Quantum Computing in The Cloud – A Systematic Literature Review

Review Paper

Amirul Asyraf Zhahir
Universiti Sains Islam Malaysia,
Faculty of Science and Technology,
Bandar Baru Nilai, Negeri Sembilan, Malaysia
asyrafzhahir@gmail.com

Siti Munirah Mohd
Universiti Sains Islam Malaysia,
Kolej PERMATA Insan,
Bandar Baru Nilai, Negeri Sembilan, Malaysia
smunirahm@usim.edu.my

Mohd Ilias M Shuhud
Universiti Sains Islam Malaysia,
Faculty of Science and Technology,
Bandar Baru Nilai, Negeri Sembilan, Malaysia
ilias@usim.edu.my

Bahari Idrus
Universiti Kebangsaan Malaysia,
Center for Artificial Intelligence Technology (CAIT),
Faculty of Information Science and Technology
Bangi, Selangor, Malaysia
bahari@ukm.edu.my

Hishamuddin Zainuddin
Xiamen University Malaysia,
Department of Physics,
School of Mathematics and Physics,
Sepang, Selangor, Malaysia
hishamuddinz@gmail.com

Nurhidaya Mohamad Jan
Universiti Sains Islam Malaysia,
Kolej PERMATA Insan,
Bandar Baru Nilai, Negeri Sembilan, Malaysia
nurhidaya.mj@usim.edu.my

Mohamed Ridza Wahiddin
Universiti Sains Islam Malaysia,
Tahmidi Centre,
Bandar Baru Nilai, Negeri Sembilan, Malaysia
mridza@usim.edu.my

Abstract *– Quantum computing was proposed to simulate processes that surpass the capabilities of its counterpart, classical computing. Utilizing the principles of quantum mechanics, it improves the computing power of quantum computing. Top developers namely IBM, Rigetti, D-Wave, Qutech and Google have invested greatly in the technology. Nowadays, users can access the quantum computing system publicly over the network in a cloud environment, this system architecture is known as cloud-based quantum computing. However, different developers deliver different architecture and functionality of the system on their platforms. This has indirectly spawned a question of which cloud-based quantum computing platform is a better option based on certain specific requirements by an individual or group. The main objective of this study is to provide a proposed framework using the existing cloud-based service of quantum computing based on previous studies for users with their specific demands.*

Keywords*:* *cloud-based quantum computing, quantum processors, quantum software development kits, quantum simulators*

1. INTRODUCTION

Quantum computing was initially intended to simulate processes surpassing the capabilities of its counterpart [1-7]. The core concept of quantum computing was principally harnessed from quantum mechanics [8, 9]. The main difference between quantum and classical mechanics is that quantum mechanics observes objects microscopically while classical mechanics observes objects macroscopically.

Same train but different coaches, quantum mechanics and classical mechanics are both extremely important in physics. In quantum computation, it harvested these main elements from quantum mechanics namely quantum entanglement, qubit (quantum bit) and superposition [10-13]. Substantially, combining these elements would definitely elevates the computing power in quantum computer.

Quantum entanglement is one of the most explored features in quantum mechanics, which is a critical element in areas, especially quantum computing. This feature is a catalyst in demonstrating the advantage of quantum computing over its adversary, classical computing. Qubit (quantum bit) is the basic unit of information carried in quantum information.

To put it into perspective, classical computing uses bit (0s or 1s) to carry its information while qubit (0s and 1s) is used in quantum computing [14-16]. A qubit vector state unit can be presented as $|0\rangle = \begin{bmatrix}1\\0\end{bmatrix}$ and $|1\rangle = \begin{bmatrix}0\\1\end{bmatrix}$.

Superposition may be described as a quantum system that is in multiple states at a given time until it is interrupted, usually by measurement [17, 18]. Created by entangled quantum subsystem, superposition exists when two or more quantum states are overlapped, it produces another valid quantum state. Mathematically, it can be denoted as $|\psi\rangle=\alpha|0\rangle+\beta|1\rangle$.

The attention towards quantum computing, a subdivision of quantum information theory has been growing over the past years not only in scientific research domain but also the industrial technology [19]. Some leading companies namely IBM, Google, Rigetti, D-Wave and Intel are investing greatly in developing the technology [20, 21]. Aside from private sector players, some countries are also joining the race for quantum technologies, including the United States, China, Britain and others [22]. It is not surprising as quantum technologies could be a significant asset, or even a threat for some.

Harnessing the principles of quantum mechanics, the quantum computing power has been growing over the years, demonstrating its capabilities over classical computing in solving complex problems in remarkable amount of time [23, 24]. Experts refer this as achieving the quantum supremacy or quantum advantage [25]. Quantum computing may definitely revolutionize various areas such as cryptography, chemistry, finance and machine learning [26-37].

Preskill [38] coined the term NISQ era, which stands for Noisy Intermediate-Scale Quantum, referred the phrase "Noisy" to be the inability to perfectly control the qubits [39, 40]. While the phrase "intermediate-scale" to be the size of quantum processors, suggested the range to be between 50 to a few hundred qubits is the milestone. This has been proven by top developers such as IBM and Google as they have developed quantum computing devices in the range asserted [41, 42].

Even though a considerably massive progress has been achieved in quantum computing, it is still a long way to go for quantum computer to be a reliable and fault-tolerant device. That said, the vigorously expanding technology should be regarded as a step towards developing a more powerful quantum computing in the future [25].

The goal to provide access of the functional quantum device to research community, clients and public users has yielded a new computer system architecture; cloud-based quantum computing [43, 44]. It serves as a connection medium between users and the quantum systems through the network via classical devices, which allows users to access the technology through the quantum cloud without even the need to have a physical quantum device.

Furthermore, these cloud-based quantum computing platforms came with software packages namely IBM's Qiskit, Google's Cirq and Rigetti's Forest which enable users to create and execute quantum algorithms on the platforms [45]. These providers also provide a manual as a guideline to use their respective quantum computing platforms.

Different developers deliver a different architecture design and functionality of their cloud-based quantum computing platforms [20, 46]. For instance, IBM's quantum computing platform enables users to do visual programming as well as code programming, while Qutech's quantum computing platform only allows users to do code programming. These indirectly prompted a dispute on which cloud-based quantum computing platforms are the most suitable for one, according to one's objective and specification on solving a complex computational problem or even exploring the technology.

In this context, this study aims to provide a general overview on the quantum computing technology, identify several existing cloud-based quantum computing platforms as well as providing a proposed framework of using the existing service of quantum computers for potential users; physicists, computer scientist, researchers, and beginners based on their specific needs, leveraging the existing cloud-based quantum computing platforms.

Contemplating from previous studies, a comprehensive analysis of various cloud-based quantum computing platforms and their functionalities is presented. By considering the specific needs, demands and skills of individual users or groups, the proposed framework aims to assist in selecting the optimal cloud-based quantum computing platform.

The significance of this review lies in its potential to layout a guide map for users in deciding the best possible options of the available platforms. By offering a systematic evaluation and comparison of the platforms' architectures and functionalities, aligned with the specific requirements set, this review is set to enhance the accessibility and usability experience of cloud-based quantum computing systems.

This paper is organized as follows. Section 2 describes the research methodology in detail. Section 3 discusses the foundations of quantum computing with the proposed conceptual framework and section 4 concludes the study.

2. MATERIALS AND METHODS

Publication standards implemented in this study will be discussed in this section which include items; (1) review protocol, (2) research question formulation, (3) systematic searching strategy, (4) quality appraisal, and (5) data extraction and analysis. Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) were used as the review protocol.

2.1. PRISMA REVIEW PROTOCOL

PRISMA review protocol was used in the study [47]. The systematic literature review was conducted on the guidance of the review protocol by formulating the research questions, systematic searching strategy, the appraisal of quality and the extraction and analysis of data. The scope of research determined was cloud-based quantum computing.

2.2. RESEARCH QUESTION FORMULATION

Research questions formulated in preliminary phase serve as a guidance in conducting the systematic literature review. In accordance with the research objectives which are to provide a general overview on the quantum computing technology, identify several existing cloud-based quantum computing platforms as well as providing a proposed framework of using the existing service of quantum computers for potential users based on their specifications. The research questions formulated are: (1) What is quantum computing? (2) What are the existing quantum computing platforms for users to use or explore? (3) Which quantum computing platforms are best for users based on their specific needs?

2.3. SYSTEMATIC SEARCHING STRATEGY

The systematic searching strategy used in the study is based on these elements: identification, screening and eligibility.

