Information and Software Technology 147 (2022) 106896

Contents lists available at ScienceDirect

Information and Software Technology

journal homepage: www.elsevier.com/locate/infsof

# Quantum computing challenges in the software industry. A fuzzy AHP-based approach

Usama Awan [a,*], Lea Hannola [a], Anushree Tandon [b], Raman Kumar Goyal [c], Amandeep Dhir [d,e,f]

[a] LUT School of Engineering Science, Lappeenranta-Lahti University of Technology (LUT), Finland
[b] Turku School of Economics, University of Turku, Finland 20500
[c] Computer Science and Engineering Department, Thapar Institute of Engineering and Technology, Patiala, India
[d] Optentia Research Focus Area, North-West University, Vanderbijlpark, South Africa
[e] Department of Management, School of Business & Law, University of Agder, Norway
[f] Norwegian School of Hotel Management, University of Stavanger, Stavanger, Norway

## ARTICLE INFO

*Keywords:*
Fuzzy analytic hierarchy process (F-AHP)
Software process automation
Multiple-criteria decision-making (MCDM)
Quantum software requirement
Quantum computing

## ABSTRACT

*Context:* The current technology revolution has posed unexpected challenges for the software industry. In recent years, the field of quantum computing (QC) technologies has continued to grow in influence and maturity, and it is now poised to revolutionise software engineering. However, the evaluation and prioritisation of QC challenges in the software industry remain unexplored, relatively under-identified and fragmented.
*Objective:* The purpose of this study is to identify, examine and prioritise the most critical challenges in the software industry by implementing a fuzzy analytic hierarchy process (F-AHP).
*Method:* First, to identify the key challenges, we conducted a systematic literature review by drawing data from the four relevant digital libraries and supplementing these efforts with a forward and backward snowballing search. Second, we followed the F-AHP approach to evaluate and rank the identified challenges, or barriers.
*Results:* The results show that the key barriers to QC adoption are the lack of technical expertise, information accuracy and organisational interest in adopting the new process. Another critical barrier is the lack of standards of secure communication techniques for implementing QC.
*Conclusion:* By applying F-AHP, we identified institutional barriers as the highest and organisational barriers as the second highest global weight ranked categories among the main QC challenges facing the software industry. We observed that the highest-ranked local barriers facing the software technology industry are the lack of resources for design and initiative while the lack of organisational interest in adopting the new process is the most significant organisational barrier. Our findings, which entail implications for both academicians and practitioners, reveal the emergent nature of QC research and the increasing need for interdisciplinary research to address the identified challenges.

## 1. Introduction

Quantum computing (QC) has received an increasing amount of attention in software engineering and information science disciplines [1]. It has inspired computer scientists, engineers and physicists, and the potential of its application is undeniably altering the current information technology (IT) landscape [2]. A technology based on quantum mechanics, QC is capable of quickly solving complex calculations and simultaneously processing and transmitting information [3]. For example, the Google Sycamore quantum processor requires only 200 s to complete a task that would take a supercomputer 10,000 years to complete [4]. According to Arute et al. [4], the technology is ideal for many business transactions because it can effectively analyse data sets [5] with substantial knowledge and less computational time [6] while also enabling businesses to decipher data-driven patterns and thereby identify new opportunities. Multiple organisations, including IT giants such as Google, Intel and IBM, as well as start-ups such as Rigetti and IonQ, have recognised the potential of QCs [7]. Although QC's application is deeply established in some business sectors, such as industrial goods and pharmaceuticals [8]; a growing number of other industries and sectors have more recently acknowledged the potential of its practical applications [9]. For instance, the finance sector is increasingly

---

* Corresponding author.
*E-mail address:* usama.awan@lut.fi (U. Awan).

https://doi.org/10.1016/j.infsof.2022.106896
Received 7 October 2021; Received in revised form 17 February 2022; Accepted 21 February 2022
Available online 24 February 2022
0950-5849/© 2022 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

recognising the benefits of QC's express data processing capacity [10]. QC applications are thus expected to increase dramatically in the future [1] as the business community recognises its important benefits in technology transformation and adopts it more widely [11].

Given the potential that this technology offers, both industry-based and academic scholars are increasingly exploring methods to improve its reliability [12]. While research on QC has thus grown, it has primarily focused on developing technical aspects, such as software tools and technologies and quantum hardware [7]. Compared to the technical aspects, research efforts focused on identifying the challenges and prospects for advancing QC knowledge remain scarce [9]. For example, scholars have little understanding of potential QC applications in various industrial sectors for project management, quality improvement and delivery management [1]. This is a critical research gap because QC applications in sectors such as healthcare, finance and energy [13–15] have the potential to increase the efficiency and effectiveness of business processes. For example, quantum technologies (QTs) may be used to develop new drugs or materials or improve manufacturing processes [10]. Thus, it is imperative to investigate the key challenges that QC applications face in practice.

Addressing such challenges, however, requires assimilating the fragmented knowledge on QC and identifying its boundaries. Moreover, because the application of QC daily industrial operations is less understood [16], setting future agendas for this field requires understanding the barriers that hinder QC applications. To address these gaps, our study adopted a two-method approach. We first conducted a systematic literature review (SLR) of 103 articles to provide a comprehensive overview of the challenges associated with QC adoption. Next, we utilised the fuzzy analytic hierarchy process (F-AHP) to rank and identify the most significant challenges hindering QC application. Scholars have recently employed F-AHP to evaluate challenges associated with software process improvement [17]. Extant studies have posited that F-AHP, a broadly applied multi-criteria decision-making (MCDM) technique , can systematically categorise and prioritise factors [18]. To the best of our knowledge, our study is the first to utilise an MCDM approach to identify and rank the key challenges hindering QC adoption. We specifically raise and address the following two research questions (RQs):

> RQ1. What primary and broad challenges hinder the adoption of quantum computing (QC) in the computing industry?
>
> RQ2. What is the best method for modelling the challenges involved in successfully adopting quantum computing (QC) in the software industry?

By answering these RQs, our study makes three valuable contributions to the state of the art. First, to the best of our knowledge, ours is the first attempt at systematically assimilating the extant research on the challenges associated with QC adoption or application in a specific sector. This is a significant contribution because the SLR allows us to (a) identify existing research gaps in the field and (b) outline a future scope for advancing academic research on QC adoption. This study can thus serve as a foundational source of knowledge for both practitioners and scholars who are interested in investigating the nuances of QC application in software or other sectors. Second, our study's use of F-AHP has the potential to inform and advance policy and public dialogue on QC adoption by identifying the most significant barriers that impede its full application. Our classification and ranking of the key challenges for QC adoption can shape the digital transformation trajectory of QC application, especially because the identified barriers may also be relevant to allied technological fields. Finally, our two-pronged research strategy is a novel approach in QC research. Thus, our study makes methodological inroads in the field as the first to jointly apply two techniques, i.e. the F-AHP and SLR, to investigate QC adoption and the challenges therein [18].

## 2. Quantum computing: milieu and concepts

In contrast to the classical bits, which consist of 0 or 1 or AND or NOT gates [14], the quantum system consists of "qubits", or `multiple status quantum systems' [16], which can take two superstition states. The qubit structure, in other words, is based on two possible orthogonal states: |0> and |1> [19]. Table 1. briefly outlines the evolution of QC as a field of study.

Quantum computers are distinguished by the use of two principles from quantum mechanics: superposition and entanglement. Superposition recognises that position and momentum are not fixed for subatomic particles, as predicted by classical physical rules. Thus, a qubit can exist anywhere between 0 and 1 QC is basically is a classical information system based on `quantum mechanics' containing the largest information unit with a qubit [5].

The other key concept of entanglement is based on concurrence measurement and `measures the degree of entanglement between two-body systems' [20]. Entanglement increases the information density of quantum computers [21]. It is possible to prepare two qubits in an entangled state, which means that they will not act independently but rather collectively once prepared. This holds true even if the qubits are thousands of light-years apart [21]. The notion of quantum entanglement (QE), in turn, is based on interconnectedness across space and time [22]. From an ontological perspective, [23] ' entangled system cannot be fully described individually but bear properties that depend on their interaction with other elements and the properties of the overall system. The evolution of the QE concept in the literature, specifically in management studies, has emphasised its potential to offer new conceptual views for re-thinking the interaction between quantum elements [24]. Continued research on these concepts has advanced the notion of quantum algorithms (QA), which Deutsch first presented in 1985 [25]. These algorithms have the ability to solve well-known complex problems much faster than conventional algorithms [26, 27]. The emergent literature addresses the development of efficient algorithms to improve communication protocols and applications in various fields [14,28].

Recent scholarly work in QC also provides much insight into industries' current application of cryptography concepts, such as `quantum key distribution', `encryption/decryption', `signature authentication' and `hashing' [47,48]. For instance, research has explored QC's potential to increase the privacy and security of information using mixed-use QC and blockchain technology [13]. Distributed ledger technologies with QC may also enhance security for data transformation and security robustness [49]. For example, QC coupled with blockchain can facilitate self-enforcement and self-authenticity without the need for intermediaries to verify the information source. However, little understanding exists regarding QC's relevance for advancing centralised solutions, such as cryptocurrencies and blockchain [14].

**Table 1**
Evolution of QC.

| | | |
|---|---|---|
| 1st Generation QC | Implemented with `ion traps' [29, 30, 31] | `kHz as physical speed' and some `Hz as logical speed' |
| 2nd Generation QC | Implemented with `distributed diamonds' [32, 33, 34], `superconducting quantum circuits' [35, 36, 37] and linear optical [29, 38] | MHz ranges as physical speed and their logical speed is in the kHz domain |
| 3rd Generation QC | Implemented with `Monolithic diamonds' [39], quantum dots [40, 41, 42] or donor [43, 42] | Physical layer speed is in the GHz range, logical speed is in the MHz range |
| 4th Generation QC | Implemented with `Topological quantum computing technology' [44, 45, 46] | Currently in development and continuously evolving |

## 3. Research design: systematic integrative literature review (SILR)

We referred to the preferred reporting items for systematic reviews and meta-analyses (PRISMA) [50] guidelines to conduct our SLR and report its results [51]. The SLR is an appropriate method for our study because it can assist in (a) synthesising the existing literature and offering a reference point for identifying future research agendas [52] and (b) identifying recent developments in a specific field of enquiry [53]. Researchers can utilise an SLR to critically and comprehensively discuss the existing literature in a field, identify associations of any phenomena being studied, explore limitations of the extant research and thereby offer a possible scope for advancing scholarly efforts [52]. SLRs are especially beneficial in information science and software development studies [53] and have been used perviously to inform researchers on QC [54, 9]. Recognising that the QC field encompasses a diverse interdisciplinary research area, we specifically employed a systematic integrative literature review (SILR) and ontological classification. Our use of the SILR was motivated by its allowance for the inclusion of published articles using quantitative or qualitative research approaches [55]. Following the logic and approach of Kitchenham [56], we conducted our SLR in three steps: (1) planning for the review, (2) conducting the review and (3) reporting the review results.

### 3.1. Planning

We utilised the three-stage literature search strategy [57] to identify, specify and evaluate the SLR evidence. We referred to previously published SLRs in the present context and related areas to identify relevant databases and search terms to conduct the search (see Section 3.2) Fig. 1. shows the detailed process and steps followed to plan and execute this SILR.

#### 3.1.1. Research questions and scope

Researchers have not yet fully outlined good practices and development methodologies that can be implemented in real-life information systems to deliver QC benefits [16]. Moreover, scholars have posited that the current literature adopts a more experiment-focused approach towards QC adoption rather than understanding the mechanisms that can promote QC's more efficient use [28]. Recently, [28] emphasised the need to focus on the theoretical limitations and details associated with QC adoption.

Similarly, other scholars have called for exploration of QC's new research possibilities [58]—for example, understanding the problems associated with its adoption in various sectors or fields of study. Such effort require evidence-based research to explore and understand the various challenges QC researchers face in adopting the technology [11]. Our SILR is positioned to answer some of these queries and contribute to the strategic IT literature by focusing attention on the challenges of QC adoption in the context of a specific industry, i.e. software. In answering RQ1, we uncovered the broad range of challenges associated with QC adoption in organisations operating in the software industry. We adopted an organisational perspective to assimilate the prior literature on the technological problems that hinder organisations' performance and pose challenges to their QC adoption. We then answered RQ2 by employing the F-AHP to develop a prioritisation taxonomy of the potential barriers to implementing QC.

#### 3.1.2. Search strategy

We adopted a hybrid research strategy, defined as combining database searches in digital libraries with iterative, parallel or sequential backwards and forward snowballing[53] . Following recommendations

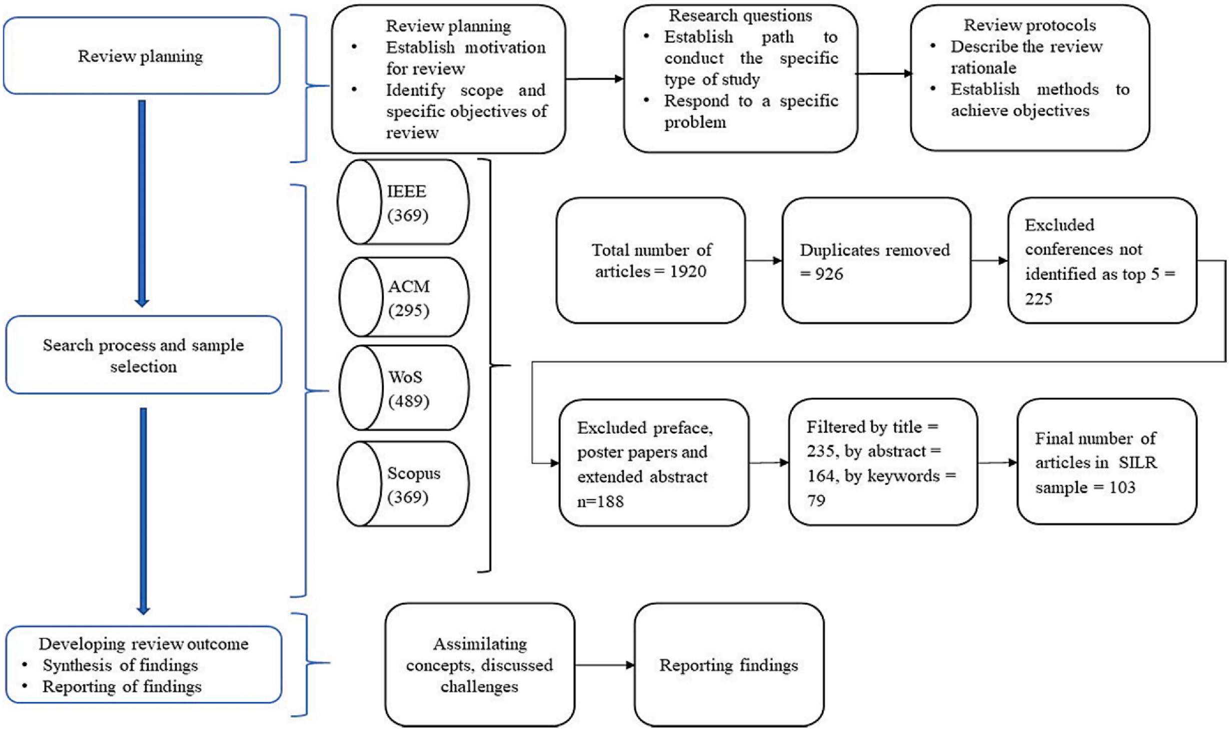


**Fig. 1.** SILR process and search results.

Note: Sample search string: TITLE-ABS-KEY ('Quantum computing') AND DOCTYPE (OR)AND (LIMIT-TO (SUBJAREA, 'COMP')) AND (LIMIT-TO (SUBJAREA, 'ENGI')) TITLE-ABS-KEY ('Quantum computing')AND DOCTYPE (ar OR re) AND (LIMIT-TO (SUBJAREA, 'COMP') OR LIMIT-TO (SUBJAREA, 'ENGI') OR LIMIT-TO (SUBJAREA,'SOCI') OR LIMIT-TO (SUBJAREA, 'MATH') OR LIMIT-TO (SUBJAREA, 'ENVI')) AND (LIMIT-TO (SUBJAREA,'MATE') OR LIMIT-TO (SUBJAREA, 'DECI') OR LIMIT-TO (SUBJAREA, 'BUSI') OR LIMIT-TO (SUBJAREA, 'ARTS') OR LIMIT-TO (SUBJAREA,'ECON')) by [53,59], we performed a keyword search in four digital libraries to ensure the best possible coverage of related articles. The search was run using the keyword `Quantum comput*'. Two authors conducted the entire search process in January 2021. To ensure that the sample showcased the evolution of QC research as it continues to mature, the screening criteria did not restrict the results to any specific time period.

