences and insights of 20 participants, including jockeys and medical professionals, regarding the design and performance of PPE, specifically safety vests used in the Australian thoroughbred horse racing. While epidemiological studies could have provided an additional source of inspiration, particularly from a medical or injury-prevalence viewpoint, this research prioritized the users' experiential perspective. This approach enabled the examination of the product through direct user interaction, taking into account how contextual factors influence the user–product relationship.

Case studies have several applications, and it is critical to define the case and establish its underlying logic from the start.[67] Qualitative research methods are particularly well-suited to achieving a comprehensive understanding of complex issues. Accordingly, the author adopted a qualitative approach for this instrumental case study, aiming to generate new insights into the design and functionality of jockeys' safety vests. The research was guided by questions that emerged through four key phases: (i) Recognition of the situation that prompted the case study, (ii) the initiating phase, (3) data collection, and (4) reaffirmation of the study's purpose.

By employing an instrumental case study, the author was able to develop contemporary knowledge and propose new ideas regarding the usability of safety vests. This approach also enabled the case to serve as a reference point for analogous situations in which similar phenomena may occur. Throughout these phases, the study revealed a notable scarcity of existing literature on the topic, thereby justifying the use of a qualitative methodology and inductive theory-building. This process allowed the author to move from specific observations toward broader theoretical premises. Importantly, the author pursued a holistic understanding of participants within their social and cultural contexts. The integration of ethnographic techniques within the qualitative framework enabled participants to be observed within their cultural environments, positioning them as active contributors to the research process.

3.1. Understanding the feasibility of a UCD approach for sports PPE

The term "design" encompasses a wide variety of disciplines and carries different implications depending on the context in which it is applied. In English, "design" functions as both a noun and a verb. As a noun, it signifies a tangible, typically human-made artifact, as well as an idea or pattern, and encompasses the ways in which it is interpreted and engaged with through human interaction. When used as a verb, "designing" refers to the mental and practical processes involved in establishing a design.[68] The concept has a long history across fields such as architecture, industrial design, product design, fashion, and graphic design, with each discipline defining the design process through its own specific nuances. Accordingly, the foundations of design often reflect the creative intent of the designer. In artisanal works, this expression typically emerges at the culmination of the craftsmanship, whereas in industrial design it is embedded from the outset of the process. Within the domain of industrial products, only those that deliberately pursue an esthetic objective during the design phase are generally considered to fall within the scope of design.[69]

The concept of "good design" encompasses a wide range of interpretations. It extends beyond visual appeal to include the capacity of a product to generate positive user experiences. A well-designed product integrates esthetic quality, functional performance, and technical construction, while also embodying symbolic and cultural significance.[70] Empathy lies at the core of effective product design, as it provides the most reliable means of understanding what users see, experience, feel, and hear. Consequently, it is critical to examine users' environments, habits, anxieties, and relationships. Through this empathetic approach, designers can uncover latent needs that shape user behavior. Users' decisions are influenced not only by good design and positive experiences but also by external factors such as advertising, which can prime preferences and elevate certain products as first-choice options.[71]

Ultimately, every user is an individual who engages with products and contexts in uniquely personal ways. Needs vary according to personal circumstances, physical abilities, and lived experiences. To foster innovation and ensure successful outcomes, designers must actively listen to users and strive to make products accessible to the widest possible audience, thereby advancing the principles of inclusive design. This process reflects a designer's empathetic commitment to understanding the diverse expectations users bring to their interactions with a product. When these expectations are met, a high level of usability can be achieved. Numerous industrial products, such as the iPhone, Vespa scooters, and the Wassily Armchair (Model B3), exhibit formal qualities that communicate their function through recognizable semantic elements, enabling intuitive user understanding.[4] Therefore, a holistic understanding of users, combined with the iterative generation of creative ideas, is essential for identifying market opportunities and supporting robust product design. While esthetic quality remains important, it must be accompanied by a positive and meaningful user experience.[72,73]

Recognizing the value of user-centered perspectives is essential, as they offer robust methodologies for understanding how users assign meaning to products. Innovation in this context typically follows two strategic pathways: One driven by breakthrough technologies and the other by enhanced product solutions informed by in-depth analyses of user needs.[74] The industrial design process is inherently problem-solving, aiming to foster innovation and improve quality of life through the creation of sophisticated products and meaningful experiences. At its core, innovation arises from the interplay between technological advancement and creative exploration, leading to the development of new goods and services.[75] Designers may pursue radical or incremental innovation; however, evidence suggests that the extent of product innovation varies across countries due to differences in regulatory standards. According to the author's study, such standards may limit innovation in certain contexts. In particular, the examination of jockeys' safety vests within the Australian racing industry revealed that existing standards constitute a significant barrier to the adoption of smart wearable technologies in PPE, a limitation consistently identified by study participants.