2.3.1. Identification

Relevant published indexed articles and other additional sources for the review was determined at this level. Indexed articles were primarily selected from the two of the most powerful multidisciplinary search engines, Scopus and Web of Science (WOS), as well as Google Scholar as an additional database. As part of a thorough search, field tags “TITLE-ABS-KEY” (title, abstract, keyword) was used in Scopus search engine, while “TS” (topic) was used in WOS. Search strings were generated with specific keywords mainly cloud-based quantum computing, quantum cloud and cloud quantum computing divided from a complex sentence into parts to frame the subject matter more precisely in searching (see Table 1).

The search process was conducted in June 2022. Related articles derived from the same keywords were handpicked manually from Google Scholar database. A total of 1636 potential related articles were identified in the process from Scopus and WOS database through systematic searching and 178 articles were downloaded for further analysis. Moreover, an additional 3 articles were added from Google Scholar database in the process. Fig. 1 depicted the search results of systematic searching in Scopus and WOS database.

Table 1. Systematic literature review search string

Database	Search strings
Scopus	TITLE-ABS-KEY ((quantum) AND (software OR platform OR emulator* OR simulator* OR processor*))
	TITLE-ABS-KEY ((quantum*) AND (cloud* OR "cloud computing" OR "computing simulator*" OR "computing software*" OR "software platform*" OR "virtual machine" OR "computer simulator*" OR " cloud service" OR "cloud computing platform" OR "cloud-based computing"))
	TITLE-ABS-KEY ((quantum*) AND (cloud* OR "cloud computing" OR "computing simulator*" OR "computing software*" OR "software platform*" OR "virtual machine" OR "computer simulator*" OR " cloud service" OR "cloud computing platform" OR "cloud-based computing")) AND (LIMIT-TO (PUBYEAR,2022) OR LIMIT-TO (PUBYEAR,2021) OR LIMIT-TO (PUBYEAR,2020))
WOS	TS=((quantum) AND (software OR platform OR emulator* OR simulator* OR processor*))
	TS = ((quantum*) AND (cloud* OR “cloud computing" OR "computing simulator*" OR "computing software*" OR "software platform*" OR "virtual machine" OR "computer simulator*" OR " cloud service" OR "cloud computing platform" OR "cloud-based computing"))
	TS = ((quantum*) AND (cloud* OR “cloud computing" OR "computing simulator*" OR "computing software*" OR "software platform*" OR "virtual machine" OR "computer simulator*" OR " cloud service" OR "cloud computing platform" OR "cloud-based computing")) – 2020-2022

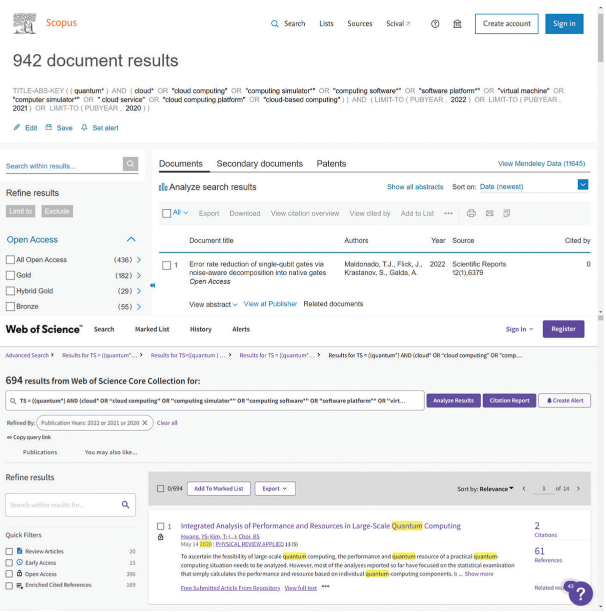

Fig. 1. Search results in Scopus and WOS databases

2.3.2. Screening

In this study, the indexed articles on the subject matter reviewed were selected based on articles published between 2015 to 2022. The maturity of the subject influenced the chosen 7-year period [48]. A total of 87 from 181 downloaded articles were excluded due to duplication of articles in both Scopus and WOS databases. The remaining articles were examined thoroughly to ensure they all meet the inclusion and exclusion criteria set in the preliminary phase. The criteria of both inclusion and exclusion were the subject matter, the type of articles, publication year and the language of articles (see Table 2).

2.3.2. Eligibility

The remaining 94 articles from screening level were then reviewed again for the suitability of the study in this level. A thorough observation was done, removing 16 articles based on their research theme which did not suit the direction of this study, cloud-based quantum computing. The remaining 78 articles were then prepared for quality appraisal (see Fig. 2).

Table 2. Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Articles related to the keywords "cloud-based quantum computing", "quantum cloud" and "cloud quantum computing"	Articles written in language other than English
Indexed journal articles	Articles published before 2015

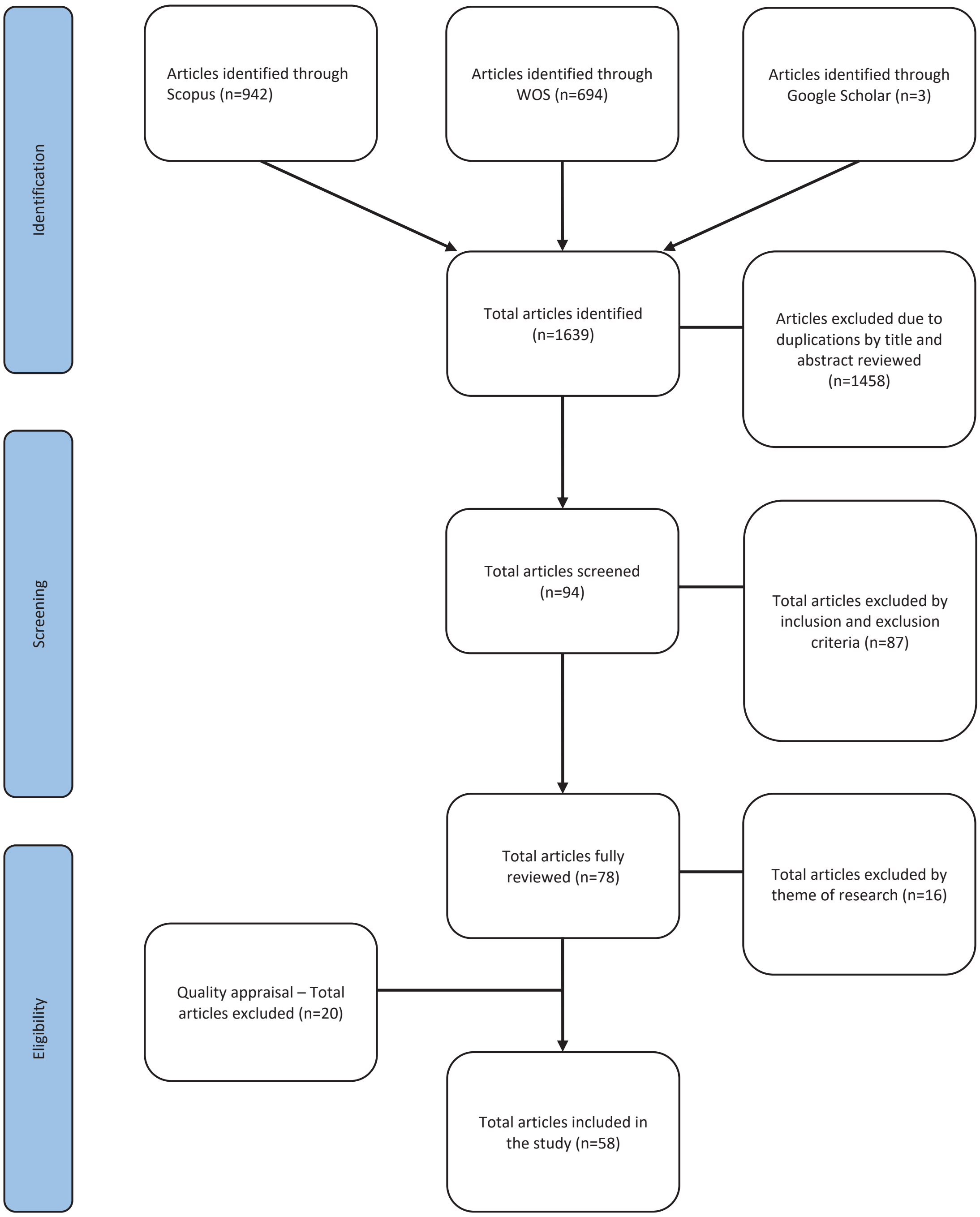

Fig. 2. Articles selection process

2.4. QUALITY APPRAISAL

In the quality appraisal phase, the remaining 78 articles selected were presented to an expert to make certain of the standard of articles used in the study. According to Petticrew & Roberts [49], the remaining articles obtained after a thorough filtering process should be ranked as high, moderate or low quality, with only high and moderate ranked standard quality articles should be included in the study.