To create a data set of high-quality studies on QC without regard to the discipline, our review mined the databases of *ACM Digital Library, Scopus, IEEE Xplore* and *Web of Science*, which index the most relevant and highly reputed journals, especially in information science studies. We chose these databases as they allowed us to explore a broad range of disciplines and, therefore, adopt an inter-disciplinary lens for studying QC adoption, an appraoch that has also been followed by prior SLRs [51, 60]. Recognising that direct search may not always identify all pertinent studies [61], however, we also conducted a citation-chaining snowballing process to retrieve additional relevant studies [51]. Citation chaining is a foundational step in most SLRs [51] and improves the rigour of the selection process [62]. Fig. 1. provides details of the SILR process and its steps.

### 3.2. Selection of relevant articles

The initial search resulted in 1920 articles, which were reviewed based on pre-determined inclusion (IC) and exclusion criteria (EC; see Table 2) adapted from prior SLRs [51]. Following the duplication removal (through Mendeley), screening and snowballing processes (see Fig. 2), the final sample selection resulted in 103 articles published in journals, books and conference proceedings (including 9 articles identified from snowballing). We opted to include book chapters (with citations) and conference papers because they can be value sources of state-of-the-art information. Moreover, conference proceedings published in lecture series notes are extremely popular dissemination channels in the information systems domain. The selected conferences were highly valuable because they were indexed in various reputed databases [60]. After removing duplicates and applying the exclusion criteria to the remaining 478 articles, we used the titles to exclude 0.39% on software modelling and 0.61% on the theory of QAs and other technical perspectives.

### 3.3. Synthesis and dissemination

The articles in the final sample were diverse and included case studies, review articles, etc. We used the content analysis approach to analyse the information in the selected articles. Both authors conducted the content analysis by consolidating a list of the key barriers to QC adoption identified in the reviewed literature. Following these efforts, we employed the F-AHP method to rank the barriers and thus identify the issues in QC adoption that should be prioritised in future investigations.

### 3.4. Threats to validity: SILR

While the SILR is a comprehensive method to understand the current boundaries of research, it is susceptible to specific limitations, which we identified in line with prior publications [63]. The first threat to the SILR's validity is the choice of key terms and databases for identifying the appropriate studies. Second, while we made efforts to reduce the subjectivity of the analysis, its execution may nevertheless have been subject to certain biases, which, in turn, may have affected our findings. Finally, we sought to understand the extant research with a focus on the software industry, which may impact the generalisability of our findings to other industries and sectors. We implore future scholars to address our limitations in future QC research.

## 4. Analysis and results

### 4.1. Answering research question 1

The fundamental benefit of QC technology is its ability to perform tasks quickly. While a traditional algorithm searches for information from a large dataset in the `time square root of its size' [64], the primary purpose of QC is to provide faster calculations and to remove the need for developing a set of queries to extract information; it has the potential to simultaneously examine many variables and thereby identify the best possible solution of many alternatives. Without a doubt, profound, radical innovation in IT and communication development has reshaped the information processing landscape in recent decades. QC has served as the leading technology in this transformation, offering a solution of confidentiality, authenticity and privacy [65].

As our literature review highlighted, achieving a scalable and functional digital transformation requires maintaining a balance between QC and macro computers. Few scholars have even suggested that organisations pursue a silicon QC platform for information processing [66]. Therefore, hybrid [67]—i.e. blended—quantum and classical approaches could be the foundation for powerful future applications . This type of system, which is also called `hybrid QC' [68], involv[es] atomic and solid-state elements to combine the advantages of the various systems' incompatible experimental setup. The QC literature [69] has revealed that organisations require a hybrid programming strategy that combines a quantum computer that handles the quantum chromosome as well as the quantum operators that modify the register, and a classical computer that evaluates the fitness function and manipulates the flow of the algorithm. In contrast, [70] asserted the need to switch entirely from classical computers to QC. Because of the problems associated with scaling up the number of qubits that can be practically realized so far, industrial quantum computers are not yet ready to completely replace classical supercomputers in their current form [9].

Our review suggests that the majority of prior research has concentrated on the application of QC [11, 14, 71] (see Table 3 for key concepts discussed in the QC literature). Moreover, the literature is characterised by a dearth of SLRs on QC [7], with the earliest literature reviews on QC discussing its conceptual development [58]. For instance, [7] provided a detailed view of quantum mechanics principles and identifies several research gaps but primarily focused on mapping the QC taxonomy and scalable quantum computer hardware. Another review addressed the data search applications over unsorted data [64]. [14] broadly

**Table 2**
Article selection criteria.

| Inclusion criteria (IC) | Exclusion criteria (EC) |
|---|---|
| i The articles must investigate the current state of development in quantum computing's vital applications | i We omitted articles written from the theory of QAs and other technical perspectives |
| ii The article must contain an adequate description of QC trends and challenges | ii We excluded papers that were not peer-reviewed and not relevant to modern QC, including editorials, prefaces, poster papers and extended abstracts and studies that were published at doctoral symposiums |
| iii Selected studies must offer applications in a variety of scientific disciplines and discuss integration challenges | |
| iv Articles must discuss practical implications and their challenges | |
| v Selected studies must be peer-reviewed articles, including book chapters (with citations), conferences proceedings and grey literature | |
| vi Selected literature must be written in English only | |
| vii vii. Selectedstudies must contain the string `quantum comput*' in the title, abstract and keywords | |

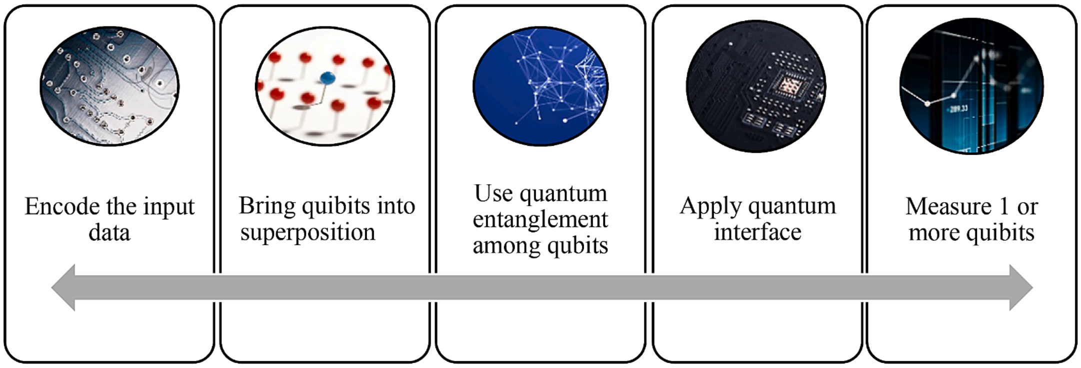


**Fig. 2.** The general quantum algorithm steps.

**Table 3**
Key concepts and definitions in QC research.

| | |
|---|---|
| Quantum mechanics | Quantum mechanics establishes a novel ontology by recognising the inherent but unquantified characteristic features of reality in terms of the probabilities of experiencing reality in a variety of ways within a particular socio-material context [93]. |
| Quantum teleportation | Quantum teleportation can nevertheless assist in the teleportation of an intact quantum state from one place to another by a sender who knows neither the state to be teleported nor the location of the intended receiver ( [92] . |
| Quantum machine learning | Quantum machine learning algorithms find patterns in classical data by mapping the data to quantum mechanical states and then manipulating those states using basic quantum linear algebra subroutines[73] . |
| Cryptograph | Cryptography is the process of securing data in transit or stored by third party adversaries[65] . |
| Quantum gates | In Quantum gates reversible, the ancilla states are cleared, and only the valuable outputs are kept [58] . Quantum gates designed methods of high-fidelity three-qubit gates [94,95]. |
| Quantum memories | According to [58], The quantum memories store these quantum systems in a quantum register for information processing . |
| Quantum central processing unit CPUs | Quantum CPUs use a quantum bus for the communication between the functional elements of a quantum computer ([58] . |

examined QC's current approaches and potential prospects in finance while [11] provided a detailed view of QC for energy system optimisation, including the potential opportunities and challenges. Additionally, multiple scholars have emphasised QC's potential to offer solutions for sectors such as quantum chemistry [72], quantum machine learning [73], cryptocurrency [65] and international relations [19].

Despite the centrality of the literature on QC concepts and the diverse nature of the approaches to QC research, its practical applications have only recently been recognised [21]. Highlighting the divergence of QC research approaches, studies have focused on its weaknesses and strengths [74], the complexity of quantum theory [75] and quantum computing ecosystem [76]. Still other studies have focused on technical issues [77], credit risk analysis [78] and security problems [79] as well as its potential applications to fault diagnosis [80], `computational molecular biology and bioinformatics' [81] and solving routing problems [82].

QA is well established today and increasingly important for enabling the quantum computer to operate with increasing power. For instance, QA can be used for information processing [83] and is essential for implementing the power of quantum hardware [11]. Previously, QA generally operated by applying the concept of Shor's algorithm [84]. Our review also finds that Grover's algorithm (1994) [85], based on amplitude application which is commonly used for searching unstructured data, is emerging in QC. More recently, the quantum approximate optimisation algorithm, which is based on hybrid QC, has become popular and is used to solve graph theory problems [7,86,87]. According to Orús et al [14]., QA consists of five steps (see Fig. 2). QA can be applied to solve various financial problems, such as asset management, investment and retail banking [10].

Our findings reveal that the prior QC literature has focused primarily on examining the basics of QC technology development and its usability, but its understanding of QC's current and future scope of applications in various industries is extremely limited. In 2008, the U.S. government released a quantum information policy (QIP) that explains the dovetailing of QT initiatives [88], which aims to develop devices that can simultaneously perform several of these tasks, namely, reliably store, process, and transmit quantum information. Hybrid quantum systems can simultaneously perform several of these tasks ([89] . As our literature review highlights, achieving a scalable and functional digital transformation requires achieving and maintaining a balance between QC and macro computers. Few scholars have even suggested that organisations pursue a silicon quantum computing platform for information processing [66].

QC also offers a potential source of quantum information, known as teleportation [90], which can transfer data or information from one place to another [91] almost instantaneously [92]. Quantum teleportation has the advantage of keeping the sender's location private. If information can be transmitted without revealing the sender's location, quantum teleportation has massive potential for knowledge-intensive industries [91]. The potential applicability of quantum teleportation is even more significant for protecting intellectual property rights. We posit that addressing QC challenges, especially for quantum teleportation, offers valuable benefits for redesigning information transmission in the privacy domain.

Seeking to support and operate with QC, scholars have recognised that machine learning (ML) has the potential to revolutionise and transform the industry due to its broad industrial applications and control in real-time. The literature has thoroughly reviewed quantum ML and artificial intelligence (AI) [96], and scholars have discovered various challenges and potential applications in the context of AI. Quantum ML can improve the performance of neural networks based on the canonical classical feedforward and backpropagation algorithms [97]. According to [3], ML refers to an area of computer science in which patterns are derived (`learned’) from data to make sense of previously unknown inputs . ML has also provided a concept of learning scenarios to make sense of previously unknown inputs. ML `addresses a variety of learning scenarios, dealing with learning from data, e.g. supervised (data classification) and unsupervised (data clustering) learning, or from interaction, e.g. reinforcement learning’ [96] .

The literature has employed AI and artificial general intelligence (AGI) interchangeably. Both concepts are similar to designing a `truly intelligent’ agent [98] [96]. suggested that as its ultimate goal, ’AI states the design of an intelligent agent that learns and thrives in unknown environments. Despite this outlook, QC can pose many AI implementation challenges, such unreadiness to adopt QC due to the non-availability of technical resources and infrastructure and limited financial support from institutions for QC investment. There is an increasing need for developing technical competencies and strategies to help organisations overcome these challenges. We argue that a change in organisational processes is required as is an investigation of the technical competencies that positively influence readiness to adopt QC. Previous research has also explored various benefits of QC, such as more effective information processing [58] or enhanced energy cost effectiveness [11]. The increased level of QC’s flexibility requires the development of post-post-quantum cryptography, which `consists of protocols of classical cryptography’ [99], and offers security against quantum computer attacks [86,100,101]. Cryptography is a mostly reliable security system for protecting communication and information [86], which is expected to benefit several industries/sectors, particularly finance where verifiable and dependable communication is required and developing trusted transactions is essential. Many studies have proposed increasing recognition of cryptography as a source of trusted transactions. Meanwhile, security issues and the resources available for infrastructural development should be considered; these issues, in turn, could affect the adoption of QC amongst both start-ups and established organisations.

We argue that procedures and governance mechanisms are required to realise cryptography’s potential benefits. Institutions can devise policy frameworks and regulations for cybersecurity law enforcement agencies to monitor and develop standards. As the literature has highlighted, the government has supported upgrading the QC infrastructure. Beyond this, however, there have been few other notable achievements in the realm of QC. For example, to develop national or organisational QC capabilities, a large number of nation states and commercial enterprises have invested in QC research. Chinese researchers have made significant strides in the realm of QC, for example, a quantum program has been devised that is expected to cost 10 billion USD over the next five years, with 3 billion USD of that amount dedicated entirely to the research and development of quantum computers [102]. Another initiative to accelerate the development of quantum information technology is the European Quantum Flagship Initiative, which is based in the United Kingdom. The Quantum Flagship Initiative, an ambitious €1 billion undertaking, was conceived with the purpose of ensuring that Europe maintains its historical leadership position in QC [103].