3.2. Empathy and design thinking in product redesign

Despite the widespread use of technology in everyday life, various potential applications remain underdeveloped. Knowledge often becomes siloed within specific disciplines, limiting the exposure and integration of new ideas. Designers who demonstrate empathy toward users are better positioned to embed inclusive design principles into their processes, addressing diverse user contexts and creating mainstream products that are not only functional but also desirable, delightful, and emotionally satisfying for a broad audience.[76] While engineering designers typically approach problems from a predominantly technical standpoint, industrial designers tend to prioritize user-centered methodologies. When grounded in users' everyday experiences and desires, HCD evolves into a powerful interpretive tool capable of decoding emotional responses and informing problem-solving strategies.[77] In recent decades, the convergence of usability and enjoyment has gained increasing attention, as emotional engagement with products significantly influences user behavior.[78] This trend underscores the complex and evolving relationship between humans and their environments—an interaction shaped by cultural, social, institutional, and historical factors.

The author's research design was grounded in Forlizzi's theoretical framework,[79] which provided a lens for understanding how products elicit social behaviors and offered methodological guidance for selecting appropriate research techniques. This framework also fostered a design-centered perspective within interaction design research. Recognizing that each user is unique and experiences products differently, the study employed the concept of product ecology alongside this framework to deepen the understanding of what a product is and what it has the potential to become.[79,80] Within this context, user experience is interpreted through three symbolic dimensions: Esthetic pleasure, emotional resonance, and symbolic meaning. The latter encompasses memory recall, identity expression, perceptions of typical users, value alignment, and social connectedness. Users bring prior experiences and expectations into product interactions, shaping enduring patterns of use and meaning.[81] This nuanced understanding of user needs and experiences was validated as both appropriate and essential for the case study.

3.3. Literature search/data collection phases

Building on the preceding discussion, the author adopted an ethnographic approach to examine a niche PPE product (safety vests for jockeys) from the users' perspective, framing the study as an inside-out design investigation. The focus on jockeys' safety vests was intentional, given their critical role in shaping and implementing product innovation within the sport. The study concentrated on the products, their users, and the standards that have emerged in response to constraints on design progression. Drawing inspiration from Harte *et al.*'s definition of UXD as "the perceptions and responses of users that result from their experience of using a product or service,"[82(p2)] the author applied this framework to identify the broader user ecosystem influencing the development of these products. Given the specificity of both the user group and the product category, the author justified the sample size using three accepted strategies in qualitative research: Referencing methodological guidance from qualitative scholars, aligning with sample sizes from comparable studies, and demonstrating internal validity through saturation within the dataset.[83] Accordingly, the sample of 20 participants (including apprentice jockeys, professional and retired jockeys, medical professionals, and paramedics) was deemed sufficient to achieve saturation, supported by Marshall *et al.*'s[83] recommendations and additional contextual factors.[84]

As an early investigation into the design of PPE for sports, the study's qualitative research design was carefully constructed to explore participants' lived experiences and perceptions of safety vests. This approach enabled the collection of rich, contextual data and provided insights into the potential integration of wearable technologies within the sector. Acknowledging the potential for researcher bias inherent in qualitative inquiry, the author employed multiple data collection methods to ensure trustworthiness and validity across diverse participant responses.[85] Grounded in a constructivist epistemology, the research design embraced a qualitative, interpretive, and sense-making approach to guideline development. It emphasized contextual meaning and utilized instruments sensitive to latent insights. The study commenced with desk research, drawing from both academic literature and industry sources, to trace the historical evolution of safety vest design. This foundational work clarified user needs and informed subsequent participant engagement.

The publications considered in this study were identified via online databases (e.g., PubMed, Google Scholar, Scopus, Web of Science, ProQuest, Elsevier, and SpringerLink) and were published between 1968 and 2018. The search strategy applied a mix of keywords (e.g., safety vests, body protectors, jockeys, horse riders, wearable technology, design of PPE, PPE for jockeys, injuries, and design innovation in horse riding). Following the initial collection of sources, duplicate entries were removed. Given the limited availability of peer-reviewed literature in this niche field, the author also included relevant materials from gray literature. Titles and abstracts were first screened to ensure alignment with predefined inclusion criteria. Only articles meeting the selection standards were read in full and assessed for inclusion in the literature review. The selection criteria were: (i) Publication in English-language journals, (ii) relevance to jockeys as the target user group, and (iii) classification as either original research or a literature review.