Specific elements, namely theme, objective and results of the articles were focused by the expert to meet the standard. As a result, a total of 20 articles were excluded and the remaining 58 articles were determined suitable for the study.

2.5. DATA EXTRACTION AND ANALYSIS

In depth analysis was observed to extract relevant data from the articles. This process undergone several steps namely analysing the abstract, discussion and conclusion section, then finally the body of the articles.

The extracted data were then tabulated in Microsoft Word software in a local device for further analysis. The articles selected can be divided into groups based on the published year (see Fig. 3). There was an article published in both 2015 and 2016, 2 articles in 2018, 6 articles in 2019, 17 articles in 2020, 23 articles in 2021 and finally, 8 articles in 2022. The main theme determined of the extracted data is cloud-based quantum computing platforms. The theme will be discussed in the next section.

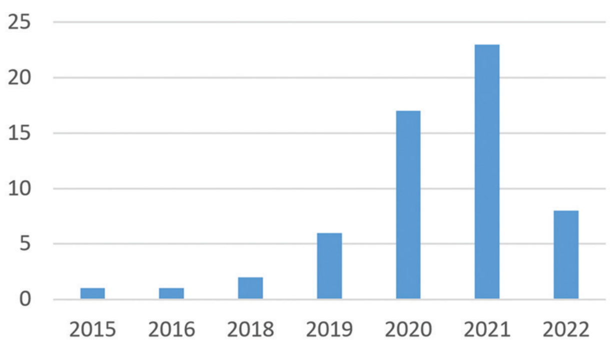

Fig. 3. Articles group by published year

3. RESULTS AND DISCUSSION

This section discusses the theme determined, the foundations of quantum computing technology comprising of the cloud-based quantum computing, quantum computing processors, quantum software development kits, quantum computing simulators and proposed conceptual framework.

3.1. CLOUD-BASED QUANTUM COMPUTING

Cloud-based quantum computing provides a quantum computing platform that can be accessed by anyone in a cloud environment which allows users to perform quantum processing tasks. Fig. 4 depicts the connection between users and quantum systems through quantum cloud.

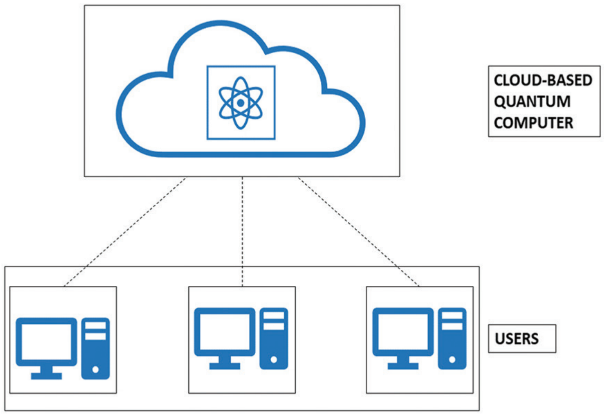

Fig. 4. Connection between users and quantum systems through quantum cloud

Leading developers of the technology have been adapting the quantum cloud concept and making it accessible for the public. Table 3 shows several existing cloud-based quantum computing platforms.

Among all available cloud-based quantum computers, it was determined that based on 58 articles accepted after quality appraisal, the used cloud-based quantum computer was summarized in Table 4. Additionally, it was determined that several articles had addressed numbers of cloud-based quantum computing platforms in its articles [20, 46, 50-59].

As shown in Fig. 5, it has been determined that the most used cloud-based quantum computing platforms from previous studies were by IBM, followed by Rigetti, D-wave, Honeywell, Qutech, Intel, IonQ, Google and Amazon.

In accordance with the pillar of this study, it can be concluded that the platform provided by IBM is the most highly acceptable platform among users. This could immensely influence the existing or potential users in the future and could also possibly shape the future of cloud-based quantum computing platforms architectures. Table 4 shows the cloud-based quantum computing platforms used in previous studies.

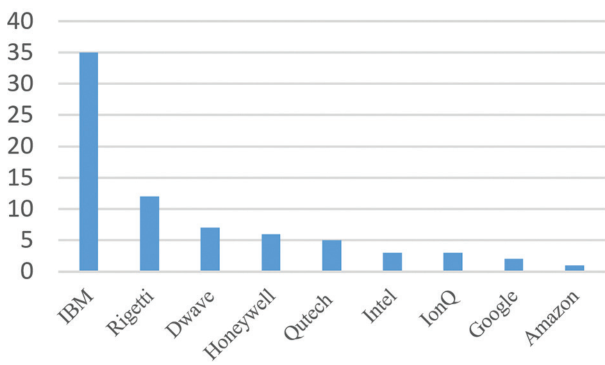

Fig. 5. The most used cloud-based quantum computing platforms from previous studies

Table 3. Existing cloud-based quantum computing platforms

Developer	Quantum cloud	Source	Descriptions
IBM	IBM Q Experience	https://quantum-computing.ibm.com/	A quantum system and simulator
D-Wave Systems	The Leap	https://www.dwavesys.com/	Provide access to a portfolio of hybrid solvers
Google	Google Quantum AI	https://quantumai.google/	A quantum system and simulator
Rigetti Computing	Forest	https://www.rigetti.com/	AI and machine learning infused quantum system
Qutech	Quantum Inspire	https://www.quantum-inspire.com/	A quantum computing platform provides a fully programmable 2-qubit electron spin quantum processor and a 5-qubit transmon processor on QX simulator
Xanadu	Xanadu Quantum Cloud	https://www.xanadu.ai/	A photonic quantum computing platform
Microsoft	Azure Quantum	https://azure.microsoft.com/en-us/	A quantum system
Amazon	Amazon Braket	https://aws.amazon.com/braket/	A quantum simulator that can be run on different quantum hardware technologies
QC Ware	Forge	https://forge.qcware.com/	Built for turn-key algorithm implementations for experts
Alpine Quantum Technologies	Pine System	https://www.aqt.eu/	Trapped ion quantum computer technology
Oxford Quantum Circuit	Quantum Computing as-a-Service (QCaaS)	https://oxfordquantumcircuits.com/	Private cloud built for strategic partners and customers
IonQ	IonQ Quantum Cloud	https://ionq.com/	Trapped ion quantum computer technology
Honeywell	Honeywell System	https://www.honeywell.com/	Trapped ion quantum computer technology

Table 4. Cloud-based quantum computing platforms used in previous studies

No.	Source	Title	Platform service
1.	[60]	Deterministic one-way logic gates on a cloud quantum computer	IBM
2.	[61]	A Novel Approach to the Implementation of Cloud-Based Quantum Programming Platforms in VR Environment	IBM
3.	[62]	Adaptive job and resource management for the growing quantum cloud	IBM
4.	[63]	Challenges and Opportunities of Near-Term Quantum Computing Systems	IBM
5.	[64]	Quantum computing: A measurement and analysis review	IBM
6.	[46]	Cloud Quantum Computing Concept and Development: A Systematic Literature Review	IBM
7.	[65]	Experimental cryptographic verification for near-term quantum cloud computing	IBM
8.	[66]	Quantum Algorithm Implementations for Beginners	IBM
9.	[58]	Measurement Crosstalk Errors in Cloud-Based Quantum Computing	IBM
10.	[67]	Error-Robust Quantum Logic Optimization Using a Cloud Quantum Computer Interface	IBM
11.	[68]	Quantum Algorithms and Experiment Implementations Based on IBM Q	IBM
12.	[69]	Quantum Pulse Coding for Rabi and Ramsey Evolution on IBM Armonk	IBM
13.	[70]	Grover algorithm-based quantum homomorphic encryption ciphertext retrieval scheme in quantum cloud computing	IBM
14.	[71]	Quantum k-means algorithm based on trusted server in quantum cloud computing	IBM
15.	[72]	Design of a quantum repeater using quantum circuits and benchmarking its performance on an IBM quantum computer	IBM
16.	[73]	Demonstration of entanglement purification and swapping protocol to design quantum repeater in IBM quantum computer	IBM
17.	[74]	Simulating molecules on a cloud-based 5-qubit IBM-Q universal quantum computer	IBM
18.	[50]	Comparison of cloud-based ion trap and superconducting quantum computer architectures	IBM
19.	[55]	Parallel quantum trajectories via forking for sampling without redundancy	IBM
20.	[53]	Quantum amplitude-amplification operators	IBM
21.	[54]	Quantum chemistry as a benchmark for near-term quantum computers	IBM
22.	[56]	Demonstration of Fidelity Improvement Using Dynamical Decoupling with Superconducting Qubits	IBM
23.	[52]	Benchmarking quantum state transfer on quantum devices	IBM
24.	[51]	Spectral quantum tomography	IBM
25.	[75]	Application of quantum machine learning using the quantum variational classifier method to high energy physics analysis at the LHC on IBM quantum computer simulator and hardware with 10 qubits	IBM
26.	[76]	Implementing efficient selective quantum process tomography of superconducting quantum gates on IBM quantum experience	IBM