Based on our SILR, we note the persistence of open research challenges and opportunities for study, especially because the design of distributed QC topics remains nascent [76]. Previous studies have also highlighted the need to overcome noise and qubits decoherence as another technical challenge. Decoherence [14], which refers to uncontrolled interactions between the system and its environment , causes interruption due to fragility and drops information from qubits to the environment, and it is the information that is imperative for data transformation [104] Table 4. details a comprehensive assimilation and reporting of challenges identified for QC research in the extant literature.

**Table 4**
Key potential challenges.

| Authors | Key challenges |
|---|---|
| [105]<br>[99] | • Resource availability and a requirement for software design.<br>• Lack of resource understanding for the adoption of secure post-quantum blockchain. |
| [106]<br>[28] | • Information processing remains in its infancy due to the unavailability of hardware.<br>• Lack of necessary skills for conducting a quantum simulation |
| [16] | • Lack of engineering design skills for software modernisation to embrace QC. |
| [5] | • Algorithm architecture design and verification challenges for a quantum computer.<br>• Lack of research on factors that mediate the collaboration between the academic community, industry and government. |
| [107] | • Inadequate architectural support for quantum algorithm execution.<br>• Organisations need to `address the optimisation requirements for efficient execution of large-scale quantum circuits’. |
| [107]<br>[32] | • Scalability, `designing and fabricating large-scale superconducting’.<br>• Room temperature poses a rather fundamental connectivity challenge. |
| [108]<br>[109] | • Understanding short-term cost and long-term benefits. |
| [21]<br>[88] | • Lack of financial support from public institutions to accelerate efforts to identify new research and development opportunities as well as the lack stability and continuity of funding. |
| [110]<br>[7] | • Lack of consensus on technical standards and process of exchange of encryption key between two or more parties. |
| [12]<br>[15] | • Challenges to implement intelligence QC.<br>• Lack of research that considers the development of algorithm systems and structure. |
| [19]<br>[111] | • Ascertaining different stakeholders’ rational expectations and perspectives especially in the field of international security.<br>• Significant planning and multi-agent coordination. |
| [112] | • Effective university-to-university, industry-to-industry and industry-to-university collaboration for the successful adoption of quantum information technology (QIT). |
| [76] | • Lack of awareness of a new ecosystem for QC. |
| [3] | • Software requirements for quantum ML for intelligent data integration. |
| [14]<br>[107] | • Decoherence issues.<br>• Encoding information and reliably storing it for extended periods in quantum RAM (qRAM). |
| [113]<br>[15] | • Lack of computational capabilities for post-quantum cryptographic transformations. |
| [15] | • Lack of comprehensive criteria for effective fault detection and diagnosis.<br>• Design of deep learning models and architectures. |
| [31] | • Scalability and quantification of resource performance for various benchmarks. |
| [114] | • Lack of comprehensive criteria for next-generation cryptography standards. |
| [115] | • Lack of resources for the development of software engineering education for QC.<br>• Lack of studies on unexpected environmental failures. |
| [88] | • Public security and privacy issues arising from QC. |
| [116]<br>[28] | • Data processing challenges.<br>• Lack of research on how and why a particular algorithm is developed with specific knowledge resources. |
| [117] | • Algorithm development challenges for hybrid quantum computers.<br>• Identification of data set and implementation for quantum machine learning. |
| [14, 37]<br>[15]<br>[31] | • Quantum hardware needs to be `scaled up to compete with classical hardware’.<br>• Lack of quantum simulation in markets, including `financial services’, `health care’ and `logistics and data analytics’.<br>• Fault detection and extending the lifetime of a quantum bit. |
| [111] | • Computational challenges to support space vehicle design, `rover coordination’, `air traffic management’, anomaly detection, large data analysis and data fusion and advanced mission planning and logistics. |

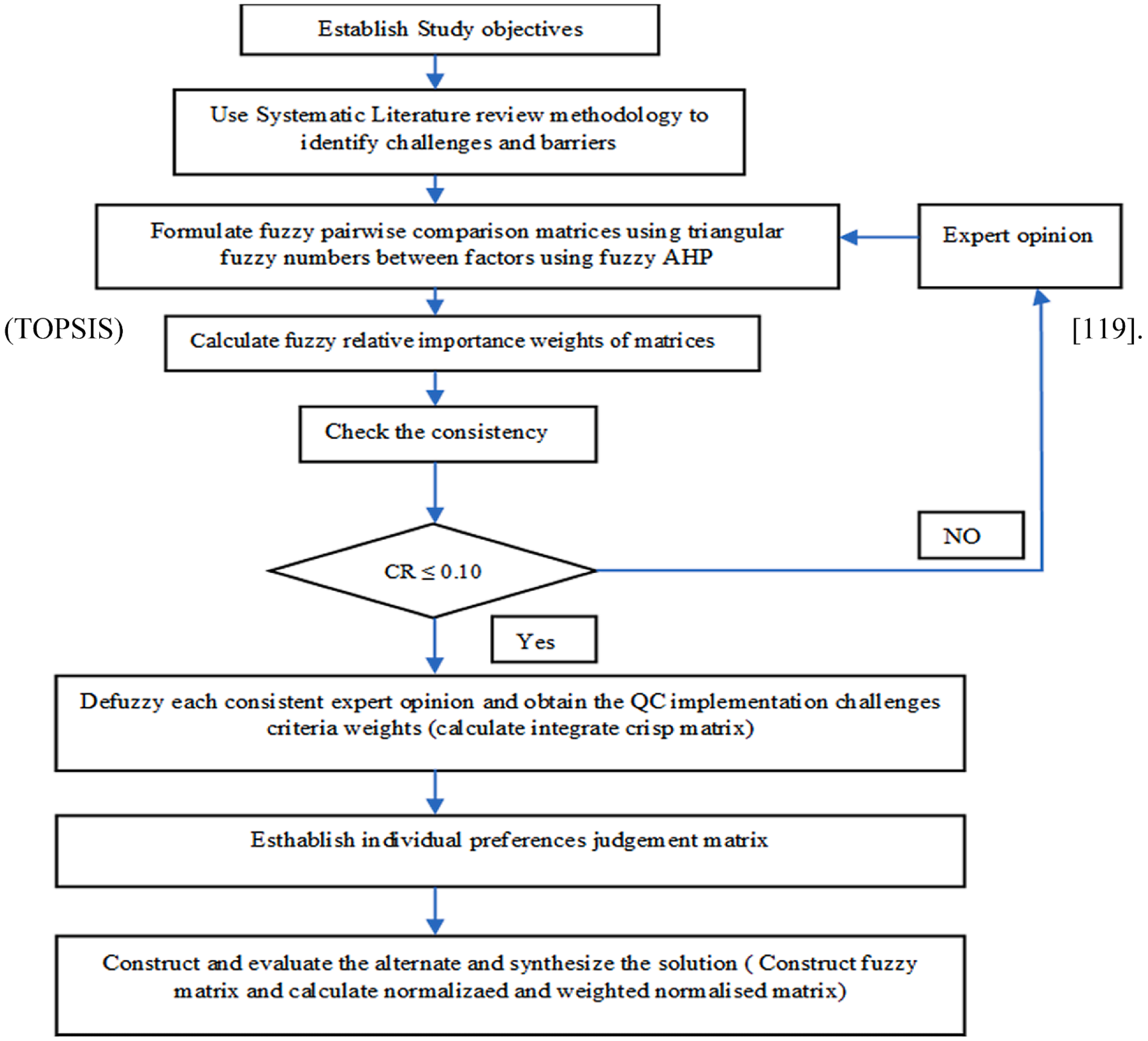


**Fig. 3.** F-AHP process flow model.

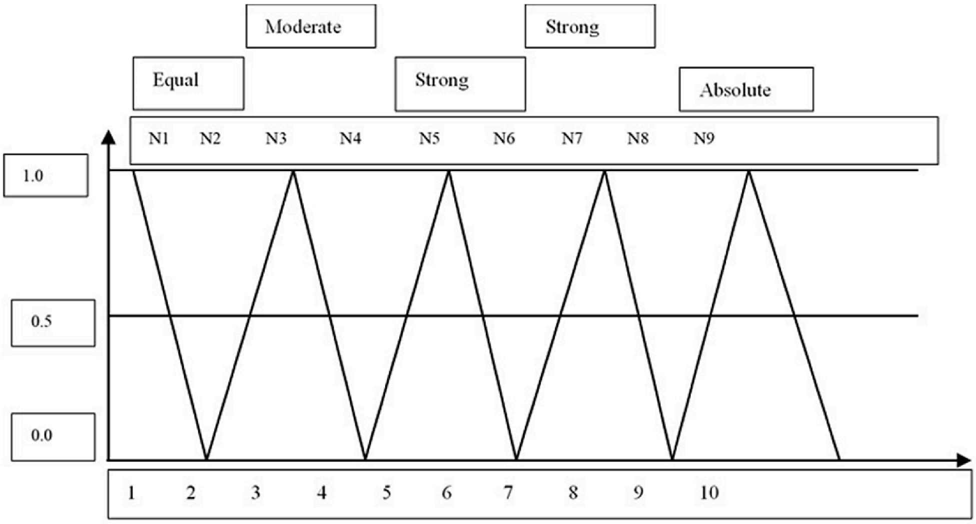


**Fig. 4.** Fuzzy membership function.

### 4.2. *Answering research question 2*

To prioritise the identified key factors and their categories, we employed the F-AHP technique (see Fig. 3 for the process flow model), which enabled a thorough understanding of decision-making issues via multiple criteria. As the previous section acknowledged, amongst the research gaps in the QC literature is the lack of organisational capabilities for accelerating and developing the algorithms necessary for rapid digital transformation.

#### 4.2.1. *Methodology: F-AHP*

The AHP methodology utilised in this study has primarily been used to solve hierarchical fuzzy problems [18]. However, scholars have suggested various approaches to the decision-making process [18,118]. The most commonly used techniques and methods include 'quality function deployment' (QFD), 'analytic hierarchy process' (AHP), 'analytic network process `(ANP), 'elimination choice expressing reality' (ELECTRE) and 'Technique for Order Preference by Similarity to Ideal Solutions' (TOPSIS) [119].

F-AHP is an extension of the AHP (see Fig. 3 for F-AHP process flow), a multi-criteria decision-making approach pioneered by [120]. The basic process of F-AHP is as follows. To define a fuzzy set, a membership function assigns values to elements based on their degree of membership within a given interval, typically [0, 1] (see Fig. 4). If the element's value is zero, it does not pertain to the set (i.e. it has no membership). If its value is one, the element is fully integrated into the package (i.e. it has total membership). Finally, if the value falls within the interval, the variable has a degree of membership. Scholars have mainly employed fuzzy logic decision systems (FLDS) for management decision-making [121]. F-AHP has been posited as the most appropriate for understanding the prioritisation and evaluation of success factors in global software development [122], and the scientific literature is characterised by a strong preference for the F-AHP concept over conventional AHP [122].

This is because the decision-maker's subjective evaluations of critical challenges and success factors entail uncertainty. Additionally, F-AHP addresses the consistency of the preference expressed by a group during the judgement process and ensures that the decision is both stable and flexible [123].

We followed the subsequently described steps to execute the F-AHP in our study:

- Step 1: Structure the problem (i.e. break the problem down into a hierarchy that includes objectives; see Fig. 5).

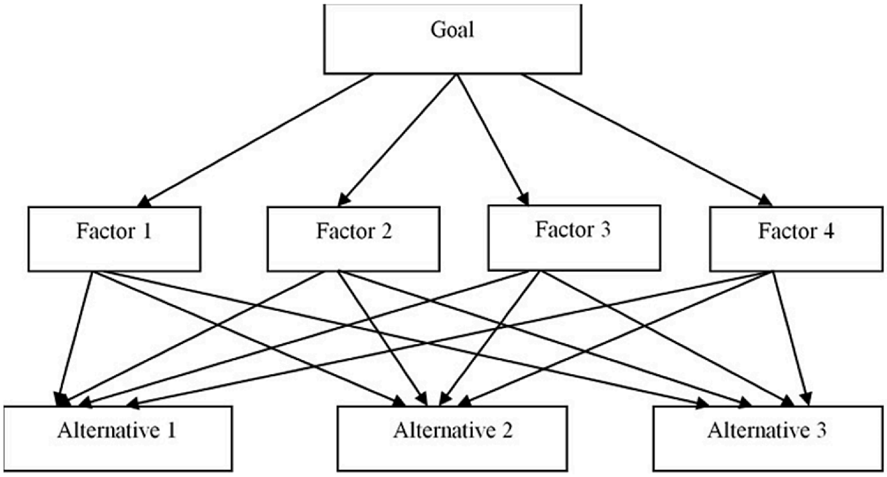


**Fig. 5.** F-AHP decision tree.

- Step 2: Develop matrices to calculate the weight of each factor across the hierarchical levels.
- Step 3: Calculate the normalised weights to arrive at the final rankings.

We used a two-stage F-AHP method. First, based on the recommendations of a previous study [122], we utilised a five-point Likert scale survey methodology to determine the critical barriers based on their importance. For a brief understanding of fuzzy AHP and arithmetic operations, please see [18]. The proposed F-AHP approach [123] can be explained as follows:

**Step 1**: To calculate the performance scores, define the problem according to the criteria identified. The following equation can be used to determine the value of a fuzzy synthetic extent with respect to the $i^{th}$ object:

$$S_i = \sum_{j=1}^{m} F^j{}_{gi} \otimes \left[ \sum_{i=1}^{n} \sum_{j=1}^{m} F^j{}_{gi} \right]^{-1}$$

To obtain the mathematical expression $\sum_{j=1}^{m} F^j{}_{gi}$, conduct the fuzzy addition operation of the m extent analysis in the following ways:

$$\sum_{j=1}^{m} F^j{}_{gi} = \left( \sum_{j=1}^{m} f^l{}_{gi}, \sum_{j=1}^{m} f^m{}_{gi}, \sum_{j=1}^{m} f^u{}_{gi} \right)$$

To achieve the desired expression $[\sum_{i=1}^{n} \sum_{j=1}^{m} F^j{}_{gi}]^{-1}$, perform the fuzzy supplement operation $F^j{}_{gi} (j = 1, 2, .....m)$ as follows:

$$\sum_{i=1}^{n} \sum_{j=1}^{m} F^j{}_{gi} = \left( \sum_{i=1}^{n} f^l{}_i, \sum_{i=1}^{n} f^m{}_i, \sum_{i=1}^{n} f^u{}_i \right)$$

Finally, compute the vector's inverse:

$$\left[ \sum_{i=1}^{n} \sum_{j=1}^{m} F^j{}_{gi} \right]^{-1} = \left( \frac{1}{\sum_{i=1}^{n} f^u{}_i}, \frac{1}{\sum_{i=1}^{n} f^m{}_i}, \frac{1}{\sum_{i=1}^{n} f^l{}_i} \right)$$

**Step 2**: Both As Fa and Fb triangular fuzzy numbers and define the degree at which

Fa = (fla, fma, fua) ≥ Fb = (flb, fmb, fub) as follows:
Y (Fa ≥ Fb) = sup [min (μ Fa (x), (μ Fb (x))]
The equation can also be specified as below:

$$Y(F_a \geq F_b) = hgt(F_a \cap F_b) = \mu_{F_a}(d)$$

$$= \left\{ \begin{array}{cc} 1 & iff^m{}_a \geq f^m{}_b \\ \dfrac{f^u{}_a - f^l{}_b}{(f^u{}_a - f^m{}_a) + (f^m{}_b - f^l{}_b)} & f^l{}_b \leq f^u{}_a \\ 0 & Otherwise \end{array} \right\}$$

In this equation, \`d' is the highest intersection point between D, μFa and μFb. The values of Y1(Fa ≥ Fb) and Y2(Fa ≥ Fb) are mandatory for calculating P1 and P2.