Participant recruitment focused on individuals closely associated with flat racing in metropolitan Melbourne (Victoria, Australia), including apprentice and professional jockeys, retired jockeys, and related local medical experts. After forming the participant group, the study proceeded with semi-structured interviews conducted primarily between July and November 2016. These interviews aimed to uncover user needs and perspectives related to safety vests. Before data collection, ethical approval was obtained from a subcommittee of Swinburne University of Technology's Human Research Ethics Committee.

During the interviews, the author employed a combination of standardized and open-ended prompt questions to guide discussion while allowing participants the freedom to share unstructured insights. This approach enabled the exploration of participants' values, experiences, and knowledge relevant to the research topic. Two types of prompts were used to accommodate the varied backgrounds of participants. Preliminary data analysis was conducted using a qualitative analysis software, NVivo (version 12, QSR International Pty Ltd, 2018), to assess the reliability and thematic consistency of responses. These initial findings informed the structure of a subsequent focus group,[86,87] which provided a platform for deeper discussion about the safety vests used throughout participants' careers. The familiarity established during earlier stages of data collection contributed to a comfortable and open environment for dialogue. The overarching aim of the study was to gain a nuanced understanding of the design context and user experiences with safety vests. Identifying user needs and expectations was central to the research, as these insights are foundational to effective design practice.

Subsequently, the author conducted an observation stage (from July 2016 to July 2017), which was performed as a non-participatory method of observing participants directly but without involvement. For many years, qualitative researchers have relied on observation as a primary method of gathering data. Observation is the process of documenting a phenomenon in the field using the observer's five senses, often with the aid of an instrument, for scientific purposes.[88] During this activity, participants are observed and recorded, with their activities, interactions, conversations, and actions noted. Effective qualitative observation engages all five senses—sight, hearing, touch, smell, and taste—as noted by experienced researchers.[89] However, capturing the full scope of sensory input during fieldwork can be challenging. Observers typically begin with broad observations before narrowing their focus to data that directly support their research objectives. In this study, the author conducted field observations in naturalistic settings relevant to participants, including the racetrack, jockeys' room, press room, community spaces, and weights room. Additional sessions were held at Victoria's Apprentices School, various local racing venues, and the Exercise Research Australia center during fitness training. These environments provided opportunities for note-taking and photography, with strict adherence to privacy protocols: Participants' identities were anonymized using coded references, and no personal information was disclosed.

One advantage of this observational method is the researcher's ability to maintain a non-intrusive stance, minimizing influence on participant behavior. Nonetheless, challenges such as time management, the time-intensive nature of observation, and the potential for observer bias were addressed through triangulation during data analysis.[85,90-92] Through this immersive approach, the author gained deeper insight into participants' emotional connections with their equipment and surroundings. All participants were over the age of 18 and identified English as their first language. To ensure psychological well-being during the study, individuals with a recent history (within the past 12 months) of anxiety, depression, or other emotional conditions were excluded.

These criteria enabled the careful selection of participants appropriate to the scope and aims of the case study. Overall, participants reported feeling comfortable and welcomed; consequently, almost all jockeys shared with the author that they had experienced at least one fall, which had occurred while wearing safety vests. In contrast, the medical professional participants—all with extensive experience treating jockeys' fall-related injuries—highlighted the need for research of this kind and emphasized how design investigations into sports PPE may benefit medical practice as well as jockey safety.

4. Design innovation in sports PPE: Implications of the findings

Athletes wear PPE to protect their safety throughout sports activities; furthermore, contemporary advanced textiles increasingly incorporate sensors capable of tracking physiological functions like heart rate, breathing, and muscle activation. Given the wide range of sports disciplines, the literature on PPE highlights how contemporary design innovations and advanced materials are being employed to mitigate injury risks among athletes.[65] Within this context, jockeys are recognized as belonging to one of the most hazardous professions, in which safety vests play a critical role in reducing the impact of unforeseen accidents. However, existing jockey safety vests do not yet meet the criteria required to compete effectively in a highly competitive market—such as rapid production cycles, strong process development, and rapid market-entry timing—and current Australian standards appear to be the primary factor slowing innovation or creating obstacles to progress.[33,93] A summary of the core data generated by this study is shown in Figure 2.