27.	[77]	A verifiable (t, n) threshold quantum state sharing scheme on IBM quantum cloud platform	IBM
28.	[78]	Comparison the performance of five-qubit IBM quantum computers in terms of Bell states preparation	IBM
29.	[20]	Realizing Quantum Algorithms on Real Quantum Computing Devices	IBM
30.	[79]	Performance Analysis of the IBM Cloud Quantum Computing Lab against MacBook Pro 2019	IBM
31.	[57]	MISTIQS: An open-source software for performing quantum dynamics simulations on quantum computers	IBM
32.	[80]	Qiskit pulse: programming quantum computers through the cloud with pulses	IBM
33.	[81]	Cryptography in Quantum Computing	IBM
34.	[59]	Playing quantum nonlocal games with six noisy qubits on the cloud	IBM
35.	[82]	Integrated Analysis of Performance and Resource of Large-Scale Quantum Computing	IBM
36.	[43]	A quantum-classical cloud platform optimized for variational hybrid algorithms	Rigetti
37.	[58]	Measurement Crosstalk Errors in Cloud-Based Quantum Computing	Rigetti
38.	[83]	Measurement-Based Adaptation Protocol with Quantum Reinforcement Learning in a Rigetti Quantum Computer	Rigetti
39.	[50]	Comparison of cloud-based ion trap and superconducting quantum computer architectures	Rigetti
40.	[84]	Variational quantum algorithm for nonequilibrium steady states	Rigetti
41.	[55]	Parallel quantum trajectories via forking for sampling without redundancy	Rigetti
42.	[59]	Playing quantum nonlocal games with six noisy qubits on the cloud	Rigetti
43.	[57]	MISTIQS: An open-source software for performing quantum dynamics simulations on quantum computers	Rigetti
44.	[85]	Experimental Implementation of a Quantum Autoencoder via Quantum Adders	Rigetti
45.	[56]	Demonstration of Fidelity Improvement Using Dynamical Decoupling with Superconducting Qubits	Rigetti
46.	[54]	Quantum chemistry as a benchmark for near-term quantum computers	Rigetti
47.	[86]	Robust implementation of generative modeling with parametrized quantum circuits	Rigetti
48.	[87]	Intel Quantum Simulator: a cloud-ready high-performance simulator of quantum circuits	Intel
49.	[88]	Practical error modeling toward realistic NISQ simulation	Intel
50.	[89]	qHiPSTER: The Quantum High Performance Software Testing Environment	Intel
51.	[46]	Cloud Quantum Computing Concept and Development: A Systematic Literature Review	Qutech
52.	[90]	Quantum Inspire: QuTech's platform for co-development and collaboration in quantum computing	Qutech
53.	[20]	Realizing Quantum Algorithms on Real Quantum Computing Devices	Qutech
54.	[51]	Spectral quantum tomography	Qutech
55.	[52]	Benchmarking quantum state transfer on quantum devices	Qutech
56.	[91]	Performance Optimization of Quantum Computing Applications using D Wave Two Quantum Computer	D-Wave
57.	[92]	Early Warning of Heat/Cold Waves as a Smart City Subsystem: A Retrospective Case Study of Non-anticipative Analog Methodology	D-Wave
58.	[93]	Thermodynamics of a quantum annealer	D-Wave
59.	[94]	Solving the Minimum Spanning Tree Problem with a Quantum Annealer	D-Wave
60.	[95]	Solving the sparse QUBO on multiple GPUs for Simulating a Quantum Annealer	D-Wave
61.	[96]	Comparison between a quantum annealer and a classical approximation algorithm for computing the ground state of an Ising spin glass	D-Wave
62.	[97]	Optimizing the Selection of Recommendation Carousels with Quantum Computing	D-Wave
63.	[50]	Comparison of cloud-based ion trap and superconducting quantum computer architectures	IONQ
64.	[53]	Quantum amplitude-amplification operators	IONQ
65.	[59]	Playing quantum nonlocal games with six noisy qubits on the cloud	IONQ
66.	[59]	Playing quantum nonlocal games with six noisy qubits on the cloud	Honeywell
67.	[98]	Entanglement from Tensor Networks on a Trapped-Ion Quantum Computer	Honeywell
68.	[99]	Filtering variational quantum algorithms for combinatorial optimization	Honeywell
69.	[100]	Suppression of midcircuit measurement crosstalk errors with micromotion	Honeywell
70.	[101]	The efficient preparation of normal distribution in quantum registers	Honeywell
71.	[102]	Qubit efficient entanglement spectroscopy using qubit resets	Honeywell
72.	[103]	Large scale multi-node simulations of Z2 gauge theory quantum circuits using Google Cloud Platform	Google
73.	[57]	MISTIQS: An open-source software for performing quantum dynamics simulations on quantum computers	Google
74.	[104]	Quantum Software as a Service Through a Quantum API Gateway	Amazon

3.2. QUANTUM COMPUTING PROCESSORS

One of the core components of a quantum computer, quantum computing processors also referred as quantum processing unit (QPUs) or quantum chip is a set of physically built electronic circuit, housing numbers of interconnected qubits [43]. The most known quantum processing unit (QPUs) types in quantum computing are circuit-based quantum processors and annealing quantum processors [8, 62, 105, 106]. Table 5 briefly describes the differences between circuit-based quantum processors and annealing quantum processors.

Based on Table 5, the circuit-based quantum processors use gate model, which means that it requires the problems to be expressed in quantum gates [107]. While in annealing quantum processors, mainly solves optimization problems but it requires the problems to be expressed in the operations language [105]. Furthermore, due to high sensitivity to noise, the circuit-based quantum processors find it difficult to produce a stable qubits state compared to annealing quantum processors. Moreover, the annealing quantum processors are less user-friendly compared to circuit-based quantum processors in term of operation due to the operations language used especially to beginners of quantum computing. Some circuit-based and annealing quantum processors devices were listed in Table 6 and Table 7 respectively.

Table 5. The differences between Circuit-based quantum processors and Annealing quantum processors

Circuit-based quantum processors	Annealing quantum processors
Gate model	Quantum annealing
Drag-and-drop tools and codes	Operations language codes
Poor qubits stability	Good qubits stability
Extremely sensitive to noise	Less affected by noise
User friendly	Less user-friendly

Table 6. Circuit-based quantum processors devices

Developer	Name	Architecture	Qubit(s)	Release year
Google	Bristlecone	Superconducting transmon	72	2018
	Sycamore	Superconducting transmon	53	2019
IBM	Eagle	Superconducting	127	2021
	Hummingbird	Superconducting	65	2020
	Falcon	Superconducting	27	2019
	Canary family	Superconducting	5-16	2017
Intel	Tangle Lake	Superconducting	49	2018
IonQ	Aria	Trapped Ion	32	2020
QuTech	Starmon-5	Superconducting	5	2020
	Spin-2	Semiconductor spin qubits	2	2020
Rigetti	Aspen-M-1	Superconducting	80	2022
	Aspen-11	Superconducting	80	2021
Xanadu	Borealis	Photonics	216	2022
	X12	Photonics	12	2020
	X8	Photonics	8	2020

Table 7. Annealing quantum processors devices

Developer	Name	Architecture	Qubit(s)	Release year
D-Wave	D-Wave 2X	Superconducting	1152	2015
	D-Wave 2000Q	Superconducting	2048	2017
	D-Wave Advantage	Superconducting	5760	2020

For one to claim which quantum processors are better than the other may not be wise as it depends on one's objectives and experiences. As listed in Table 6 and Table 7, superconducting is the most preferred by developers as an architecture of a quantum computing system. This is due to its advantages which are, high designability, scalability, easy to couple and easy to control [60, 108].

Furthermore, developers seem to prefer the circuit-based over annealing quantum processors. This may have been influenced by the complexity of annealing quantum processors language of operations. In addition, towards the end of 2021, D-Wave Systems announced in a conference that its organization are keen to adopt the circuit-based quantum processors into their next-generation quantum computing platform which includes both annealing and circuit-based model [109].

Top developers such as IBM and D-Wave Systems are working in full swing towards developing reliable, fault-tolerance, NISQ quantum devices. In accordance, both developers among others have produced a development roadmap of their quantum computer technology for the coming years. IBM's near-term goals is to achieve an astonishing over 1000 qubits by the end of 2023 [110, 111]. While D-Wave Systems aiming with its next-generation Advantage 2 quantum system which contains over 7000 qubits in the coming years [109].