**Step 3:** Calculate the value of convex fuzzy numbers F$_i$ ($i = 1, 2, \ldots, k$) using the equation below:

$$Y(F \geq F_1, F_2, F_3....F_k) = \min Y(F \geq F_i)$$

The above equation assumes the following:

$$d'(F_i) = Y(F_i \geq F_k)$$

for $k = 1, 2, 3, 4, 5, \ldots\ldots\ldots\ldots\ldots, n; k \neq i$.

Each element's weight vector can be calculated as follows:

$$W' = (d'(F_1), d'(F_2), d'(F_3), .....d'(F_n))$$

**Step 4**: To determine the priority weight criteria, normalise and transform the weight vector's outcomes into a non-fuzzy number as follows:

$$W = (d(F_1), d(F_2), d(F_3), .....d(F_n))$$

The value of W represents a non-fuzzy number, and $F_i$ ($i = 1, 2, 3, 4, \ldots\ldots\ldots\ldots\ldots, n$) consists of n manifested elements.

**Step 5**: When comparing pairs of matrices, it is critical to determine their consistency [124]. The obtained graded mean integration can be calculated as the reliability coefficient for defuzzifying the matrix. A triangular fuzzy number, $N =$ (g, u, l), can be defuzzified to a crisp number as follows:

$$N_{crisp} = \frac{(4g + u + l)}{6})$$

After calculating $N_{crisp}$, it is necessary to ascertain the value of the \`consistency index' (CI) and \`consistency ratio' (CR).

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

$$CR = \frac{CI}{RI}$$

Where $\lambda_{max}$ indicates the largest eigenvalue and n is the dimension of the pairwise comparisons. If CR is less than 0.1, the pairwise comparison

**Table 6**
Membership function and output interval fuzzy scale for criteria and sub-criteria ratings.

| Intensity of importance | Definitions | Triangular fuzzy numbers | Triangular fuzzy reciprocal numbers |
|---|---|---|---|
| 6 | Extreme importance | 9, 9, 9 | 0.11, 0.11, 0.11 |
| 5 | Very strong to extreme importance | 7, 8, 9 | 0.14, 0.12, 0.11 |
| 4 | Very strong importance | 6, 7, 8 | 0.16, 0.14, 0.12 |
| 3 | Strong importance | 4, 5, 6 | 0.5, 0.20, 0.16 |
| 2 | Moderate importance | 2, 3, 4 | 0.5, 0.3, 0.25 |
| 1 | Equal importance | 1, 1, 1 | 1, 1, 1 |

Conversation scale adopted.

**Table 5**
Random consistency index (RI).

| Size of the matrix | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| RI | 0 | 0 | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

**Table 7**
Pairwise comparison of all criteria.

| | IB | | | MB | | | OB | | | STB | | | Normalised weights |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| IB | 1 | 1 | 1 | 2 | 3 | 4 | 9 | 9 | 9 | 4 | 5 | 6 | 0.532 |
| MB | ¼ | 1/3 | ½ | 1 | 1 | 1 | 7 | 8 | 9 | 7 | 8 | 9 | 0.343 |
| OB | 1/9 | 1/9 | 1/9 | 1/9 | 1/8 | 1/7 | 1 | 1 | 1 | ¼ | 1/3 | ½ | 0.042 |
| STB | 1/6 | 1/5 | ¼ | 1/9 | 1/8 | 1/7 | 2 | 3 | 4 | 1 | 1 | 1 | 0.083 |

**Table 8**
. Pairwise comparison matrix of institutional barriers (IB).

| | IB1 | | | IB 2 | | | IB 3 | | | IB 4 | | | Normalised weights |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| IB 1 | 1 | 1 | 1 | 1/6 | 1/5 | ¼ | 2 | 3 | 4 | ¼ | 1/3 | ½ | 0.122 |
| IB 2 | 4 | 5 | 6 | 1 | 1 | 1 | 6 | 7 | 8 | 4 | 5 | 6 | 0.645 |
| IB 3 | ¼ | 1/3 | ½ | 1/8 | 1/7 | 1/6 | 1 | 1 | 1 | 4 | 5 | 6 | 0.127 |
| IB 4 | 2 | 3 | 4 | 1/6 | 1/5 | ¼ | 1/6 | 1/5 | ¼ | 1 | 1 | 1 | 0.106 |

$\lambda_{max} = 4.2144$, CI = 0.0714, CR = 0.0794.

**Table 9**
. Pairwise comparison matrix of management barriers (MB).

| | MB1 | | | MB4 | | | MB4 | | | MB4 | | | Normalised weights |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MB1 | 1 | 1 | 1 | 7 | 8 | 9 | 6 | 7 | 8 | 6 | 7 | 8 | 0.674 |
| MB2 | 1/9 | 1/8 | 1/7 | 1 | 1 | 1 | ¼ | 1/3 | ½ | 2 | 3 | 4 | 0.092 |
| MB3 | 1/8 | 1/7 | 1/6 | 2 | 3 | 4 | 1 | 1 | 1 | 4 | 5 | 6 | 0.184 |
| MB4 | 1/8 | 1/7 | 1/6 | ¼ | 1/3 | ½ | 1/6 | 1/5 | ¼ | 1 | 1 | 1 | 0.049 |

$\lambda_{max} = 4.1924$, CI = 0.0641,CR = 0.0712.

**Table 10**
Pairwise comparison of all alternatives on organisational barriers (OB).

| | OB1 | | | MB2 | | | OB3 | | | OB4 | | | Normalised weights |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OB1 | 1 | 1 | 1 | 6 | 7 | 8 | 6 | 7 | 8 | 2 | 3 | 4 | 0.631 |
| OB2 | 1/8 | 1/7 | 1/6 | 1 | 1 | 1 | ¼ | 1/3 | ½ | 4 | 5 | 6 | 0.130 |
| OB3 | 1/8 | 1/7 | 1/6 | 2 | 3 | 4 | 1 | 1 | 1 | ¼ | 1/3 | ½ | 0.114 |
| OB4 | ¼ | 1/3 | ½ | 1/6 | 1/5 | ¼ | 2 | 3 | 4 | 1 | 1 | 1 | 0.125 |

$\lambda_{max} = 4.1645$, CI = 0.0548, CR = 0.0609.

**Table 11**
Pairwise comparison of all alternatives on software technology barriers (STB).

| | STB1 | | | STB2 | | | STB3 | | | STB4 | | | Normalised weights |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| STB1 | 1 | 1 | 1 | 4 | 5 | 6 | 6 | 7 | 8 | 7 | 8 | 9 | 0.648 |
| STB2 | 1/6 | 1/5 | ¼ | 1 | 1 | 1 | ¼ | 1/3 | ½ | 2 | 3 | 4 | 0.109 |
| STB3 | 1/8 | 1/7 | 1/6 | 2 | 3 | 4 | 1 | 1 | 1 | 4 | 5 | 6 | 0.193 |
| STB4 | 1/9 | 1/8 | 1/7 | ¼ | 1/3 | ½ | 1/6 | 1/5 | ¼ | 1 | 1 | 1 | 0.049 |

$\lambda_{max} = 4.1653$, CI = 0.0551, CR = 0.0612.

is considered consistent Table 5. presents the values for the random consistency index (RI) [124].

#### 4.2.2. *Applying F-AHP to prioritize QC adoption challenges and sub-criteria*

We employed the F-AHP approach step-by-step to determine the priority weight and categories of each success factor identified. F-AHP is critical to choose the appropriate challenges to implement QC and its sub-categories. To achieve this, we conducted an SILR and discovered various challenges (see Table 4). The questionnaire was designed to facilitate data collection (see Appendix 1: Survey questionnaire sample). Subsequently, we pilot-tested the draft survey questionnaire with academic professors and three experienced professionals to ensure its face validity and the appropriateness of the wording as well as the content of the items. We followed the guidelines to minimise common method bias (CMB) [125]. To this end, we carefully selected academic professors who had at least six years of experience in teaching software engineering courses and professional experts who had a high level of knowledge and experience in software technology development. We also interviewed five experts (computer and information science) via Skype™ to categorise the items into various dimensions. The experts evaluated the potential challenges (and questions formulated for the same) found through the and based on their feedback, we made a few

**Table 12**
Local and Global priorities and their Ranking.

| Category | Category Weight | Success Scores | Local weight | Local Rank | Global Rank | Global Rank |
|---|---|---|---|---|---|---|
| Institutional Barriers (IB) | 0.532 | IB1 | 0.122 | 2 | 0.0649 | 13 |
| | | IB2 | 0.645 | 4 | 0.3431 | 16 |
| | | IB3 | 0.127 | 3 | 0.0675 | 14 |
| | | IB4 | 0.106 | 1 | 0.0563 | 11 |
| Management Barriers (MB) | 0.343 | MB1 | 0.674 | 4 | 0.2311 | 15 |
| | | MB2 | 0.092 | 2 | 0.0315 | 9 |
| | | MB3 | 0.184 | 3 | 0.0631 | 12 |
| | | MB4 | 0.049 | 1 | 0.0168 | 6 |
| Organizational Barriers (OB) | 0.042 | OB1 | 0.631 | 4 | 0.0265 | 8 |
| | | OB2 | 0.130 | 3 | 0.0054 | 3 |
| | | OB3 | 0.114 | 1 | 0.0047 | 2 |
| | | OB4 | 0.125 | 2 | 0.0175 | 7 |
| Software Technology Barriers (STB) | 0.083 | STB1 | 0.648 | 4 | 0.0537 | 10 |
| | | STB2 | 0.109 | 2 | 0.0090 | 4 |
| | | STB3 | 0.193 | 3 | 0.0160 | 5 |
| | | STB4 | 0.049 | 1 | 0.0040 | 1 |

minor changes to improve the questionnaire's validity and readability. We also deleted two items from the management category and moved one item from the organisational category to the management category.

The final survey questionnaire was distributed to 110 software computer professionals via email along with a cover letter and a copy of the survey to each professional. The barriers identified were categorised into criteria and sub-criteria. Our study identified 16 key challenges through the SILR and mapped them into four categories using expert evaluation as follows: software technology barriers (STB), management barriers (MB), organisational barriers (OB) and institutional barriers (IB). After categorising the barriers, we collected data pairwise from key respondents (Appendix 2: F-AHP survey questionnaire). We designed the F-AHP questionnaire survey in response to the findings of the initial survey study and the criteria that were established. Data was collected between June and August 2021 from experts responsible for developing QC and technologies across multiple platforms and sectors. We identified key professionals from LinkedIn, Facebook groups and various industry magazines and compiled their emails. To increase generalisability, we sent emails to randomly identified experts from the list, and to determine the critical barriers, we asked the respondents to make pairwise comparisons amongst four main categories that define QC barriers and all sub-categories within each of the four major categories. In total, we sent the questionnaire to 54 experts, out of which we received 21 responses (Appendix 3: Respondents' background information). To increase the response rate, we send follow-up emails after two weeks.

Our sample size was similar to that of previously published studies on F-AHP [18]. For example, [122] collected data from 21 experts to prioritise software process improvement using the F-AHP methodology. Our results show that the CR for the given criteria is within the threshold value $< 0.10$, which suggests that group decision-making is consistent across respondents. We tested the given CR using the method outlined in [126]. A large number of researchers in a variety of fields have recently adopted this approach Table 6. shows the membership function and output interval fuzzy scale for criteria and sub-criteria ratings.

The pairwise comparisons of each sub-criteria—software technology, management barriers, organisational barriers and institutional barriers—appear in Tables 7–11, respectively. Table 12 presents the global and local weights of pairwise comparisons between key challenges.

### 4.2.3. *Discussion on F-AHP findings*

Prioritising each criterion by the F-AHP global weight (GW) versus other local weights revealed some interesting findings. For example, Table 12 shows that significant planning and multi-stakeholder collaboration (IB2) is amongst the top-ranked global factors. The results also show that respondents acknowledged the lack of commitment to research and development initiatives (MB1) as a critical barrier. The third most critical barrier is the lack of government support for commercialisation (IB3), which is amongst the most significant factors for implementing QC.

A lack of understanding of market demand is another critical management barrier. A large and growing body of literature has examined the importance of QC in information and data privacy, but relatively few studies have described the importance of QC in education [127]. We assert that this research gap on QC education is a significant barrier that needs to be addressed. Prior research on QC has revealed various contrasting themes; however, more recent research has focused on teaching QC via a software-driven approach [128]. Recent opinions, such as those of [115], have distinguished between the software engineering (SE) education challenges of classical computing and those of QC. There is a rapidly increasing demand for a skilled workforce educated in the basics of `quantum computing' and, in particular, in `quantum programming' [128]. These challenges reflect the importance of building dynamic technical competencies to understand QC and SE's characteristics. In addition, our results reveal that the highest-ranked local software technology barriers is the lack of resources for design and initiative (STB4), while amongst organisational barriers, it is the lack of organisational interest in adopting new processes (OB3). These challenges have significant implications for the optimal allocation of resources to formulate policy initiatives aimed at implementing basic QC programming in the curriculum [129]. The other major challenges offer many promising future research avenues to examine the impact of technological capabilities on organisations' QC implementations.

Similarly, multi-stakeholder collaboration is the highest-ranked institutional barrier. Such collaboration provides partners within the debate a central vision for linking their activities and sharing and combining resources [130]. Typically, collaboration with stakeholders is understood as collecting stakeholders' suggestions, which are then considered in decision-making, and according to scholars [131], decision-making is central to the stakeholder theory. Organisations face challenges in effective decision-making in a fast-paced and unpredictable technological environment. QC makes decision-making easy, however, and it is thus critical to surviving in the digital environment. Primary and secondary stakeholders have a direct relationship with the firm and are important to firm success [132]. They further argue that all stakeholders with legitimate power and interest should participate in the firm to achieve benefits. In their model, Donaldson and Preston depicted all stakeholders in the same size and shape and placed them in the centre [131].

However, evidence on the impact of research and development (R&D) collaboration involving academics and industry remains scarce. Funding agencies in many countries could encourage academics to invest resources into understanding the transformative impact of QC on various sectors. Indeed, QC is crucial for enterprise R&D investment planning, public sector research and strategic development planning to identify emerging trends with disruptive potential as early as possible [133].

Previous research has emphasised firm application development performance as an essential antecedent in the successful commercialisation of technology [134]. At this level of aggregation, scholars have argued that human and technical capital as well as manager mindfulness can influence the ease with which classical computers can be scaled up using QC. Initiatives such as designing smaller quantum computers may overcome the qubits coherence challenges and leverage the key benefits of QC for small and medium enterprises and new start-ups [11]. Integrating the supporting infrastructure also has the potential to boost quantum information science and technology across many industries—for example, by designing new materials, drugs and chemicals, simulating energy physics, machine learning, pattern and image recognition and optimising supply chain and financial problems [112].