The introduction of a new product, whether tangible or intangible, is often referred to as the new product development process. This process typically includes identifying a market opportunity, developing the product, and ultimately launching it. If a product fails to fulfill users' needs, the entire process—and the product itself—is likely to fail.[94,95] To avoid such outcomes, a deep understanding of users' needs is a prerequisite for effective product design. Users bring expectations regarding both functionality and the role of design within the new product development process, an understanding that has been consistently reinforced over time.[96-100] As users rapidly adjust their perceptions of what is meaningful, a singular focus on static solutions becomes less effective, given that the problems being addressed may lose relevance as new needs emerge. Consequently, the ideal objective is to produce the right product, achieved through the interaction of design and technology research.[101-104] Through their interaction with wearable interfaces increasingly integrated into products, users contribute to the creation of new meanings and are progressively invited to participate in the development process.[65,105,106] Moreover, perceptions of innovation from an esthetic perspective are not fixed but

Core findings	Implications	Limitations
Users described safety vests as rigid and restricting their movements	In case of a fall, jockeys must use their fall skills, and this may expose them to a higher level of injuries	This study is based on data gathered; thus, the investigation of riding style may be a limitation
Users complained because safety vests may bump into their helmets during races	Jockeys can have restricted vision, and this exposes them to more risks	The analysis of knowledge available in the field confirmed some data. e.g., details of the process to approve safety vests or its standards are not completely shared with the audience
Users must have faith in those responsible for revising the standards or approving their vests	Despite jockeys being conscious about their risky professions, they need to believe that is something has been approved, it is good for sure	The standards' life cycle is partly hidden or not clearly explained to the public
Users shared concerns about how standards are made, developed, and revised	Jockeys are not involved in the revision and development of safety vest standards. Consequently, their needs are not completely satisfied	Manufacturers and standards have not yet specified why one safety vest template should fit all jockeys. Revisions and updates are missing
Users cried for better-performing safety vests that are easier to remove	Jockeys still experience severe injuries: Thus, the safety vests need a better design	The data shared by standards and manufacturers neglects research for innovative materials applicable to the safety vests
Users demanded for gender-based safety vests	Male and female users may have various body shapes; one vest cannot fit them all	Even if a new prototype is designed, current standards seem to be the obstacles to applying wearable tech and advanced materials to enhance jockeys' safety
Users need a lighter-in-weight vest as possible	Jockeys live under pressure to keep a light weight. Having a lighter safety vest may reduce some of it	

Figure 2. Core findings, implications, and limitations of this study (author's work)

vary according to contextual frameworks. In response to this complexity, the structured application of established design methodologies to emerging problems and opportunities is widely recognized as "design thinking," a versatile approach embraced and adopted across both design and non-design disciplines. Over the past 60 years, businesses have significantly increased their investment in product development, often employing mixed methods of innovation that combine product and process innovation.[107] Nevertheless, certain sports PPE products, such as jockeys' safety vests, continue to face barriers to innovation due to restrictive standards and the limited application of HCD approaches.

The findings of this study underscore the importance of continued research into the design and advancement of jockey safety vests, emphasizing the potential benefits of incorporating cutting-edge materials and wearable technologies already adopted in other sports disciplines. These advancements present opportunities to significantly enhance protective performance, contributing to improved rider well-being, faster recovery times, and reduced injury severity in the event of accidents. Drawing on this case study, the author critically reflects on the regulatory landscape governing safety equipment in Australia. While current product standards play an essential role in ensuring baseline safety, they may also constrain iterative, forward-looking design processes that drive innovation. The research highlights the latent potential for reimagining jockey safety vests as platforms for wearable technology, delivering functional benefits not only to jockeys themselves but also to medical professionals and insurers. This reframing positions product standards and design values not as opposing forces, but as complementary imperatives in advancing protective equipment design.

Within this context, flexible intelligent sensors represent a pivotal technological frontier. These next-generation components surpass conventional sensors in their ability to collect, process, and transmit data within compact and conformable forms. Their capacity to deliver precise, real-time feedback from complex surfaces, such as human skin or soft tissue, has already shown promise in applications ranging from humanoid robotics to healthcare monitoring. Translating these capabilities to sports PPE, and specifically to jockey safety vests, opens new possibilities for embedding intelligence into protective equipment in ways that are both ergonomic and deeply user-centered.