These quantum race on the road to quantum advantage has paved the way for a promising future of quantum computing. As stated by Preskill [38], even though it is still a long way to achieve the promising future of quantum computing, quantum computers will be a useful tool to solve complex problems and to explore more on other areas of the technology. Experts believe it will definitely benefit various fields namely security, material science and pharmaceuticals. In addition, the creation of quantum software development kits has been beneficial for potential users of quantum computers.

3.3. QUANTUM SOFTWARE DEVELOPMENT KITS

Quantum software development kits are a tool for users to develop quantum algorithms to be executed in a quantum computer. Some developers namely IBM, Rigetti and Google developed an open-source quantum software development kit. These developed kits allow users to utilize classical programming language such as Python or even quantum programming language such as Q#. By using these kits provided, users can run and solve problems through the cloud accessing the available quantum computer platforms available. Table 8 shows several known developers' quantum software development kits and brief descriptions.

3.4. QUANTUM COMPUTING SIMULATORS

Quantum computing simulator is a device allowing users to solve computational problems in a programming environment adhering to the principles of quantum mechanics. It performs quantum gates operation by the use of classical gates. Presently, various existing quantum computing simulators developed are considerably hospitable as it serves users to access with classical programming languages, catering their needs. This occasion will likely draw more potential users to explore quantum computing technology. Several quantum computing simulators were tabulated in Table 9.

3.5. CONCEPTUAL FRAMEWORK OF USING CLOUD-BASED QUANTUM COMPUTING SERVICE

As part of the main objective of this study, which to provide a conceptual framework of using cloud-based quantum computing service, the conceptual framework was developed on the basis of the cloud-based quantum computing platforms used in previous studies with quantum simulators, software development kits and language. The proposed conceptual framework will only cover several quantum computing platforms of circuit-based quantum processors, not the annealing quantum processors quantum computers. Fig. 6 illustrates the proposed conceptual framework of using cloud-based quantum computing service.

Table 8. Quantum software development kits

Developer	Name	Language
IBM (https://www.ibm.com/quantum)	Qiskit	Open QASM/Python
D-Wave (https://www.dwavesys.com/)	Ocean	Qbsolv/QMASM/Python
Rigetti (https://www.rigetti.com/)	Forest	Quil
Xanadu (https://www.xanadu.ai/)	PennyLane	Blackbird/ Python/C++/Java/C#/JavaScript
Google (https://quantumai.google/)	Cirq	Python
Microsoft (https://azure.microsoft.com/en-us/)	Quantum Development Kit	Q#/Python/C#/F#
Amazon (https://aws.amazon.com/braket/)	Braket	Python
Intel (https://www.intel.com/content/www/us/en/research/quantum-computing.html)	N/A	C/C++
Qutech (https://qutech.nl/)	Quantum Inspire	cQASM/Python
Cambridge Quantum Computing (https://cambridgequantum.com/)	Tket	Python

Table 9. Quantum computing simulators

Source	Developer	Software Development Kit	Simulator
https://quantum-computing.ibm.com/lab/docs/iql/manage/simulator/	IBM	Qiskit	QASM, Statevector, stabilizer, extended stabilizer, Matrix Product State (MPS)
https://pyquil-docs.rigetti.com/en/1.9/qvm.html	Rigetti	Forest	Quantum Virtual Machine (QVM)
https://www.xanadu.ai/products/lightning/ https://www.xanadu.ai/products/jet/	Xanadu	PennyLane Strawberry Fields	Lightning and Jet
https://quantumai.google/cirq	Google	Cirq	cirq.Simulator (pure state) and cirq.DensityMatrixSimulator (mixed state)
https://visualstudio.microsoft.com/	Microsoft	Quantum Development Kit	Visual Studio
https://github.com/iqusoft/intel-qs https://intel-qs.readthedocs.io/en/docs/getting-started.html	Intel	N/A	Intel Parallel Studio Compiler/Intel-Quantum Simulator (IQS)
http://quantum-studio.net/ https://github.com/QuTech-Delft/qx-simulator	Qutech	Quantum Inspire	QX Simulator

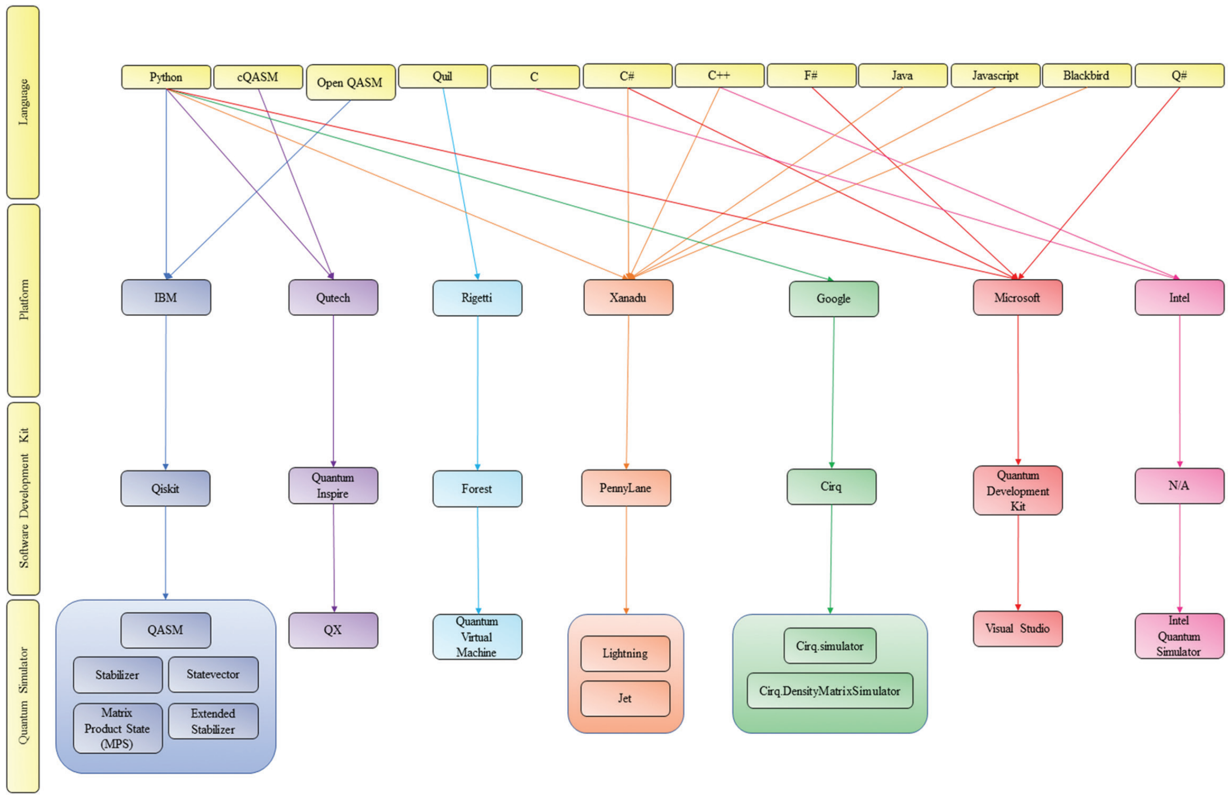

Fig. 6. Proposed conceptual framework

4. CONCLUSION

Utilizing developed cloud-based quantum computing platforms poses challenges for potential individual users or groups as different developers deliver different architecture and functionality of the existing platforms. This disparity sparks a dispute on which cloud-based quantum computing platforms are the most suitable based on one's specific requirements and needs.

This study presents a comprehensive overview of the fundamentals of quantum computing with several existing numbers of cloud-based quantum computing platforms used in earlier studies. Additionally, it has discussed quantum computing processors, quantum software development kits and quantum computing simulators. Furthermore, a conceptual framework of using cloud-based quantum computing services as a guidance and reference for future work is delivered, enabling users to navigate cloud-based quantum computing services by particular requirements and needs by an individual or groups.

The understanding and development of quantum computing technology is progressing rapidly. However, developed cloud-based quantum computing platforms are still not considerably inclusive to existing and potential users. Future research efforts should be built upon the proposed conceptual framework to develop a universal cloud-based quantum computer that addresses the diverse needs of users.

In conclusion, this study aids as a valuable resource for individuals and groups interested in getting a first-hand experience on quantum computing. By offering insights into the complexities of quantum computing platforms and providing a framework for choosing the best options available, this review aims to enhance the accessibility and usability of these systems. Future advancements aligned with the proposed framework will contribute to the realization of more universal cloud-based quantum computing platforms.