Improvements in these areas open new opportunities for R&D collaboration between industries and universities. At the same time, information processing and data security are usually considered dominant in the QC literature. University–industry collaboration (UIC) studies have increased exponentially [135]. In contrast, the literature offers little evidence regarding various industries' adoption of QC in the presence of stakeholders' support or pressure. Concerning the technology's potential benefits, the QC view aims to reduce human involvement in handling big data and thus ensure that QC's rapid information processing capacity can provide results more quickly than classical computers.

The lack of information on short-term cost (MB4) ranks high in the management category, while multi-stakeholder collaboration also has a high local and global weight. This shows that technology firms should focus more on increasing R&D collaboration for implementing and executing QC. Given that these firms' commitment to resource availability and requirements vary in scope, the impact of institutional and organisational factors on system requirements for R&D initiatives remains unclear. Studies on architecture design and engineering design highlight changes in the external automation environment, such as understanding long-term cost [108], the lack of consensus on technical standards in the exchange of encryption key information between two or more parties [7] and opportunities brought by distributed ledger technologies [49]. [136] argued that efficient standard formulation is key to promoting the industry's competitiveness. Uncertain technical environments make it difficult to predict and solve the evolving challenges [137]. Thus, a shift in a company's digital infrastructure capability is necessary for developing consensus in response to these significant challenges and reconfiguring tangible and intangible digital assets.

While addressing the above factors has the potential to enhance the commercialisation of QC, technology firms can play a crucial role in addressing many challenges at various levels. Our findings reveal that the role of organisational structure and effective intra-industry, industry–university and intra-university collaborations has been largely neglected in QC research, and these offer important areas for future research.

## 5. Conclusion

We identified potential barriers using an SILR, and using the F-AHP method, we ranked the categories of these barriers based on their significance and prioritisation. Overall, we find a definitive scarcity of existing evidence about the potential barriers and challenges. Our review suggests increasing interest in the development of QTs but less emphasis on QC's commercialisation. Further, the F-AHP analysis reveals that the major barriers hindering QC adoption occur across four dimensions: management, software technology, management, institutional and organisational barriers. According to our findings, the key causes of and most prominent barriers to QC adoption include the lack of technical expertise, reduced understanding of the market demands of QC applications and the lack of engineering and design methodologies for software development and verification. Through the SILR and F-AHP results, we demonstrate the need to increase R&D collaboration on QC investment decisions between industry and universities to develop hybrid quantum computers and improve quantum cryptography's evaluation methods. The results conclusively indicate a growing need for developing technical competencies and strategies to help firms overcome these challenges.

## 6. Theoretical implications

Our study makes three important contributions with implications for research. First, through the SILR, we provide a comprehensive overview of the current state of research into QC adoption and identify various barriers that impact its adoption. Our findings advance scholarly efforts by assimilating information on the various approaches to QC research and its investigative contexts. We also highlight the key concepts and evolution of QC, which is fundamentally helpful for new scholars interested in this field of research. Our identification of the current boundaries of QC adoption research also benefits existing scholars who can use our findings to explore new issues and directions for advancing the state-of-the-art knowledge. We believe that our findings will encourage public dialogue on QC adoption and support the digital transformation trajectory upon which our society has embarked [16].

Second, our results imply the need for inter-disciplinary investigations into QC and for an intersecting interface for QC research amongst business administration, engineering, computer science, mathematics, physics and information science. Such efforts can facilitate a more nuanced understanding of the challenges and complexity of QC application, which is necessary because the information on these topics remains limited. For instance, more empirical studies from organisational and employee perspectives could deepen our understanding of the individual-, team- and organisation-level challenges on QC adoption or implementation.

Finally, by adopting a dual-pronged methodological approach to identify and prioritise the barriers to QC adoption, we address prior scholars' calls for an examination of the challenges and conditions that facilitate the development of QC. To our knowledge, our study is among the most comprehensive SILRs on the topic and pioneers the application of F-AHP to QC research. This is a significant contribution because the societal influence of emerging technologies will continue to increase as we become a progressively technology-centric society. We believe that QC will transform society and various fields, including finance, logistics, healthcare and entertainment, via its integrative application with cryptography, ML and AI, which may provide enhanced digital security and data privacy. Our findings thus imply the need to develop technical competencies and strategies to enable organisations to reap the benefits of QC.

## 7. Practical implications

Our study offers recommendations for practitioners (such as developers, testers and R&D personnel) to facilitate QC implementation in various fields. First, although QC is an emerging topic among organisations, our findings suggest that significant efforts are required from an organisational perspective to fully utilise its benefits. Quantum computing has evolved significantly in the last years and is becoming an increasingly mature area and will revolutionize the economic, industrial, academic, and societal landscape. There has been successful adoption of QC in industrial applications for a decision support system and process improvement; still, there is a lack of understanding of its potential applications, required technological resources, and knowledge of how to bring its application into the mainstream sociocultural-environmental context. While the results provide QC developers and software engineers with insights into various organisational and management barriers, we suggest the need for intra- and inter-organisational studies to empirically validate our results. Such efforts could allow practitioners to fine-tune their current management strategies to maximise their resources and facilitate QC adoption more efficiently.

Second, our results specifically imply the need for organisational documentation of the processes, requirements and inherent rules to redefine and align existing organisational infrastructure to enable QC adoption and implementation. For example, organisations must document the processes involved in developing standards and procedures for handling quantum cryptography keys. Such efforts can help organisations and management to establish a detailed organisational structure that adds greater value to the organisational process for QC adoption by merging knowledge across functional departments to disseminate learning by sharing experiences regarding QC adoption.

Third, we believe that practitioners can benefit from seeking active R&D and educational collaborations with stakeholders, including individual scholars and university-based research groups. Such collaborations have the potential to facilitate the development of a shared understanding of the usage and implications of QC applications and promote improvements in QC education to ensure the technological competencies and skills of the future workforce in this field. We imply the need for such collaborations at both local (i.e. individual nations) and global (i.e. across nations) levels to establish standard protocols, e.g. cryptographic protocols, in QC and thereby improve process implementation and efficiency. Moreover, such standards can help practitioners to address technical problems (e.g. development of information processing capabilities) at a global level with inputs from multiple stakeholders. We believe that such collaboration will influence QC research and practice at both macro (i.e. setting global standards for technology development) and micro levels (i.e. setting goals for improving education and university curricula that align with each nation's workforce requirements).

## 8. Future research directions

Although the extant literature highlights the importance of QC via an increasing number of articles on QC advancements and applications [14], such as those asserting the value of ML [73], our SILR identifies specific knowledge gaps that indicate viable future research agendas. Future research must expand the knowledge boundaries of this field by improving conceptual knowledge on QC and the various application scenarios for this technology. For example, to understand the interplay between technological advancement and business strategies, scholars can focus attention on QC development and implementation specifically from the lens of strategic IT. Despite the broad utilisation of QC, strategic cost mechanisms must be developed to encourage enterprises to invest in software engineering requirements' scalability, which requires empirical explorations. We urge scholars to adopt a management perspective for future research and utilise existing frameworks (e.g. the business canvas model) to understand the pros and cons of integrating QC with existing business models and strategies.

Second, the existing literature discusses the benefits of QC adoption [99], but further empirical investigations are required to understand how organisations' adoption of this technology can compete with classical hardware—for example, by measuring stakeholder expectations from QC and required hardware vis-à-vis traditional computing or identifying key requirements in material supply chains. Moreover, our review highlights the lack of software development initiatives, prototype formations and task composition requirements discussed from the QC adoption perspective, which could be promising for commercialising QC applications.

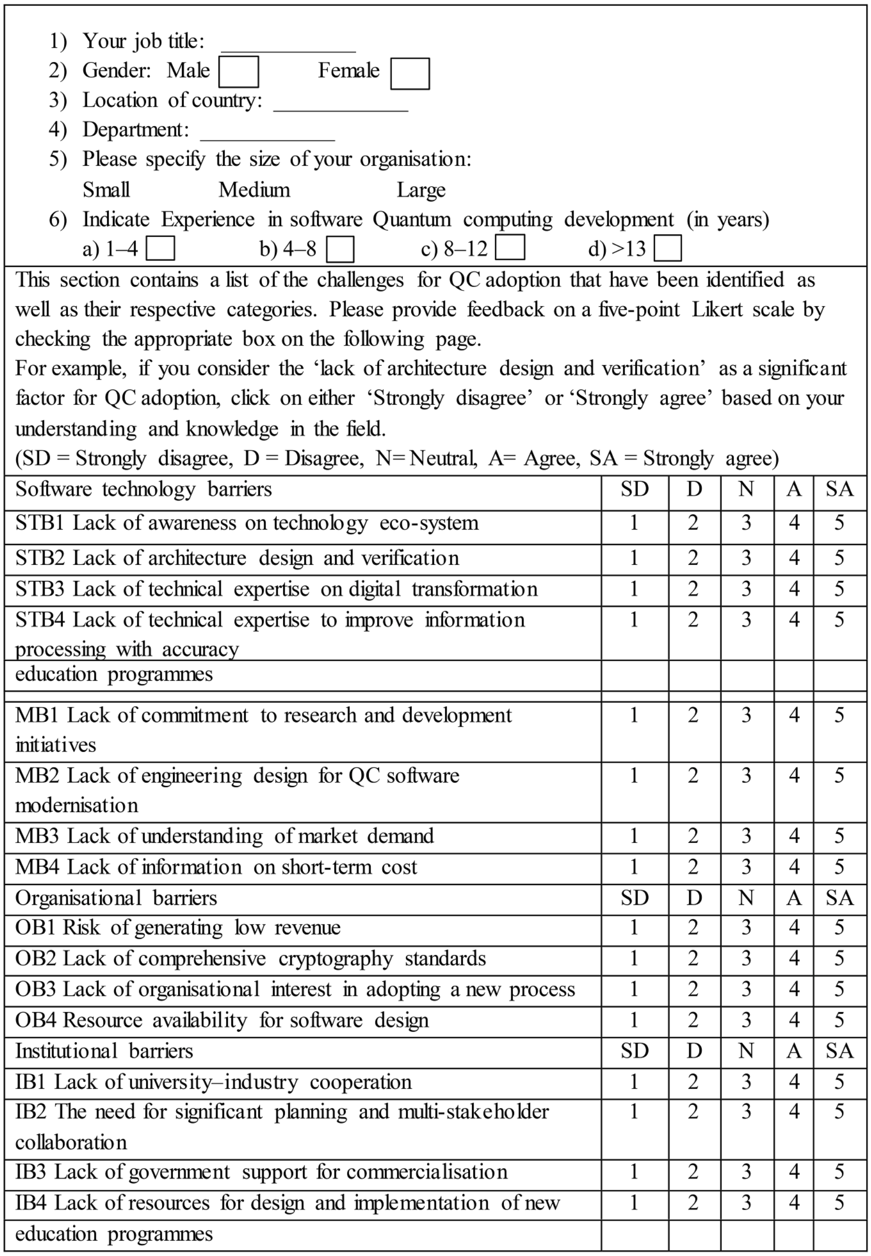
Third, our findings emphasise that the process of adopting QC is fraught with daunting challenges, many of which surround existing practices and expectations, e.g. the importance of scalability and the quantification of resource performance [31]. Because QC adoption remains a persistent challenge for many industries, we urge scholars to study the potential of the technology assimilation process to reduce the organisational learning burden and facilitate organisations' adoption of new technology [138]. We also suggest that future scholars employ theories from fields such as mathematics, management studies and information systems science to conduct in-depth investigations of the factors that could facilitate QC adoption. For example, the dual-factor [63] theory may be a viable framework for the concurrent study of the facilitators and inhibitors of QC adoption in organisational settings. While our findings identify some such facilitating (benefits) and inhibiting (barriers) factors, scholars can explore others identified in extant literature as well. Further, our findings demonstrate the differential intensity of challenges that organisations may face during QC adoption. For example, compared to larger firms, small and medium enterprises (SMEs) may find it much more difficult to implement QC. The use of the suggested theoretical frameworks may thus assist scholars in comparing and distinguishing QC adoption enablers and challenges for larger IT firms versus SMEs and start-ups. Our findings suggests increasing interest in the development of quantum computing technologies, but there is less emphasis on the commercialization of QC and tackling the value chain issues.

Unsurprisingly, the IT industry is collectively geared towards pursuing new computation opportunities to advance data transformation, communication, information security, data privacy and protection [28]. We believe that future scholars' focus on niche QC applications, e.g. cryptography and blockchain, must become more prevalent to promote this digital transformation. Such advances will significantly benefit scholars and practitioners' efforts to address global issues, including data protection. Our findings provide a foundation for future research, and despite the limitations of our study, we urge future scholars to utilise our results to advance research in QC, which is an emergent yet critical area of enquiry.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix 1. Survey questionnaire sample



1) Your job title: _____________
2) Gender: Male ☐ Female ☐
3) Location of country: _____________
4) Department: _____________
5) Please specify the size of your organisation:
Small Medium Large
6) Indicate Experience in software Quantum computing development (in years)
a) 1–4 ☐ b) 4–8 ☐ c) 8–12 ☐ d) >13 ☐

This section contains a list of the challenges for QC adoption that have been identified as well as their respective categories. Please provide feedback on a five-point Likert scale by checking the appropriate box on the following page.
For example, if you consider the 'lack of architecture design and verification' as a significant factor for QC adoption, click on either 'Strongly disagree' or 'Strongly agree' based on your understanding and knowledge in the field.
(SD = Strongly disagree, D = Disagree, N= Neutral, A= Agree, SA = Strongly agree)

| Software technology barriers | SD | D | N | A | SA |
|---|---|---|---|---|---|
| STB1 Lack of awareness on technology eco-system | 1 | 2 | 3 | 4 | 5 |
| STB2 Lack of architecture design and verification | 1 | 2 | 3 | 4 | 5 |
| STB3 Lack of technical expertise on digital transformation | 1 | 2 | 3 | 4 | 5 |
| STB4 Lack of technical expertise to improve information processing with accuracy | 1 | 2 | 3 | 4 | 5 |
| education programmes | | | | | |
| | | | | | |
| MB1 Lack of commitment to research and development initiatives | 1 | 2 | 3 | 4 | 5 |
| MB2 Lack of engineering design for QC software modernisation | 1 | 2 | 3 | 4 | 5 |
| MB3 Lack of understanding of market demand | 1 | 2 | 3 | 4 | 5 |
| MB4 Lack of information on short-term cost | 1 | 2 | 3 | 4 | 5 |
| Organisational barriers | SD | D | N | A | SA |
| OB1 Risk of generating low revenue | 1 | 2 | 3 | 4 | 5 |
| OB2 Lack of comprehensive cryptography standards | 1 | 2 | 3 | 4 | 5 |
| OB3 Lack of organisational interest in adopting a new process | 1 | 2 | 3 | 4 | 5 |
| OB4 Resource availability for software design | 1 | 2 | 3 | 4 | 5 |
| Institutional barriers | SD | D | N | A | SA |
| IB1 Lack of university–industry cooperation | 1 | 2 | 3 | 4 | 5 |
| IB2 The need for significant planning and multi-stakeholder collaboration | 1 | 2 | 3 | 4 | 5 |
| IB3 Lack of government support for commercialisation | 1 | 2 | 3 | 4 | 5 |
| IB4 Lack of resources for design and implementation of new | 1 | 2 | 3 | 4 | 5 |
| education programmes | | | | | |

This section contains a list of the challenges for QC adoption that have been identified as well as their respective categories. Please provide feedback on a five-point Likert scale by checking the appropriate box on the following page.