5. User-derived core findings for improved design

Although initially surprised by the inquiry into their experiences with safety vests and the broader context of occupational safety, participants openly reflected on several concerns. They expressed frustration with restrictive product standards, a lack of responsiveness to their feedback, and the absence of opportunities to contribute to the design and development of both the vests and the standards governing them. At the same time, they shared enthusiasm with the author and expressed appreciation for the research. Several participants noted that they continue to envision a brighter future for the field, largely due to the current absence of a UCD approach, as described by one participant:

> … the people doing the test might be engineers and experts in testing equipment, but they are not experts in riding, racing, or dealing with the animals or what we deal with. They are only dealing with numbers, facts, and obviously video footage, but they are not the people actually riding, or the ones actually falling in it.

In general, the participants from the jockey group regarded their safety vests as mandatory PPE rather than as equipment essential to preserving their safety. Given their awareness of the inherent risks associated with their profession, one participant specifically noted experiencing restricted mobility while wearing the safety vest:

> "… for what we do there is always no guarantee… And again, the perception is not that we expect the vest to save our lives…All we want it to do is to help us, not hinder us in a racing incident."

From the jockeys' perspective, unrestricted movement is essential. Their role demands physical agility, such as lowering the head, scanning for approaching horses, communicating mid-race, and instinctively curling into a protective posture during forward falls, which are a frequent type of accident in their profession. Despite advancements in vest design and materials, existing standards often hinder rather than enhance safety, presenting functional challenges that compromise the very mobility jockeys rely on. Current Australian standards tend to generate additional issues rather than offering increased safety, while also limiting the application of advanced materials and sensor technologies. Female participants highlighted the increasing presence of women in the horse racing industry and compared their experiences with those in other high-impact sports, such as motorcycling, American football, and ice hockey. In many of these sports, gender-specific PPE options (like body protectors) have been available for some time. In contrast, while jockeys' safety vests are offered in a range of sizes, they do not provide ergonomic designs tailored to male and female anatomical differences, as one participant reported:

> From a female's point of view or perspective, I think definitely they need to have a male and a female vest. That is my opinion. They do it with all the motorbike gear and all that sort of stuff. The only reason I know is because I used to ride a lot of dirt bikes when I was younger. There is a big difference with the female body suits compared to the male's body suit. Obviously, we have got our breasts and our hips and stuff—our curves. It was all fitted, it was completely different. I just think, as a female, they definitely need to work on that a little bit. Just to make it a little bit more comfortable for us. Also, you want that light vest, but you also want stability and comfort, material-wise, too. So, it is probably saying the impossible, really…

A significant number of participants voiced concerns regarding the protection of the neck and spine, areas that are particularly vulnerable in horse racing. Their feedback highlighted how inadequate ergonomic design in safety vests negatively affects user experience, especially among female jockeys and medical professionals involved in trackside care, both of whom play a vital role in informing design improvements. This research reinforces the understanding that jockeying is a high-risk and highly specialized profession, underscoring the necessity for PPE such as safety vests to contribute meaningfully to injury prevention. Despite this, limited scholarly attention has been given to how vest design might mitigate injury severity. Existing studies tend to focus on broader themes such as rider health, psychological and physiological performance, and general well-being. While the importance of protective gear in equestrian activities is well-documented,[108-111] the literature reveals a gap in research specifically addressing the design and safety implications of these products for jockeys.

Although a substantial body of medical literature exists on horse riding,[112-117] much of it remains tangential to the design-focused concerns central to this study. Health professional participants validated the compulsory introduction of safety vests in Australia as beneficial; however, they emphasized that current designs remain limiting for users. For instance, they reported challenges encountered during emergency care situations, such as assisting injured jockeys after a fall, when rapid decisions are required, and removing the vest from a jockey lying on the turf may be necessary. Moreover, medical studies addressing jockey injuries often compare them with those sustained by motorcyclists or hockey players due to similarities in injury patterns. However, despite these medical parallels, jockeys face unique conditions: They interact with animals, must maintain extremely low body weight, and compete on Australian turf surfaces.