5. ACKNOWLEDGEMENT

This research is part of a research project supported by the Malaysian Ministry of Higher Education Fundamental Research Grant Nos. FRGS/1/2021/ICT04/USIM/01/1 (USIM/FRGS/KGI/KPT/50121).

6. REFERENCES

[1] S. M. Ardelean, M. Udrescu, "Graph coloring using the reduced quantum genetic algorithm", PeerJ Computer Science, Vol. 8, 2022, p. e836.

[2] D. Maslov, J.-S. Kim, S. Bravyi, T. J. Yoder, S. Sheldon, "Quantum advantage for computations with limited space", Nature Physics, Vol. 17, No. 8, 2021, pp. 894-897.

[3] G. Nannicini, L. S. Bishop, O. Günlük, P. Jurcevic, "Optimal qubit assignment and routing via integer programming", ACM Transactions on Quantum Computing Vol. 4, No. 1, 2022, pp. 1-31.

[4] K. Seyhan, S. Akleylek, "Indistinguishability under adaptive chosen-ciphertext attack secure double-NTRU-based key encapsulation mechanism", PeerJ Computer Science, Vol. 9, 2023, p. e1391.

[5] A. Singh, H. Singh, K. Dorai, "Experimental classification of entanglement in arbitrary three-qubit pure states on an NMR quantum information processor", Physical Review A, Vol. 98, No. 3, 2018, p. 032301.

[6] R. Wille, S. Hillmich, L. Burgholzer, "Tools for Quantum Computing Based on Decision Diagrams", ACM Transactions on Quantum Computing, Vol. 3, No. 3, 2022, pp. 1-17.

[7] X. Wu, "Introduction to the Special issue on the Techniques of Programming Languages, Logic, and Formal Methods in Quantum Computing", ACM Transactions on Quantum Computing, Vol. 2, No. 4, 2021, pp. 1-3.

[8] D. Chen, "Intelligent Retrieval Platform for University Digital Resources Based on Quantum Cloud Computing", Proceedings of the Fifth International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud), Palladam, India, 11-13 November 2021, pp. 633-636.

[9] Y. Xu et al. "Automatic Qubit Characterization and Gate Optimization with QubiC", ACM Transactions on Quantum Computing Vol. 4, No. 1, 2022, pp. 1-12.

[10] Y. Y. Ghadi, T. AlShloul, Z. I. Nezami, H. Ali, M. Asif, H. Aljuaid, S. Ahmad, "An efficient optimizer for the 0/1 knapsack problem using group counseling", PeerJ Computer Science, Vol. 9, 2023, p. e1315.

[11] Abhijith J. et al. "Quantum Algorithm Implementations for Beginners", ACM Transactions on Quantum Computing, Vol. 3, No. 4, 2022, pp. 1-92.

[12] A. Li, S. Stein, S. Krishnamoorthy, J. Ang, "QASMBench: A Low-Level Quantum Benchmark Suite for NISQ Evaluation and Simulation", ACM Transactions on Quantum Computing, Vol. 4, No. 2, 2023, pp. 1-26.

[13] Y. Shingu, Y. Takeuchi, S. Endo, S. Kawabata, S. Watabe, T. Nikuni, H. Hakoshima, Y. Matsuzaki, "Variational secure cloud quantum computing", Physical Review A, Vol. 105, No. 2, 2022, p. 022603.

[14] H. F. Fakhruldeen, R. A. Alkaabi, I. Jabbar, I. Al-Kharsan, S. Shoja, "Post-quantum Techniques in Wireless Network Security: An Overview", Malaysian Journal of Fundamental and Applied Sciences, Vol. 19, 2023, pp. 337-344.

[15] P. Fremantle, P. Scott, "A survey of secure middleware for the Internet of Things", PeerJ Computer Science, Vol. 3, 2017, p. e114.

[16] K. K. Soni, A. Rasool, "Quantum-effective exact multiple patterns matching algorithms for biological sequences", PeerJ Computer Science, Vol. 8, No., 2022, p. e957.

[17] X.-J. Huang et al. "Entanglement-interference complementarity and experimental demonstration in a superconducting circuit", Quantum Information, Vol. 9, No. 1, 2023, p. 43.

[18] A. Ivashkin, D. Abdurashitov, A. Baranov, F. Guber, S. Morozov, S. Musin, A. Strizhak, I. Tkachev, "Testing entanglement of annihilation photons", Scientific Reports, Vol. 13, No. 1, 2023, p. 7559.

[19] A. Suau, G. Staffelbach, H. Calandra, "Practical Quantum Computing: Solving the Wave Equation Using a Quantum Approach", ACM Transactions on Quantum Computing, Vol. 2, No. 1, 2021, pp. 1-35.

[20] C. G. Almudever, L. Lao, R. Wille, G. G. Guerreschi, "Realizing Quantum Algorithms on Real Quantum Computing Devices", arXiv:2007.01000, 2020.

[21] S. Hillmich, A. Zulehner, R. Kueng, I. L. Markov, R. Wille, "Approximating Decision Diagrams for Quantum Circuit Simulation", ACM Transactions on Quantum Computing, Vol. 3, No. 4, 2022, pp. 1-21.

[22] M. Messmer, J. Shires, A. V. Rij, "Quantum technology competition must not become an arms race", https://www.chathamhouse.org/publications/the-world-today/2023-10/quantum-technology-competition-must-not-become-arms-race (accessed: 2023)

[23] X. Wang, J. Huang, Z. Duan, Y. Xu, Y. Yao, "Randomness analysis of end-to-end delay in random forwarding networks", PeerJ Computer Science, Vol. 8, 2022, p. e942.

[24] A. A. Zhahir, S. M. Mohd, M. I. M. Shuhud, B. Idrus, H. Zainuddin, N. M. Jan, M. R. Wahiddin, "Quantum Computing and Its Application", International

Journal of Advanced Research in Technology and Innovation, Vol. 4, No. 1, 2022, pp. 55-65.

[25] J. Preskill, "Quantum computing 40 years later", arXiv:2106.10522, 2021.

[26] A. M. Aboussalah, C. Chi, C.-G. Lee, "Quantum computing reduces systemic risk in financial networks", Scientific Reports, Vol. 13, No. 1, 2023, p. 3990.

[27] P. Díez-Valle et al. "Multiobjective variational quantum optimization for constrained problems: an application to cash handling", Quantum Science and Technology, Vol. 8, No. 4, 2023, p. 045009.

[28] D. Herman, C. Googin, X. Liu, Y. Sun, A. Galda, I. Safro, M. Pistoia, Y. Alexeev, "Quantum computing for finance", Nature Reviews Physics, Vol. 5, No. 8, 2023, pp. 450-465.

[29] Z. Udvarnoki, G. Fáth, N. Fogarasi, "Quantum advantage of Monte Carlo option pricing", Journal of Physics Communications, Vol. 7, No. 5, 2023, p. 055001.

[30] R. K. Ahalya, F. M. Almutairi, U. Snekhalatha, V. Dhanraj, S. M. Aslam, "RANet: a custom CNN model and quanvolutional neural network for the automated detection of rheumatoid arthritis in hand thermal images", Scientific Reports, Vol. 13, No. 1, 2023, p. 15638.

[31] B. Fliszkiewicz, M. Sajdak, "Fragments quantum descriptors in classification of bio-accumulative compounds", Journal of Molecular Graphics and Modelling, Vol. 125, 2023, p. 108584.

[32] A. Ajagekar, F. You, "Molecular design with automated quantum computing-based deep learning and optimization", Computational Materials, Vol. 9, No. 1, 2023, p. 143.

[33] J. Kim, J. Huh, D. K. Park, "Classical-to-quantum convolutional neural network transfer learning", Neurocomputing, Vol. 555, 2023, p. 126643.

[34] C. Feniou, M. Hassan, D. Traoré, E. Giner, Y. Maday, J.-P. Piquemal, "Overlap-ADAPT-VQE: practical quantum chemistry on quantum computers via overlap-guided compact Ansätze", Communications Physics, Vol. 6, No. 1, 2023, p. 192.

[35] C. Cao, J. Sun, X. Yuan, H.-S. Hu, H. Q. Pham, D. Lv, "Ab initio quantum simulation of strongly correlated materials with quantum embedding", Computational Materials, Vol. 9, No. 1, 2023, p. 78.

[36] N. S. Kirsanov, V. A. Pastushenko, A. D. Kodukhov, M. V. Yarovikov, A. B. Sagingalieva, D. A. Kronberg, M. Pflitsch, V. M. Vinokur, "Forty thousand kilometers under quantum protection", Scientific Reports, Vol. 13, No. 1, 2023.

[37] H. C. Ukwuoma, G. Arome, A. Thompson, B. K. Alese, "Post-quantum cryptography-driven security framework for cloud computing", Open Computer Science, Vol. 12, No. 1, 2022, pp. 142-153.