For example, if you consider the `lack of architecture design and verification' as a significant factor for QC adoption, click on either `Strongly disagree' or `Strongly agree' based on your understanding and knowledge in the field.

(SD = Strongly disagree, *D* = Disagree, *N*= Neutral, *A*= Agree, SA = Strongly agree)

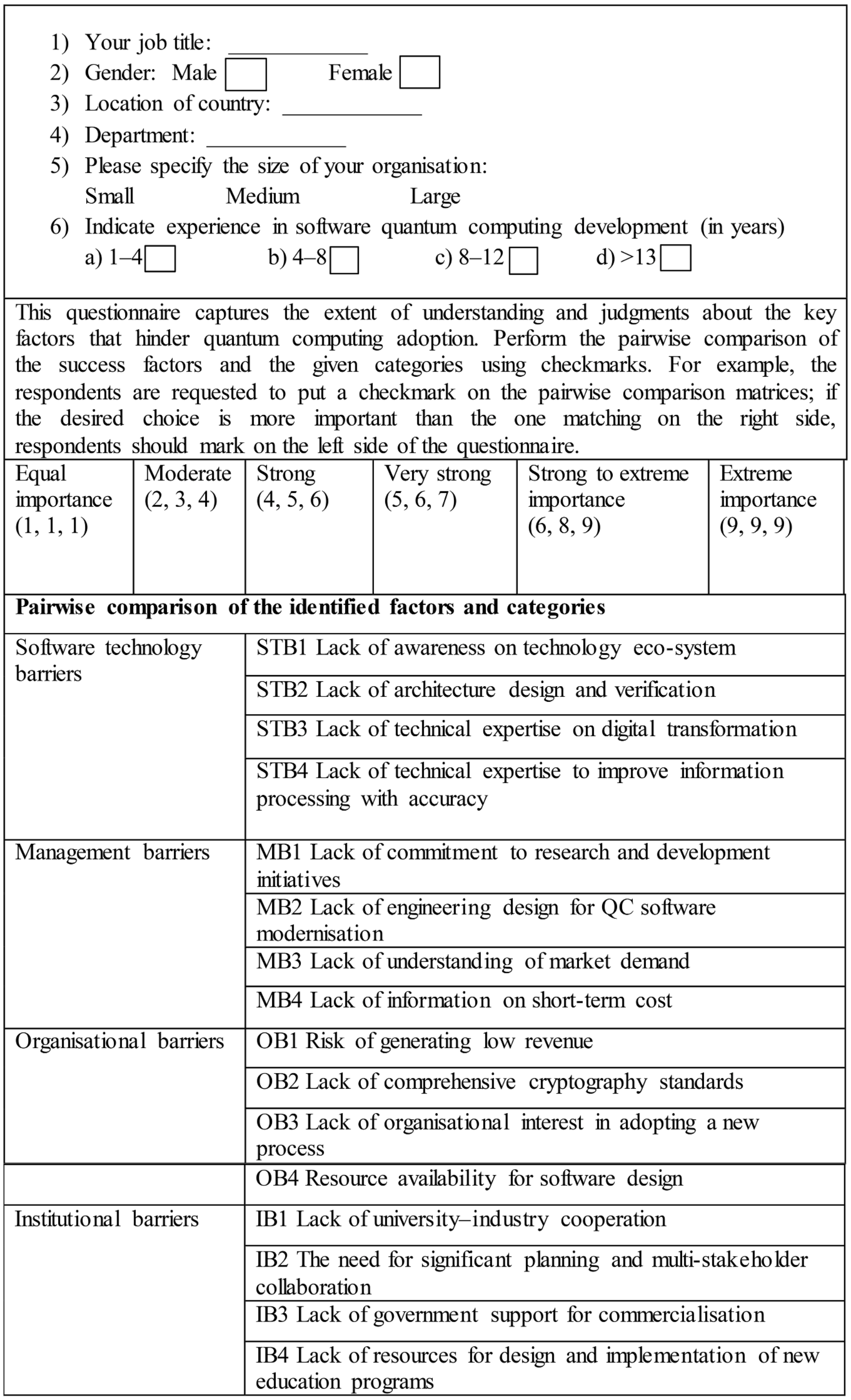
| Software technology barriers | SD | D | N | A | SA |
|---|---|---|---|---|---|
| STB1 Lack of awareness on technology eco-system | 1 | 2 | 3 | 4 | 5 |
| STB2 Lack of architecture design and verification | 1 | 2 | 3 | 4 | 5 |
| STB3 Lack of technical expertise on digital transformation | 1 | 2 | 3 | 4 | 5 |
| STB4 Lack of technical expertise to improve information processing with accuracy | 1 | 2 | 3 | 4 | 5 |
| Management barriers | SD | D | N | A | SA |
| MB1 Lack of commitment to research and development initiatives | 1 | 2 | 3 | 4 | 5 |
| MB2 Lack of engineering design for QC software modernisation | 1 | 2 | 3 | 4 | 5 |
| MB3 Lack of understanding of market demand | 1 | 2 | 3 | 4 | 5 |
| MB4 Lack of information on short-term cost | 1 | 2 | 3 | 4 | 5 |
| Organisational barriers | SD | D | N | A | SA |
| OB1 Risk of generating low revenue | 1 | 2 | 3 | 4 | 5 |
| OB2 Lack of comprehensive cryptography standards | 1 | 2 | 3 | 4 | 5 |
| OB3 Lack of organisational interest in adopting a new process | 1 | 2 | 3 | 4 | 5 |

(*continued on next page*)

(*continued*)

| | | | | | |
|---|---|---|---|---|---|
| OB4 Resource availability for software design | 1 | 2 | 3 | 4 | 5 |
| Institutional barriers | SD | D | N | A | SA |
| IB1 Lack of university–industry cooperation | 1 | 2 | 3 | 4 | 5 |
| IB2 The need for significant planning and multi-stakeholder collaboration | 1 | 2 | 3 | 4 | 5 |
| IB3 Lack of government support for commercialisation | 1 | 2 | 3 | 4 | 5 |
| IB4 Lack of resources for design and implementation of new education programmes | 1 | 2 | 3 | 4 | 5 |

## Appendix 2. Pairwise comparison questionnaire sample



1) Your job title: ____________
2) Gender: Male ☐ Female ☐
3) Location of country: ____________
4) Department: ____________
5) Please specify the size of your organisation:
   Small Medium Large
6) Indicate experience in software quantum computing development (in years)
   a) 1–4☐ b) 4–8☐ c) 8–12☐ d) >13☐

This questionnaire captures the extent of understanding and judgments about the key factors that hinder quantum computing adoption. Perform the pairwise comparison of the success factors and the given categories using checkmarks. For example, the respondents are requested to put a checkmark on the pairwise comparison matrices; if the desired choice is more important than the one matching on the right side, respondents should mark on the left side of the questionnaire.

| Equal importance (1, 1, 1) | Moderate (2, 3, 4) | Strong (4, 5, 6) | Very strong (5, 6, 7) | Strong to extreme importance (6, 8, 9) | Extreme importance (9, 9, 9) |
|---|---|---|---|---|---|

| **Pairwise comparison of the identified factors and categories** | |
|---|---|
| Software technology barriers | STB1 Lack of awareness on technology eco-system |
| | STB2 Lack of architecture design and verification |
| | STB3 Lack of technical expertise on digital transformation |
| | STB4 Lack of technical expertise to improve information processing with accuracy |
| Management barriers | MB1 Lack of commitment to research and development initiatives |
| | MB2 Lack of engineering design for QC software modernisation |
| | MB3 Lack of understanding of market demand |
| | MB4 Lack of information on short-term cost |
| Organisational barriers | OB1 Risk of generating low revenue |
| | OB2 Lack of comprehensive cryptography standards |
| | OB3 Lack of organisational interest in adopting a new process |
| | OB4 Resource availability for software design |
| Institutional barriers | IB1 Lack of university–industry cooperation |
| | IB2 The need for significant planning and multi-stakeholder collaboration |
| | IB3 Lack of government support for commercialisation |
| | IB4 Lack of resources for design and implementation of new education programs |

(*continued on next page*)

(*continued*)

This questionnaire captures the extent of understanding and judgments about the key factors that hinder quantum computing adoption. Perform the pairwise comparison of the success factors and the given categories using checkmarks. For example, the respondents are requested to put a checkmark on the pairwise comparison matrices; if the desired choice is more important than the one matching on the right side, respondents should mark on the left side of the questionnaire.

| Equal importance | Moderate | Strong | Very strong | Strong to extreme importance | Extreme importance |
|---|---|---|---|---|---|
| (1, 1, 1) | (2, 3, 4) | (4, 5, 6) | (5, 6, 7) | (6, 8, 9) | (9, 9, 9) |

**Pairwise comparison of the identified factors and categories**

| | |
|---|---|
| Software technology barriers | STB1 Lack of awareness on technology eco-system |
| | STB2 Lack of architecture design and verification |
| | STB3 Lack of technical expertise on digital transformation |
| | STB4 Lack of technical expertise to improve information processing with accuracy |
| Management barriers | MB1 Lack of commitment to research and development initiatives |
| | MB2 Lack of engineering design for QC software modernisation |
| | MB3 Lack of understanding of market demand |
| | MB4 Lack of information on short-term cost |
| Organisational barriers | OB1 Risk of generating low revenue |
| | OB2 Lack of comprehensive cryptography standards |
| | OB3 Lack of organisational interest in adopting a new process |
| | OB4 Resource availability for software design |
| Institutional barriers | IB1 Lack of university–industry cooperation |
| | IB2 The need for significant planning and multi-stakeholder collaboration |
| | IB3 Lack of government support for commercialisation |
| | IB4 Lack of resources for design and implementation of new education programs |

## Appendix 3. Profile details of survey respondents

| S. no. | Title | Department | Experience in years | Location |
|---|---|---|---|---|
| 1 | Software engineer | Engineering | 7 | Finland |
| 2 | Quantum architecture engineer | Project management | 4 | Finland |
| 3 | Front-end engineer | Quality control | 11 | Australia |
| 4 | Quantum systems development engineer | Technology development | 13 | Canada |
| 5 | Product manager | Project management | 9 | USA |
| 6 | Software quality manager | Quality control | 16 | Finland |
| 7 | Quantum computing architect | Software development | 4 | China |
| 8 | Software designer | Engineering | 14 | Russia |
| 9 | Quantum technology developer | Technology development | 7 | Australia |
| 10 | Quantum business developer | Project management | 6 | China |
| 11 | Project leader in quantum information science | Management information system | 7 | USA |
| 12 | Quantum algorithm researcher | Engineering | 9 | Germany |
| 13 | Quantum computational scientist | Management information system | 10 | Canada |
| 14 | Team leader in QC | Software development | 4 | Finland |
| 15 | Quantum software engineer | Software development | 5 | Finland |
| 16 | Software developer | Software development | 8 | Canada |
| 17 | Software engineer | Process improvement | 5 | Canada |
| 18 | Agile software project manager | Business function | 6 | Germany |
| 19 | Continuous process improvement | Software development | 4 | China |
| 20 | Manager - quality assurance | Business function | 6 | Estonia |
| 21 | Quantum technology researcher | Engineering | 3 | Estonia |

## References

[1] M. Piattini, G. Peterssen, R. Pérez-Castillo, Quantum computing: a new software engineering golden age, ACM SIGSOFT Softw. Eng. Notes 45 (2020) 12–14.

[2] A.D. Corcoles, A. Kandala, A. Javadi-Abhari, D.T. McClure, A.W. Cross, K. Temme, P.D. Nation, M. Steffen, J.M. Gambetta, Challenges and opportunities of near-term quantum computing systems, Proc. IEEE. 108 (2020) 1338–1352. https://doi.org/10.1109/JPROC.2019.2954005.

[3] M. Schuld, I. Sinayskiy, F. Petruccione, An introduction to quantum machine learning, Contemp. Phys. 56 (2015) 172–185, https://doi.org/10.1080/00107514.2014.964942.

[4] F. Arute, K. Arya, R. Babbush, D. Bacon, J.C. Bardin, R. Barends, R. Biswas, S. Boixo, F.G.S.L. Brandao, D.A. Buell, Quantum supremacy using a programmable superconducting processor, Nature 574 (2019) 505–510.

[5] W. Wu, T. Zhang, P.-.X. Chen, Quantum computing and simulation with trapped ions: on the path to the future, Fundam. Res. (2021), https://doi.org/10.1016/j.fmre.2020.12.004.

[6] A. Mielke, T. Ricken, Evaluating artificial neural networks and quantum computing for mechanics, Pamm. 19 (2019) 2019–2020, https://doi.org/10.1002/pamm.201900470.

[7] S.S. Gill, A. Kumar, H. Singh, M. Singh, K. Kaur, M. Usman, R. Buyya, Quantum computing: a taxonomy, System. Rev. Fut. Direct. (2020) 1–35.

[8] A. Bayerstadler, G. Becquin, J. Binder, T. Botter, H. Ehm, T. Ehmer, M. Erdmann, N. Gaus, P. Harbach, M. Hess, J. Klepsch, M. Leib, S. Luber, A. Luckow, M. Mansky, W. Mauerer, F. Neukart, C. Niedermeier, L. Palackal, R. Pfeiffer, C. Polenz, J. Sepulveda, T. Sievers, B. Standen, M. Streif, T. Strohm, C. Utschig-Utschig, D. Volz, H. Weiss, F. Winter, Industry quantum computing applications, EPJ Quantum Technol. 8 (2021), https://doi.org/10.1140/epjqt/s40507-021-00114-x.

[9] S.S. Gill, A. Kumar, H. Singh, M. Singh, K. Kaur, M. Usman, R. Buyya, Quantum computing: a taxonomy, systematic review and future directions, Softw. - Pract. Exp. 52 (2022) 66–114, https://doi.org/10.1002/spe.3039.

[10] D.J. Egger, C. Gambella, J. Marecek, S. McFaddin, M. Mevissen, R. Raymond, A. Simonetto, S. Woerner, E. Yndurain, Quantum computing for Finance: state of the art and future prospects, ArXiv. 1 (2020). https://doi.org/10.1109/tqe.2020.3030314.

[11] A. Ajagekar, F. You, Quantum computing for energy systems optimization: challenges and opportunities, Energy 179 (2019) 76–89, https://doi.org/10.1016/j.energy.2019.04.186.

[12] N. Schradle, In algorithms we trust: magical thinking, superintelligent AI and quantum computing, Zygon. 55 (2020) 733–747. https://doi.org/10.1111/zygo.12637.