The readers should know that jockeys must wear a combination of PPE products (e.g., goggles, helmets, safety vests, gloves). Despite this, approximately 90% of jockeys participating in this study discussed serious injuries sustained during their careers, reinforcing the concerns raised by medical professionals. Both jockeys and medical professionals expressed concerns regarding inconsistencies in the standards governing safety vests and helmets. Conflicting regulations often result in functional incompatibilities between these PPE products, which may compromise user safety and hinder medical personnel during urgent interventions. Consequently, the author recommends that future research consider the development of harmonized standards applicable to both helmets and safety vests, or alternatively, explore the feasibility of designing a new product. Such advancements may also benefit other horse riders and/or athletes participating in high-impact sports that share similar injury profiles.

5.1. The Martini glass style and the conceptual design framework

To understand the author's recommendations, it is necessary to look back. In the past century, an American jockey named Tod Sloan spent several years perfecting his effective riding style (then called the "monkey crouch"), which seemed unusual at the time but is still widely used by jockeys today. By adjusting his riding technique, shortening the stirrups, and positioning himself high in the saddle near the horse's neck, Sloan played a pivotal role in shaping what is now recognized as the "Martini Glass" jockey posture (refer to Figure 3). This innovation aimed to minimize aerodynamic drag and enhance performance.

Figure 3. The "Martini Glass" riding style (author's work)

Each horse rider understands the importance of a correct posture, and for jockeys, it is crucial because a proper posture allows them to act like a bungee-powered backpack, with their legs acting as the cords. The majority of jockeys, especially during the last 400 m of a race, ride using this posture (also called Martini glass) to let the horses stride freely with minimal weight on their backs. In doing so, they may boost the horse's pace by 5–7%. Insights from motion-tracking technology indicate that jockeys exhibit less movement than the horses they ride, which allows skilled riders to minimize the physical exertion required from the animal, thereby enhancing its performance.[118] To achieve and sustain the Martini glass posture (characterized by a high saddle position near the horse's neck), jockeys undergo rigorous training focused on core stability, lower body strength, and leg control. Effective horse handling also demands exceptional upper-body strength and balance. Although this posture has become internationally recognized as the standard in professional racing, data collected during this study revealed that it is often difficult to maintain due to discomfort caused by safety vests and helmet-related issues.

This research also explored the importance of cultivating empathy in design practice, positioning it as a foundational element in experience-driven design. Similar to qualitative research, empathic design encourages designers to immerse themselves in the user's perspective. In high-risk domains such as horse racing, this empathetic approach, alongside introspection, is frequently overlooked despite its critical role.[119] The study advocates for recognizing design researchers as human participants within the HCD framework, reinforcing the relevance of this methodology to the current investigation. In light of the challenges reported by participants regarding jockeys' safety vests, the author recommends adopting an HCD strategy that prioritizes user perspectives in the development of future products and solutions. This approach ensures that both primary and secondary users' needs are addressed without diminishing the importance of their contributions or access to design outcomes.[120,121]

Although design research often attempts to identify users, there are situations where this might be difficult. In this study, the author found jockeys to be classified as primary users. Although medical professionals interact directly with PPE products, they cannot be classified as secondary users, nor do they fit the definition of tertiary users, as they are not responsible for procurement decisions. In response to this ambiguity, the author introduced a new classification, dependent-based users, to describe individuals whose roles are closely tied to the product but who lack decision-making authority. Based on this insight, the author developed a conceptual framework that extends traditional models such as UCD, HCD, and UXD. This framework, referred to as D-UX, addresses scenarios where users exist outside conventional categories (neither secondary, tertiary, nor stakeholders) but still exert influence through their co-dependent relationship with the product. The D-UX model (refer to Figure 4) is proposed as a flexible tool applicable to a wide range of design research contexts where such user dynamics are present.

There are design scenarios where product success relies not solely on traditional user engagement, whether through personas in UXD or individual-centered approaches in HCD and UCD, but also on the active involvement of a co-dependent user whose role is equally critical. The author proposes that such cases be addressed through the D-UX framework. This model invites further exploration into the concept of co-dependent users, particularly within specialized product ecosystems like those studied in this research. The need for such a framework is especially evident in the context of sports PPE design, where multiple user roles intersect and influence product outcomes.

6. Discussion

Design innovation continues to be a fundamental contributor to industrial growth and market differentiation. While there is no universally accepted definition, design innovation is often regarded as the application of creative design principles to solve challenging challenges and develop unique goods, services, or systems that provide real value to users and stakeholders. It incorporates design thinking, human-centered methodologies, and interdisciplinary collaboration to produce sustainable and scalable solutions.[74,122] In this context, design innovation not only enhances esthetic and functional qualities but also fosters systemic change by reimagining how industries operate and evolve.