[38] J. Preskill, "Quantum computing in the NISQ era and beyond", Quantum, Vol. 2, 2018, p. 79.

[39] C.-C. Chen, M. Watabe, K. Shiba, M. Sogabe, K. Sakamoto, T. Sogabe, "On the Expressibility and Overfitting of Quantum Circuit Learning", ACM Transactions on Quantum Computing, Vol. 2, No. 2, 2021, pp. 1-24.

[40] X. Fu et al. "Quingo: A Programming Framework for Heterogeneous Quantum-Classical Computing with NISQ Features", ACM Transactions on Quantum Computing, Vol. 2, No. 4, 2021, pp. 1-37.

[41] P. Ball, "First quantum computer to pack 100 qubits enters crowded race", Vol. 599, 2021, p. 542.

[42] M. Günes, H. Majumdar, P. Muratore-Ginanneschi, J. Pekola, "InstituteQ: The Finnish National Quantum Institute", Arkhimedes, 2022.

[43] P. J. Karalekas, N. A. Tezak, E. C. Peterson, C. A. Ryan, M. P. da Silva, R. S. Smith, "A quantum-classical cloud platform optimized for variational hybrid algorithms", Quantum Science and Technology, Vol. 5, No. 2, 2020, p. 024003.

[44] A. Mccaskey, T. Nguyen, A. Santana, D. Claudino, T. Kharazi, H. Finkel, "Extending C++ for Heterogeneous Quantum-Classical Computing", ACM Transactions on Quantum Computing, Vol. 2, No. 2, 2021, pp. 1-36.

[45] A. A. Saki, M. Alam, K. Phalak, A. Suresh, R. O. Topaloglu, S. Ghosh, "A survey and tutorial on security and resilience of quantum computing", Proceedings of the IEEE European Test Symposium, Bruges, Belgium, 24-28 May 2021, pp. 1-10.

[46] H. Soeparno, A. S. Perbangsa, "Cloud Quantum Computing Concept and Development: A Sys-

tematic Literature Review", Procedia Computer Science, Vol. 179, 2021, pp. 944-954.

[47] M. J. Page et al. "The PRISMA 2020 statement: an updated guideline for reporting systematic reviews", BMJ, Vol. 372, 2021, p. 71.

[48] S. Kraus, M. Breier, S. Dasí-Rodríguez, "The art of crafting a systematic literature review in entrepreneurship research", International Entrepreneurship and Management Journal, Vol. 16, No. 3, 2020, pp. 1023-1042.

[49] M. Petticrew, H. Roberts, "Systematic Reviews in the Social Sciences: A Practical Guide", Wiley, 2006.

[50] S. Blinov, B. Wu, C. Monroe, "Comparison of cloud-based ion trap and superconducting quantum computer architectures", AVS Quantum Science, Vol. 3, No. 3, 2021, p. 033801.

[51] J. Helsen, F. Battistel, B. M. Terhal, "Spectral quantum tomography", npj Quantum Information, Vol. 5, No. 1, 2019, p. 74.

[52] Y.-T. Huang, J.-D. Lin, H.-Y. Ku, Y.-N. Chen, "Benchmarking quantum state transfer on quantum devices", Physical Review Research, Vol. 3, No. 2, 2021, p. 023038.

[53] H. Kwon, J. Bae, "Quantum amplitude-amplification operators", Physical Review A, Vol. 104, No. 6, 2021, p. 062438.

[54] A. J. McCaskey, Z. P. Parks, J. Jakowski, S. V. Moore, T. D. Morris, T. S. Humble, R. C. Pooser, "Quantum chemistry as a benchmark for near-term quantum computers", Quantum Information, Vol. 5, No. 1, 2019, p. 99.

[55] D. K. Park, I. Sinayskiy, M. Fingerhuth, F. Petruccione, J.-K. K. Rhee, "Parallel quantum trajectories via forking for sampling without redundancy", New Journal of Physics, Vol. 21, No. 8, 2019, pp. 083024.

[56] B. Pokharel, N. Anand, B. Fortman, D. A. Lidar, "Demonstration of fidelity improvement using dynamical decoupling with superconducting qubits", Physical review letters, Vol. 121, No. 22, 2018, p. 220502.

[57] C. Powers, L. Bassman, T. M. Linker, K.-i. Nomura, S. Gulania, R. K. Kalia, A. Nakano, P. Vashishta, "MISTIQS: An open-source software for performing quantum dynamics simulations on quantum computers", SoftwareX, Vol. 14, 2021, p. 100696.

[58] S. Seo, J. Bae, "Measurement Crosstalk Errors in Cloud-Based Quantum Computing", IEEE Internet Computing, Vol. 26, No. 1, 2021, pp. 26-33.

[59] M. Sheffer, D. Azses, E. G. D. Torre, "Playing Quantum Nonlocal Games with Six Noisy Qubits on the Cloud", Advanced Quantum Technologies, Vol. 5, No. 3, 2022, p. 2100081.

[60] Z.-P. Yang et al. "Deterministic one-way logic gates on a cloud quantum computer", Physical Review A, Vol. 105, No. 4, 2022, p. 042610.

[61] H. H. Genç, S. Aydın, H. Erdal, "A Novel Approach to the Implementation of Cloud-Based Quantum Programming Platforms in VR Environment", Proceedings of the Innovations in Intelligent Systems and Applications Conference, Istanbul, Turkey, 15-17 October 2020, pp. 1-6.

[62] G. S. Ravi, K. N. Smith, P. Murali, F. T. Chong, "Adaptive job and resource management for the growing quantum cloud", Proceedings of the IEEE International Conference on Quantum Computing and Engineering, Broomfield, CO, USA, 17-22 October 2021, pp. 301-312.

[63] A. D. Córcoles et al. "Challenges and opportunities of near-term quantum computing systems", arXiv:1910.02894, 2019.

[64] M. Gupta, M. J. Nene, "Quantum computing: A measurement and analysis review", Concurrency and Computation: Practice and Experience, Vol. 33, No. 20, 2021, p. e6344.

[65] Chen, X., B. Cheng, Z. Li, X. Nie, N. Yu, M.-H. Yung, X. Peng, "Experimental cryptographic verification for near-term quantum cloud computing", Science Bulletin, Vol. 66, No. 1, 2021, pp. 23-28.

[66] A. Adedoyin et al. "Quantum algorithm implementations for beginners", arXiv:1804.03719, 2018.

[67] A. R. R. Carvalho, H. Ball, M. J. Biercuk, M. R. Hush, F. Thomsen, "Error-Robust Quantum Logic Optimization Using a Cloud Quantum Computer Interface", Physical Review Applied, Vol. 15, No. 6, 2021, p. 064054.

[68] W. Liu, J. Chen, Y. Xu, J. Tang, L. Tong, X. Song, "Quantum Algorithms and Experiment Implementations Based on IBM Q", Computers, Materials & Continua, Vol. 65, No. 2, 2020, pp. 1671-1689.

[69] M. A. Ullah, A. Farooq, Y. Jeong, H. Shin, "Quantum Pulse Coding for Rabi And Ramsey Evolution on IBM Armonk", Proceedings of the International Conference on Information and Communication Technology Convergence, Jeju Island, Korea, 20-22 October 2021, pp. 848-850.

[70] C. Gong, J. Du, Z. Dong, Z. Guo, A. Gani, L. Zhao, H. Qi, "Grover algorithm-based quantum homomorphic encryption ciphertext retrieval scheme in quantum cloud computing", Quantum Information Processing, Vol. 19, No. 3, 2020, pp. 105.

[71] C. Gong, Z. Dong, A. Gani, H. Qi, "Quantum k-means algorithm based on trusted server in quantum cloud computing", Quantum Information Processing, Vol. 20, No. 4, 2021, p. 130.

[72] S. Das, M. S. Rahman, M. Majumdar, "Design of a quantum repeater using quantum circuits and benchmarking its performance on an IBM quantum computer", Quantum Information Processing, Vol. 20, No. 7, 2021, p. 245.

[73] B. K. Behera, S. Seth, A. Das, P. K. Panigrahi, "Demonstration of entanglement purification and swapping protocol to design quantum repeater in IBM quantum computer", Quantum Information Processing, Vol. 18, No. 4, 2019, p. 108.

[74] S. Leontica, F. Tennie, T. Farrow, "Simulating molecules on a cloud-based 5-qubit IBM-Q universal quantum computer", Communications Physics, Vol. 4, No. 1, 2021, p. 112.

[75] S. L. Wu et al. "Application of quantum machine learning using the quantum variational classifier method to high energy physics analysis at the LHC on IBM quantum computer simulator and hardware with 10 qubits", Journal of Physics G: Nuclear and Particle Physics, Vol. 48, No. 12, 2021, pp. 125003.