[13] M. Bhavin, S. Tanwar, N. Sharma, S. Tyagi, N. Kumar, Blockchain and quantum blind signature-based hybrid scheme for healthcare 5.0 applications, J. Inf. Secur. Appl. 56 (2021), 102673, https://doi.org/10.1016/j.jisa.2020.102673.

[14] R. Orús, S. Mugel, E. Lizaso, Quantum computing for finance: overview and prospects, Rev. Phys. 4 (2019), https://doi.org/10.1016/j.revip.2019.100028.

[15] A. Ajagekar, F. You, Quantum computing assisted deep learning for fault detection and diagnosis in industrial process systems, Comput. Chem. Eng. 143 (2020), 107119, https://doi.org/10.1016/j.compchemeng.2020.107119.

[16] R. Pérez-Castillo, M.A. Serrano, M. Piattini, Software modernization to embrace quantum technology, Adv. Eng. Softw. 151 (2021), https://doi.org/10.1016/j.advengsoft.2020.102933.

[17] M.A. Akbar, M. Shameem, A.A. Khan, M. Nadeem, A. Alsanad, A. Gumaei, A fuzzy analytical hierarchy process to prioritize the success factors of requirement change management in global software development, J. Softw. Evol. Process. 33 (2021) e2292.

[18] A.A. Khan, M. Shameem, M. Nadeem, M.A. Akbar, Agile trends in Chinese global software development industry: fuzzy AHP based conceptual mapping, Appl. Soft Comput. 102 (2021), 107090, https://doi.org/10.1016/j.asoc.2021.107090.

[19] J. Der Derian, A. Wendt, `Quantizing international relations': the case for quantum approaches to international theory and security practice, Secur. Dialogue. 51 (2020) 399–413, https://doi.org/10.1177/0967010620901905.

[20] M. Zidan, A.H. Abdel-Aty, A. Younes, E.A. Zanaty, I. El-khayat, M. Abdel-Aty, A novel algorithm based on entanglement measurement for improving speed of quantum algorithms, Appl. Math. Inf. Sci. 12 (2018) 265–269, https://doi.org/10.18576/amis/120127.

[21] V. Hassija, V. Chamola, V. Saxena, V. Chanana, P. Parashari, S. Mumtaz, M. Guizani, Present landscape of quantum computing, IET Quantum Commun 1 (2020) 42–48, https://doi.org/10.1049/iet-qtc.2020.0027.

[22] B. Dyck, N.S. Greidanus, Quantum sustainable organizing theory: a study of organization theory as if matter mattered, J. Manag. Inq. 26 (2016) 32–46, https://doi.org/10.1177/1056492616656407.

[23] T. Hahn, E. Knight, The ontology of organizational paradox: a quantum approach, Acad. Manag. Rev. (2019), https://doi.org/10.5465/amr.2018.0408.

[24] R. Horodecki, M.H.K. Horodecki, Paweland Horodecki, Quantum entanglement, Rev. Mod. Phys. 81 (2009) 865.

[25] A. Montanaro, Quantum algorithms: an overview, Npj Quantum Inf 2 (2016) 1–8.

[26] D. Deutsch, Quantum theory, the Church–Turing principle and the universal quantum computer, Proc. R. Soc. London. A 400 (1985) 97–117.

[27] G.B. Lesovik, I.A. Sadovskyy, M.V. Suslov, A.V. Lebedev, V.M. Vinokur, Arrow of time and its reversal on the IBM quantum computer, Sci. Rep. 9 (2019) 1–8.

[28] S. Imre, Quantum computing and communications - Introduction and challenges, Comput. Electr. Eng. 40 (2014) 134–141, https://doi.org/10.1016/j.compeleceng.2013.10.008.

[29] R. Van Meter, S.J. Devitt, Local and distributed quantum computation, ArXiv Prepr. ArXiv1605.06951. (2016).

[30] C. Monroe, R. Raussendorf, A. Ruthven, K.R. Brown, P. Maunz, L.-.M. Duan, J. Kim, Large-scale modular quantum-computer architecture with atomic memory and photonic interconnects, Phys. Rev. A. 89 (2014) 22317.

[31] M. Ahsan, R. Van Meter, J. Kim, Designing a million-qubit quantum computer using a resource performance simulator, ACM J. Emerg. Technol. Comput. Syst. 12 (2015) 1–25.

[32] P.C. Maurer, G. Kucsko, C. Latta, L. Jiang, N.Y. Yao, S.D. Bennett, F. Pastawski, D. Hunger, N. Chisholm, M. Markham, Room-temperature quantum bit memory exceeding one second, Science 336 (2012) 1283–1286, https://doi.org/10.1126/science.1220513.

[33] H. Bernien, B. Hensen, W. Pfaff, G. Koolstra, M.S. Blok, L. Robledo, T. H. Taminiau, M. Markham, D.J. Twitchen, L. Childress, Heralded entanglement between solid-state qubits separated by three metres, Nature 497 (2013) 86–90.

[34] E. Togan, Y. Chu, A.S. Trifonov, L. Jiang, J. Maze, L. Childress, M.V.G. Dutt, A. S. Sørensen, P.R. Hemmer, A.S. Zibrov, Quantum entanglement between an optical photon and a solid-state spin qubit, Nature 466 (2010) 730–734.

[35] R. Barends, J. Kelly, A. Megrant, A. Veitia, D. Sank, E. Jeffrey, T.C. White, J. Mutus, A.G. Fowler, B. Campbell, Superconducting quantum circuits at the surface code threshold for fault tolerance, Nature 508 (2014) 500–503.

[36] L. DiCarlo, J.M. Chow, J.M. Gambetta, L.S. Bishop, B.R. Johnson, D.I. Schuster, J. Majer, A. Blais, L. Frunzio, S.M. Girvin, Demonstration of two-qubit algorithms with a superconducting quantum processor, Nature 460 (2009) 240–244.

[37] N. Ofek, A. Petrenko, R. Heeres, P. Reinhold, Z. Leghtas, B. Vlastakis, Y. Liu, L. Frunzio, S.M. Girvin, L. Jiang, Extending the lifetime of a quantum bit with error correction in superconducting circuits, Nature 536 (2016) 441–445.

[38] N. Somaschi, V. Giesz, L. De Santis, J.C. Loredo, M.P. Almeida, G. Hornecker, S. L. Portalupi, T. Grange, C. Antón, J. Demory, Near-optimal single-photon sources in the solid state, Nat. Photonics. 10 (2016) 340–345.

[39] N.Y. Yao, L. Jiang, A.V. Gorshkov, P.C. Maurer, G. Giedke, J.I. Cirac, M.D. Lukin, Scalable architecture for a room temperature solid-state quantum information processor, Nat. Commun. 3 (2012) 1–8.

[40] K. Takeda, J. Kamioka, T. Otsuka, J. Yoneda, T. Nakajima, M.R. Delbecq, S. Amaha, G. Allison, T. Kodera, S. Oda, others, A fault-tolerant addressable spin qubit in a natural silicon quantum dot, Sci. Adv. 2 (2016), e1600694.

[41] M. Veldhorst, J.C.C. Hwang, C.H. Yang, A.W. Leenstra, B. de Ronde, J. P. Dehollain, J.T. Muhonen, F.E. Hudson, K.M. Itoh, A. Morello, others, An addressable quantum dot qubit with fault-tolerant control-fidelity, Nat. Nanotechnol. 9 (2014) 981–985.

[42] F.A. Zwanenburg, A.S. Dzurak, A. Morello, M.Y. Simmons, L.C.L. Hollenberg, G. Klimeck, S. Rogge, S.N. Coppersmith, M.A. Eriksson, Silicon quantum electronics, Rev. Mod. Phys. 85 (2013) 961.

[43] H. Seddiqi, T.S. Humble, Adiabatic quantum optimization for associative memory recall, Front. Phys. 2 (2014) 1–12, https://doi.org/10.3389/fphy.2014.00079.

[44] V. Mourik, K. Zuo, S.M. Frolov, S.R. Plissard, E.P.A.M. Bakkers, L. P. Kouwenhoven, Signatures of Majorana fermions in hybrid superconductor-semiconductor nanowire devices, Science 336 (2012) 1003–1007.

[45] M. Freedman, A. Kitaev, M. Larsen, Z. Wang, Topological quantum computation, Bull. Am. Math. Soc. 40 (2003) 31–38.

[46] C. Nayak, S.H. Simon, A. Stern, M. Freedman, S.Das Sarma, Non-Abelian anyons and topological quantum computation, Rev. Mod. Phys. 80 (2008) 1083.

[47] N. Abura'ed, F.S. Khan, H. Bhaskar, Advances in the quantum theoretical approach to image processing applications, ACM Comput. Surv. 49 (2017) 1–49.

[48] Y. Qassim, M.E. Magana, A. Yavuz, Post-quantum hybrid security mechanism for MIMO systems, in: 2017 Int. Conf. Comput. Netw. Commun. ICNC 2017, 2017, pp. 684–689, https://doi.org/10.1109/ICCNC.2017.7876212.

[49] J. Villalba-Diez, X. Zheng, Quantum strategic organizational design: alignment in industry 4.0 complex-networked cyber-physical lean management systems, Sensors (Switzerland) 20 (2020) 1–22, https://doi.org/10.3390/s20205856.

[50] D. Moher, A. Liberati, J. Tetzlaff, D.G. Altman, Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement, Int J Surg 8 (2010) 336–341.

[51] C. Wohlin, E. Mendes, K.R. Felizardo, M. Kalinowski, Guidelines for the search strategy to update systematic literature reviews in software engineering, Inf. Softw. Technol. 127 (2020), 106366, https://doi.org/10.1016/j.infsof.2020.106366.

[52] A.M. Møller, P.S. Myles, What makes a good systematic review and meta-analysis? Br. J. Anaesth. 117 (2016) 428–430.

[53] E. Mourão, J.F. Pimentel, L. Murta, M. Kalinowski, E. Mendes, C. Wohlin, On the performance of hybrid search strategies for systematic literature reviews in software engineering, Inf. Softw. Technol. 123 (2020), https://doi.org/10.1016/j.infsof.2020.106294.

[54] J. Wang, L. Shen, W. Zhou, A bibliometric analysis of quantum computing literature: mapping and evidences from scopus, Technol. Anal. Strateg. Manag. 33 (2021) 1347–1363.

[55] K. Mills, D.K. Creedy, R. West, Experiences and outcomes of health professional students undertaking education on Indigenous health: a systematic integrative literature review, Nurse Educ. Today. 69 (2018) 149–158.

[56] B. Kitchenham, O.P. Brereton, D. Budgen, M. Turner, J. Bailey, S. Linkman, Systematic literature reviews in software engineering–a systematic literature review, Inf. Softw. Technol. 51 (2009) 7–15.

[57] B. Kitchenham, Procedures for Performing Systematic Reviews, 33, Keele Univ., Keele, UK, 2004, pp. 1–26.

[58] L. Gyongyosi, S. Imre, A Survey on quantum computing technology, Comput. Sci. Rev. 31 (2019) 51–71, https://doi.org/10.1016/j.cosrev.2018.11.002.

[59] A. Silva, T. Araújo, J. Nunes, M. Perkusich, E. Dilorenzo, H. Almeida, A. Perkusich, A systematic review on the use of Definition of Done on agile software development projects, in: Proc. 21st Int. Conf. Eval. Assess. Softw. Eng, 2017, pp. 364–373.

[60] H. Engström, B. Berg Marklund, P. Backlund, M. Toftedahl, Game development from a software and creative product perspective: a quantitative literature review approach, Entertain. Comput. 27 (2018) 10–22, https://doi.org/10.1016/j.entcom.2018.02.008.

[61] M. Dadkhah, S. Araban, S. Paydar, A systematic literature review on semantic web enabled software testing, J. Syst. Softw. 162 (2020), 110485, https://doi.org/10.1016/j.jss.2019.110485.

[62] D. Badampudi, C. Wohlin, K. Petersen, Experiences from using snowballing and database searches in systematic literature studies, in: Proc. 19th Int. Conf. Eval. Assess. Softw. Eng., 2015, pp. 1–10.

[63] M. Younas, D.N.A. Jawawi, I. Ghani, T. Fries, R. Kazmi, Agile development in the cloud computing environment: a systematic review, Inf. Softw. Technol. 103 (2018) 142–158.

[64] L.K. Grover, Quantum mechanics helps in searching for a needle in a haystack, Phys. Rev. Lett. 79 (1997) 325–328, https://doi.org/10.1103/PhysRevLett.79.325.

[65] V. Mavroeidis, K. Vishi, M.D. Zych, A. Jøsang, The impact of quantum computing on present cryptography, Int. J. Adv. Comput. Sci. Appl. 9 (2018) 405–414, https://doi.org/10.14569/IJACSA.2018.090354.

[66] E. Ferraro, E. Prati, Is all-electrical silicon quantum computing feasible in the long term? Phys. Lett. Sect. A. 384 (2020), 126352 https://doi.org/10.1016/j.physleta.2020.126352.

[67] M. Mohseni, P. Read, H. Neven, S. Boixo, V. Denchev, R. Babbush, A. Fowler, V. Smelyanskiy, J. Martinis, Commercialize quantum technologies in five years, Nature 543 (2017) 171–174, https://doi.org/10.1038/543171a.

[68] M. Wallquist, K. Hammerer, P. Rabl, M. Lukin, P. Zoller, Hybrid quantum devices and quantum engineering, Phys. Scr. T. T137 (2009) 1–13, https://doi.org/10.1088/0031-8949/2009/T137/014001.

[69] O.H. Montiel Ross, A review of quantum-inspired metaheuristics: going from classical computers to real quantum computers, IEEE Access 8 (2020) 814–838, https://doi.org/10.1109/ACCESS.2019.2962155.

[70] R.C. Poonia, M. Kalra, Bridging approaches to reduce the gap between classical and quantum computing, J. Inf. Optim. Sci. 37 (2016) 279–283, https://doi.org/10.1080/02522667.2015.1131024.

[71] A. Ajagekar, T. Humble, F. You, Quantum computing based hybrid solution strategies for large-scale discrete-continuous optimization problems, Comput. Chem. Eng. 132 (2020), 106630, https://doi.org/10.1016/j.compchemeng.2019.106630.

[72] B.P. Lanyon, J.D. Whitfield, G.G. Gillett, M.E. Goggin, M.P. Almeida, I. Kassal, J. D. Biamonte, M. Mohseni, B.J. Powell, M. Barbieri, A. Aspuru-Guzik, A.G. White, Towards quantum chemistry on a quantum computer, Nat. Chem. 2 (2010) 106–111, https://doi.org/10.1038/nchem.483.

[73] J. Biamonte, P. Wittek, N. Pancotti, P. Rebentrost, N. Wiebe, S. Lloyd, Quantum machine learning, Nature 549 (2017) 195–202.

[74] C.H. Bennett, E. Bernstein, G. Brassard, U. Vazirani, Strengths and weaknesses of quantum computing, SIAM J. Comput. 26 (1997) 1510–1523, https://doi.org/10.1137/S0097539796300933.

[75] E. Bernstein, U. Vazirani, Quantum complexity theory, SIAM J. Comput. 26 (1997) 1411–1473.