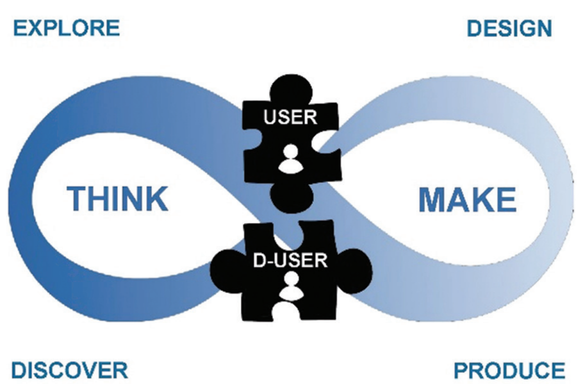

Figure 4. Dependency-based user experience conceptual framework (Copyright © 2019, The Author)[32]

In the thoroughbred horse racing field, the use of design innovation is both implicit and underexplored, particularly in the Australian context. The industry has a substantial global economic footprint, with multibillion-dollar markets spanning breeding, training, wagering, tourism, and media broadcasting.[123,124] Countries, including the United States, the UK, Japan, Australia, and the United Arab Emirates, have developed strong horse racing industries, supported by global breeding initiatives and internationally recognized auctions that draw significant attention worldwide. Elite horses may sell for millions of dollars, and stallions with prominent bloodlines can provide consistent income streams through stud fees.[125] In Australia, the 2024 Spring Racing Carnival held in Victoria generated exceptional economic returns, contributing approximately Australian $785.1 million to the state's economy, the highest figure recorded in a decade of analysis.[126] Beyond its financial impact, thoroughbred racing is deeply embedded in cultural heritage and social customs. Prestigious events such as the Kentucky Derby, Royal Ascot, and Melbourne Cup exemplify this dual significance, functioning both as premier sporting competitions and as major cultural celebrations. These races foster national identity, showcase fashion and entertainment, and attract global audiences, thereby enhancing the symbolic value of the sport.[127,128] The convergence of tradition, competition, and spectacle underlines the enduring appreciation of horse racing worldwide.

However, academic research and industrial innovation in this area have often concentrated on the non-human element, specifically, the horse. Historically, research has prioritized the optimization of equine performance, physiology, genetics, and injury prevention.[129,130] Equine-focused empirical research has been facilitated by the availability of standardized measures, including speed, heart rate, and pedigree data. On the other hand, human participants, such as jockeys, have received very little scholarly attention. Jockeys are frequently viewed as bureaucrats rather than fellow athletes, even though they are essential to performance outcomes. The perception that jockeys are interchangeable, along with the difficulties in portraying the complex demands of their job, may contribute to this underrepresentation. Jockeys must maintain precise weight control, possess sophisticated riding techniques, and make calculated decisions in high-stakes situations due to the tremendous physical and psychological strain they endure.[32,131] Yet, these complexities are often overlooked in favor of equine-focused research paradigms. Consequently, even their sport PPE products are rarely investigated, and their design is neglected. By exploring the human aspects of the sport—such as jockey health, career longevity, gender discrepancies, and the psychological effects of competition—recent studies have started to address this imbalance.[32,131-134] These perspectives highlight the necessity for a comprehensive and holistic approach to understanding the equestrian industry, one that acknowledges the interplay between human users and technological systems through the lens of design innovation. Prior research conducted by the author has emphasized the transformative potential of integrating advanced materials and sensor technologies into jockeys' protective vests.[36,65] Such innovations not only promise enhanced safety but also open avenues for ergonomic improvements inspired by biomimetic principles. Collectively, these developments suggest meaningful benefits for jockeys, ranging from improved comfort and mobility to real-time performance and impact monitoring.[3,32,36] Despite this potential, progress in the field remains limited; meanwhile, product design in other sports is evolving rapidly.[52,135-137]

7. Limitations

The limitations posed by the small sample size, as well as the evolving availability of advanced technologies and smart materials, should be acknowledged in interpreting these findings. To build upon this research, future studies should engage a broader participant base—both nationally and internationally—and prioritize the co-development of a safety vest prototype in collaboration with end-users. Such efforts would enable a more robust validation of the proposed concepts and ensure alignment with the principles of the D-UX framework.