[76] A. Gaikwad, K. Shende, Arvind, K. Dorai, "Implementing efficient selective quantum process tomography of superconducting quantum gates on IBM quantum experience", Scientific Reports, Vol. 12, No. 1, 2022, p. 3688.

[77] X. Song, Y. Liu, M. Xiao, H. Deng, S. Yang, "A verifiable (t, n) threshold quantum state sharing scheme on IBM quantum cloud platform", Quantum Information Processing, Vol. 19, No. 9, 2020, p. 337.

[78] M. Sisodia, "Comparison the performance of five-qubit IBM quantum computers in terms of Bell states preparation", Quantum Information Processing, Vol. 19, No. 8, 2020, pp. 215.

[79] A. Martin Grande, R. Ayala, I. Khan, P. Sarkar, T. K. Mohd, "Performance Analysis of the IBM Cloud Quantum Computing Lab Against MacBook Pro 2019", Intelligent Human Computer Interaction, 2022, pp. 449-459.

[80] T. Alexander, N. Kanazawa, D. J. Egger, L. Capelluto, C. J. Wood, A. Javadi-Abhari, D. C. McKay, "Qiskit pulse: Programming quantum computers through the cloud with pulses", Quantum Science and Technology, Vol. 5, No. 4, 2020, p. 044006.

[81] P. Choy, D. Cates, F. Chehwan, C. Rodriguez, A. Leider, C. Tappert, "Cryptography in Quantum Computing", Advances in Intelligent Systems and Computing, 2019.

[82] Y. Hwang, T. Kim, C. Baek, B.-S. Choi, "Integrated Analysis of Performance and Resources in Large-Scale Quantum Computing", Physical Review Applied, Vol. 13, No. 5, 2020, p. 054033.

[83] J. Olivares-Sánchez, J. Casanova, E. Solano, L. Lamata, "Measurement-based adaptation protocol with quantum reinforcement learning in a Rigetti quantum computer", Quantum Reports, Vol. 2, No. 2, 2020, pp. 293-304.

[84] N. Yoshioka, Y. O. Nakagawa, K. Mitarai, K. Fujii, "Variational quantum algorithm for nonequilibrium steady states", Physical Review Research, Vol. 2, No. 4, 2020, p. 043289.

[85] Y. Ding, L. Lamata, M. Sanz, X. Chen, E. Solano, "Experimental implementation of a quantum autoencoder via quantum adders", Advanced Quantum Technologies, Vol. 2, No. 7-8, 2019, p. 1800065.

[86] V. Leyton-Ortega, A. Perdomo-Ortiz, O. Perdomo, "Robust implementation of generative modeling with parametrized quantum circuits", Quantum Machine Intelligence, Vol. 3, No. 1, 2021, p. 17.

[87] G. G. Guerreschi, J. Hogaboam, F. Baruffa, N. Sawaya, "Intel Quantum Simulator: A cloud-ready high-performance simulator of quantum circuits", arXiv:2001.10554, 2020.

[88] T. Tanimoto, S. Matsuo, S. Kawakami, Y. Tabuchi, M. Hirokawa, K. Inoue, "Practical Error Modeling Toward Realistic NISQ Simulation", Proceedings of the IEEE Computer Society Annual Symposium on VLSI, Limassol, Cyprus, 6-8 July 2020, 2020, pp. 291-293.

[89] M. Smelyanskiy, N. P. Sawaya, A. Aspuru-Guzik, "qHiPSTER: The quantum high performance software testing environment", arXiv:1601.07195, 2016.

[90] T. Last et al. "Quantum Inspire: QuTech's platform for co-development and collaboration in quantum computing", SPIE, Vol. 11324, 2020.

[91] G. Sundar, D. Narmadha, "Performance Optimization of Quantum Computing Applications using D Wave Two Quantum Computer", Proceedings of the 5th International Conference on Trends in Electronics and Informatics, Tirunelveli, India, 3-5 June 2021.

[92] Z. Dmytro, "Early Warning of Heat/Cold Waves as a Smart City Subsystem: A Retrospective Case Study of Nonanticipative Analog Methodology", BRAIN. Broad Research in Artificial Intelligence and Neuroscience, Vol. 6, 2015, pp. 44-54.

[93] L. Buffoni, M. Campisi, "Thermodynamics of a quantum annealer", Quantum Science and Technology, Vol. 5, No. 3, 2020, p. 035013.

[94] W. O'Quinn, S. Mao, "Solving the Minimum Spanning Tree Problem with a Quantum Annealer", Proceedings of the IEEE Globecom Workshops, Taipei, Taiwan, 7-11 December 2020, pp. 1-6.

[95] T. Imanaga, K. Nakano, R. Yasudo, Y. Ito, Y. Kawamata, R. Katsuki, S. Ozaki, T. Yazane, K. Hamano, "Solving the sparse QUBO on multiple GPUs for Simulating a Quantum Annealer", Proceedings of the Ninth International Symposium on Computing and Networking, Matsue, Japan, 23-26 November 2021, pp. 19-28.

[96] R. Yaacoby, N. Schaar, L. Kellerhals, O. Raz, D. Hermelin, R. Pugatch, "Comparison between a quantum annealer and a classical approximation algorithm for computing the ground state of an Ising spin glass", Physical Review E, Vol. 105, No. 3, 2022, p. 035305.

[97] M. F. Dacrema, N. Felicioni, P. Cremonesi, "Optimizing the Selection of Recommendation Carousels with Quantum Computing", Proceedings of the 15th ACM Conference on Recommender Systems, September 2021, pp. 691-696.

[98] M. Foss-Feig et al. "Entanglement from Tensor Networks on a Trapped-Ion Quantum Computer", Physical Review Letters, Vol. 128, No. 15, 2022, p. 150504.

[99] D. Amaro, C. Modica, M. Rosenkranz, M. Fiorentini, M. Benedetti, M. Lubasch, "Filtering variational quantum algorithms for combinatorial optimization", Quantum Science and Technology, Vol. 7, No. 1, 2022, p. 015021.

[100] J. P. Gaebler, C. H. Baldwin, S. A. Moses, J. M. Dreiling, C. Figgatt, M. Foss-Feig, D. Hayes, J. M. Pino, "Suppression of midcircuit measurement crosstalk errors with micromotion", Physical Review A, Vol. 104, No. 6, 2021, p. 062440.

[101] A. G. Rattew, Y. Sun, P. Minssen, M. Pistoia, "The efficient preparation of normal distributions in quantum registers", Quantum, Vol. 5, 2021, p. 609.

[102] J. Yirka, Y. Subaşı, "Qubit-efficient entanglement spectroscopy using qubit resets", Quantum, Vol. 5, 2021, p. 535.

[103] E. Gustafson et al. "Large scale multi-node simulations of Z 2 gauge theory quantum circuits using Google Cloud Platform", Proceedings of the IEEE/ACM Second International Workshop on Quantum Computing Software, 2021, pp. 72-79.

[104] J. Garcia-Alonso, J. Rojo, D. Valencia, E. Moguel, J. Berrocal, J. M. Murillo, "Quantum Software as a Service Through a Quantum API Gateway", IEEE Internet Computing, Vol. 26, No. 1, 2022, pp. 34-41.

[105] R. Biswas et al. "A NASA perspective on quantum computing: Opportunities and challenges", Parallel Computing, Vol. 64, 2017, pp. 81-98.

[106] Z. G. Izquierdo, I. Hen, T. Albash, "Testing a Quantum Annealer as a Quantum Thermal Sampler", ACM Transactions on Quantum Computing, Vol. 2, No. 2, 2021, pp. 1-20.

[107] F. Ahmed, P. Mähönen, "Quantum computing for artificial intelligence based mobile network optimization", Proceedings of the IEEE 32nd Annual International Symposium on Personal, Indoor and Mobile Radio Communications, Helsinki, Finland, 13-16 September 2021, pp. 1128-1133.

[108] H.-L. Huang, D. Wu, D. Fan, X. Zhu, "Superconducting quantum computing: a review", Science China Information Sciences, Vol. 63, No. 8, 2020, pp. 1-32.

[109] B. C. Burnaby, "Let's Get Practical*: D-Wave Details Product Expansion & Cross Platform Roadmap", https://www.dwavesys.com/company/newsroom/press-release/let-s-get-practical-d-wave-details-product-expansion-cross-platform-roadmap/ (accessed: 2021)

[110] IBM, https://www.ibm.com/quantum/roadmap (accessed: 2023)

[111] H. Riel, "Quantum Computing Technology", Proceedings of the IEEE International Electron Devices Meeting, San Francisco, CA, USA, 11-16 December 2021.