[76] D. Cuomo, M. Caleffi, A.S. Cacciapuoti, Towards a Distributed Quantum Computing Ecosystem, ArXiv. 1 (2020) 3–8. https://doi.org/10.1049/iet-qtc.2020.0002.

[77] F. Chiarello, P. Carelli, M.G. Castellano, M. Cirillo, C. Cosmelli, G. Frossati, N. Grønbech-Jensen, F. Mattioli, S. Poletto, G. Torrioli, A. De Waard, Potential characterization of a double SQUID device for quantum computing experiments, IEEE Trans. Appl. Supercond. 17 (2007) 124–127, https://doi.org/10.1109/TASC.2007.897367.

[78] D.J. Egger, R. Garcia Gutierrez, J. Cahue Mestre, S. Woerner, Credit risk analysis using quantum computers, IEEE Trans. Comput. 9340 (2020) 1–12, https://doi.org/10.1109/TC.2020.3038063.

[79] R. Eskandarpour, P. Gokhale, A. Khodaei, F.T. Chong, A. Passo, S. Bahramirad, Quantum computing for enhancing grid security, IEEE Trans. Power Syst. 35 (2020) 4135–4137, https://doi.org/10.1109/TPWRS.2020.3004073.

[80] L. Wang, Q. Niu, M. Fei, A novel quantum ant colony optimization algorithm and its application to fault diagnosis, Trans. Inst. Meas. Control. 30 (2008) 313–329, https://doi.org/10.1177/0142331207088191.

[81] C. Outeiral, M. Strahm, J. Shi, G.M. Morris, S.C. Benjamin, C.M. Deane, The prospects of quantum computing in computational molecular biology, Wiley Interdiscip. Rev. Comput. Mol. Sci. 11 (2021) 1–23, https://doi.org/10.1002/wcms.1481.

[82] S. Harwood, C. Gambella, D. Trenev, A. Simonetto, D.E. Bernal Neira, D. Greenberg, Formulating and solving routing problems on quantum computers, IEEE Trans. Quantum Eng. (2021) 1, https://doi.org/10.1109/tqe.2021.3049230.

[83] A.B. de Avila, R.H.S. Reiser, M.L. Pilla, A.C. Yamin, State-of-the-art quantum computing simulators: features, optimizations, and improvements for D-GM, Neurocomputing 393 (2020) 223–233, https://doi.org/10.1016/j.neucom.2019.01.118.

[84] C.S. Park, R. Park, G. Krishna, Constitutive expression and structural diversity of inducible isoform of nitric oxide synthase in human tissues, Life Sci 59 (1996) 219–225, https://doi.org/10.1016/0024-3205(96)00287-1.

[85] Z. Kato, T. Kato, N. Kondo, T. Orii, Interstitial deletion of the short arm of chromosome 10: report of a case and review of the literature, Jpn. J. Hum. Genet. 41 (1996) 333–338, https://doi.org/10.1007/BF01913177.

[86] D.J. Bernstein, T. Lange, Post-quantum cryptography, Nature 549 (2017) 188–194.

[87] E. Farhi, J. Goldstone, S. Gutmann, A quantum approximate optimization algorithm, ArXiv Prepr. ArXiv1411.4028. (2014).

[88] R.D. Taylor, Quantum Artificial Intelligence: a "precautionary" U.S. approach? Telecomm. Policy. 44 (2020) https://doi.org/10.1016/j.telpol.2020.101909.

[89] G. Kurizki, P. Bertet, Y. Kubo, K. Mølmer, D. Petrosyan, P. Rabl, J. Schmiedmayer, Quantum technologies with hybrid systems, Proc. Natl. Acad. Sci. U. S. A. 112 (2015) 3866–3873, https://doi.org/10.1073/pnas.1419326112.

[90] Q. Zhang, A. Goebel, C. Wagenknecht, Y.-A. Chen, B. Zhao, T. Yang, A. Mair, J. Schmiedmayer, J.-W. Pan, Experimental quantum teleportation of a two-qubit composite system, Nat. Phys. 2 (2006) 678–682.

[91] D. Boschi, S. Branca, F. De Martini, L. Hardy, S. Popescu, Experimental realization of teleporting an unknown pure quantum state via dual classical and einstein-podolsky-rosen channels, Phys. Rev. Lett. 80 (1998) 1121–1125, https://doi.org/10.1103/PhysRevLett.80.1121.

[92] C.H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres, W.K. Wootters, Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels, Phys. Rev. Lett. 70 (1993) 1895–1899, https://doi.org/10.1103/PhysRevLett.70.1895.

[93] K. Barad, Meeting the Universe halfway: Quantum physics and the Entanglement of Matter and Meaning, duke university Press, 2007.

[94] E. Zahedinejad, J. Ghosh, B.C. Sanders, Designing high-fidelity single-shot three-qubit gates: a machine-learning approach, Phys. Rev. Appl. 6 (2016) 54005.

[95] S. Imre, L. Gyongyosi, Advanced Quantum communications: an Engineering Approach, John Wiley & Sons, 2012.

[96] V. Dunjko, H.J. Briegel, Machine learning and artificial intelligence in the quantum domain, ArXiv. (2017).

[97] J. Allcock, C.Y. Hsieh, I. Kerenidis, S. Zhang, Quantum algorithms for feedforward neural networks, ArXiv. (2018). https://doi.org/10.1145/3411466.

[98] J.R. Stuart, P. Norvig, Artificial intelligence: a Modern Approach, Prentice Hall, 2009.

[99] K. Li, P.-G. Yan, Q.-Y. Cai, Quantum computing and the security of public key cryptography, Fundam. Res. 1 (2021) 85–87, https://doi.org/10.1016/j.fmre.2020.12.001.

[100] B. Koziel, R. Azarderakhsh, M.M. Kermani, D. Jao, Post-quantum cryptography on FPGA based on isogenies on elliptic curves, IEEE Trans. Circuits Syst. I Regul. Pap. 64 (2016) 86–99.

[101] J. Ding, B.-Y. Yang, Multivariate public key cryptography, in: Post-Quantum Cryptogr., Springer, 2009, pp. 193–241.

[102] D. Otorbaev, Quantum computers: China has Ambitious Plans, CGTN, 2021. https://news.cgtn.com/news/2021-08-02/Quantum-computers-China-has-ambitious-plans-12oN4j4xWUM/index.html. accessed February 4, 2022.

[103] O. Access, Europe's Quantum Flagship initiative Europe's Quantum Flagship initiative, 2019, pp. 0–6.

[104] E. Donkor, P.D. Kumavor, Prospects and challenges for the realization of quantum computers, in: Photonic Quantum Technol. Aerosp. Appl. IV, 2002, pp. 153–159.

[105] T.M. Fernandez-Carames, P. Fraga-Lamas, Towards post-quantum blockchain: a review on blockchain cryptography resistant to quantum computing attacks, IEEE Access. 8 (2020) 21091–21116, https://doi.org/10.1109/ACCESS.2020.2968985.

[106] T.A. Shaikh, R. Ali, Quantum computing in big data analytics: a survey, in: Proc. - 2016 16th IEEE Int. Conf. Comput. Inf. Technol. CIT 2016, 2016 6th Int. Symp. Cloud Serv. Comput. IEEE SC2 2016 2016 Int. Symp. Secur. Priv. Soc. Netwo., 2017, pp. 112–115, https://doi.org/10.1109/CIT.2016.79.

[107] C.G. Almudever, L. Lao, X. Fu, N. Khammassi, I. Ashraf, D. Iorga, S. Varsamopoulos, C. Eichler, A. Wallraff, L. Geck, A. Kruth, J. Knoch, H. Bluhm, K. Bertels, The engineering challenges in quantum computing, in: Proc. 2017 Des. Autom. Test Eur. DATE 2017, 2017, pp. 836–845, https://doi.org/10.23919/DATE.2017.7927104.

[108] T.M. Fernández-Caramés, From pre-quantum to post-quantum IoT security: a survey on quantum-resistant cryptosystems for the Internet of Things, IEEE Internet Things J 7 (2019) 6457–6480.

[109] M. Njorbuenwu, B. Swar, P. Zavarsky, A survey on the impacts of quantum computers on information security, in: Proc. - 2019 2nd Int. Conf. Data Intell. Secur. ICDIS 2019, 2019, pp. 212–218, https://doi.org/10.1109/ICDIS.2019.00039.

[110] C.H. Bennett, Quantum cryptography using any two nonorthogonal states, Phys. Rev. Lett. 68 (1992) 3121–3124, https://doi.org/10.1103/PhysRevLett.68.3121.

[111] R. Biswas, Z. Jiang, K. Kechezhi, S. Knysh, S. Mandrà, B. O'Gorman, A. Perdomo-Ortiz, A. Petukhov, J. Realpe-Gómez, E. Rieffel, D. Venturelli, F. Vasko, Z. Wang, A NASA perspective on quantum computing: opportunities and challenges, Parallel Comput 64 (2017) 81–98, https://doi.org/10.1016/j.parco.2016.11.002.

[112] D. Awschalom, K.K. Berggren, H. Bernien, S. Bhave, L.D. Carr, P. Davids, S.E. Economou, D. Englund, A. Faraon, M. Fejer, S. Guha, M.V. Gustafsson, E. Hu, L. Jiang, J. Kim, B. Korzh, P. Kumar, P.G. Kwiat, M. Lončar, M.D. Lukin, D.A.B. Miller, C. Monroe, S.W. Nam, P. Narang, J.S. Orcutt, M.G. Raymer, A.H. Safavi-Naeini, M. Spiropulu, K. Srinivasan, S. Sun, J. Vučković, E. Waks, R. Walsworth, A.M. Weiner, Z. Zhang, Development of quantum interConnects (QuICs) for Next-Generation information technologies, ArXiv. (2019) 1–31.

[113] M.M. Savchuk, A.V. Fesenko, Quantum computing: survey and analysis, Cybern. Syst. Anal. 55 (2019) 10–21, https://doi.org/10.1007/s10559-019-00107-w.

[114] M. Mosca, Cybersecurity in an era with quantum computers: will we be ready? IEEE Secur. Priv. 16 (2018) 38–41, https://doi.org/10.1109/MSP.2018.3761723.

[115] N. Kiefl, G. Hagel, Software engineering education of classical computing vs. quantum computing: a competency-centric approach, in: Proc. 4th Eur. Conf. Softw. Eng. Educ., 2020, pp. 27–31.

[116] M. Henderson, J. Gallina, M. Brett, Methods for accelerating geospatial data processing using quantum computers, Quantum Mach. Intell 3 (2021) 4, https://doi.org/10.1007/s42484-020-00034-6.

[117] M. Benedetti, J. Realpe-Gómez, R. Biswas, A. Perdomo-Ortiz, Estimation of effective temperatures in quantum annealers for sampling applications: a case study with possible applications in deep learning, Phys. Rev. A. 94 (2016) 22308.

[118] K. Shaw, R. Shankar, S.S. Yadav, L.S. Thakur, Supplier selection using fuzzy AHP and fuzzy multi-objective linear programming for developing low carbon supply chain, Expert Syst. Appl. 39 (2012) 8182–8192, https://doi.org/10.1016/j.eswa.2012.01.149.

[119] M.Z. Mistarihi, R.A. Okour, A.A. Mumani, An integration of a QFD model with Fuzzy-ANP approach for determining the importance weights for engineering characteristics of the proposed wheelchair design, Appl. Soft Comput. J. 90 (2020), 106136, https://doi.org/10.1016/j.asoc.2020.106136.

[120] T.L. Saaty, L.G. Vargas, Prediction, projection and forecasting: applications of the analytic hierarchy process in economics, Finance, Polit. Games, Sport. Bost. (1991).

[121] S. Kubler, J. Robert, W. Derigent, A. Voisin, Y.Le Traon, A state-of the-art survey & testbed of fuzzy AHP (FAHP) applications, Expert Syst. Appl. 65 (2016) 398–422, https://doi.org/10.1016/j.eswa.2016.08.064.

[122] A.A. Khan, M. Shameem, R.R. Kumar, S. Hussain, X. Yan, Fuzzy AHP based prioritization and taxonomy of software process improvement success factors in global software development, Appl. Soft Comput. J. 83 (2019), 105648, https://doi.org/10.1016/j.asoc.2019.105648.

[123] D.-.Y. Chang, Applications of the extent analysis method on fuzzy AHP, Eur. J. Oper. Res. 95 (1996) 649–655.

[124] T.L. Saaty, How to make a decision: the analytic hierarchy process, Interfaces (Providence) 24 (1994) 19–43.

[125] P.M. Podsakoff, D.W. Organ, Self-reports in organizational research: problems and prospects, J. Manage. 12 (1986) 531–544.

[126] R.W. Saaty, The analytic hierarchy process—What it is and how it is used, Math. Model. 9 (1987) 161–176.

[127] A. Zable, L. Hollenberg, E. Velloso, J. Goncalves, Investigating immersive virtual reality as an educational tool for quantum computing, in: 26th ACM Symp. Virtual Real. Softw. Technol., 2020, pp. 1–11.

[128] M. Mykhailova, K.M. Svore, Teaching Quantum Computing Through a Practical Software-Driven Approach Experience Report, Association for Computing Machinery, 2020, https://doi.org/10.1145/3328778.3366952.

[129] R.P. Uhlig, P.P. Dey, S. Jawad, B.R. Sinha, M. Amin, Generating student interest in quantum computing, in: 2019 IEEE Front. Educ. Conf., 2019, pp. 1–9.

[130] M.M. Van Huijstee, M. Francken, P. Leroy, Partnerships for sustainable development: a review of current literature, Environ. Sci. 4 (2007) 75–89, https://doi.org/10.1080/15693430701526336.

[131] T. Donaldson, L.E. Preston, The Stakeholder Theory of the Corporation: concep, Acad. Manag. Rev. 20 (1995) 65–91, https://doi.org/10.5465/amr.1995.9503271992.

[132] M.E. Clarkson, A stakeholder framework for analyzing and evaluating corporate social performance, Acad. Manag. Rev. 20 (1995) 92–117.
[133] X. Li, Q. Xie, L. Huang, Identifying the development trends of emerging technologies using patent analysis and web news data mining: the case of perovskite solar cell technology, IEEE Trans. Eng. Manag. (2019).
[134] K.H. Bong, Y. Shin, J. Park, Do firms' efforts matter? An innovation mechanism in public technology commercialization, IEEE Trans. Eng. Manag. (2020).
[135] S.H. Chang, The technology networks and development trends of university-industry collaborative patents, Technol. Forecast. Soc. Change. 118 (2017) 107–113, https://doi.org/10.1016/j.techfore.2017.02.006.
[136] H. Jiang, S. Zhao, S. Zhang, X. Xu, The adaptive mechanism between technology standardization and technology development: an empirical study, Technol. Forecast. Soc. Change. 135 (2018) 241–248, https://doi.org/10.1016/j.techfore.2017.11.015.
[137] G. Ruhe, others, A systematic approach for solving the wicked problem of software release planning, Soft Comput 12 (2008) 95–108.
[138] T. Ravichandran, Organizational assimilation of complex technologies: an empirical study of component-based software development, IEEE Trans. Eng. Manag. 52 (2005) 249–268.