8. Conclusion

The application of data analytics in sports medicine is widely recognized for its therapeutic value, particularly when derived from wearable technologies that monitor and predict athletes' physiological and behavioral patterns.[3] These tools have proven effective in assessing metrics such as cardiovascular performance and sleep quality. However, certain sports, such as professional horse racing, have yet to fully leverage these advancements. This study identifies a critical gap in the design and functionality of safety vests worn by Australian jockeys, highlighting the need for innovation that enhances both the protective capabilities and the overall user experience of these PPE products. Professional horse racing is widely recognized as a high-risk occupation, with jockeys routinely exposed to significant physical hazards, including high-speed falls, collisions, and repetitive impact forces that can result in serious injury or long-term health consequences.[138,139] In particular, the adoption of a new design may facilitate product innovation, thereby reducing the time required to remove vests from injured jockeys and benefiting both jockeys and medical professionals. Australian health professionals must record jockeys' injuries via a form to be submitted to the Australian Racing Incident Database, a centralized database established to systematically document injury incidents involving racing staff and horses.[140] More data could be collected and utilized if jockeys' safety vests were integrated with wearable technology; this dataset could function as denominator data for individual race rides, providing a foundational reference point for future research and analysis. This study's findings confirmed that Australian jockeys' safety vests are currently inadequate, as a successful product must meet the "must work" criterion, but these vests fail to guarantee impeccable safety.

The author relied on the key characteristics of case study research, which encompass the ability to formulate insightful questions, actively listen, demonstrate adaptability and flexibility, possess a thorough understanding of the subjects under investigation, and maintain objectivity. These findings emphasize the importance of a research-informed design approach that places users, specifically jockeys and medical professionals, at the core of the development process. Such a user-centric perspective not only facilitates the creation of more effective safety vests but also drives context-sensitive revisions to regulatory standards. In line with the principles of the D-UX framework, designers in the sports PPE domain should be empowered to critically evaluate and challenge existing product norms and standards. This approach enables the consideration of multiple user categories—including primary users, secondary stakeholders, and co-dependent actors—who interact with or are affected by the same design solution, applicable across various fields.

This study provides robust empirical support for integrating wearable sensor technologies into jockeys' safety vests, demonstrating their potential to enhance impact protection and enable timely medical response through real-time physiological monitoring. Within the well-resourced Australian thoroughbred racing industry, there is a clear opportunity to deliver high-performance, user-responsive PPE designs. These innovations should be accompanied by iterative updates to standards that reflect the evolving needs of all user groups.

The revision of current safety vest standards is both necessary and urgent, and must be informed by active user participation throughout the design and development process. Based on these insights, the author recommends further research aimed specifically at the co-development of a smart safety vest prototype in collaboration with end-users. Such a prototype would serve as a practical application of the D-UX framework, ensuring that design decisions are grounded in real-world user experiences and needs.[141] This initiative would not only advance the design of jockeys' PPE but also lay the groundwork for future research methodologies that prioritize user engagement and regulatory responsiveness.

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Conflict of Interest

The author declares no conflict of interest.

Author contributions

This is a single-authored article.

Ethics approval and consent to participate

The study was approved by a subcommittee of Swinburne University of Technology's Human Research Ethics Committee (SHR Project 2016/125). In accordance with the terms of the ethical approval, participant information statements and consent forms were provided to enable informed consent. The assistance and support provided by relevant authorities (such as Racing Victoria, RA, the National Jockeys' Trust, and Wilson Medic One) ensured that all participants were over the age of 18 and had not been diagnosed with anxiety, depression, or any other emotional disturbance within the previous 12 months.

Consent for publication

All participants provided written informed consent for the publication of their anonymous data before participating in the study, after receiving a comprehensive explanation of the research design and data collection procedures.

Availability of data

The data presented in this study are available on request from the corresponding author upon reasonable request.

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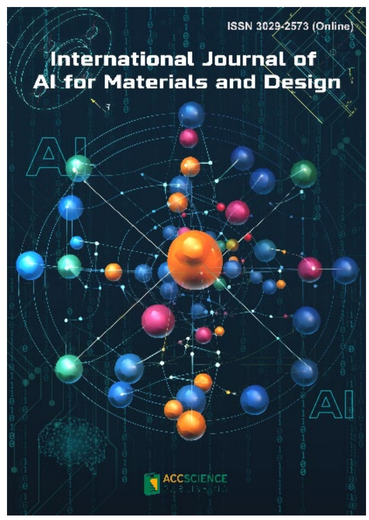

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