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QUANTUM SOFWARE DEVELOPMENT RISKS

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In the last five years we have witnessed the emergence of numerous quantum computers, as well as dozens of quantum programming languages, platforms, etc... But it must be borne in mind that quantum computing is still in a state of technological flux, so it is essential to carry out a good risk assessment. Furthermore, it is necessary to try to mitigate the risks to safeguard the investments that organisations are starting to make in quantum software development. We identify some of the major risks associated with quantum computing, and specially quantum software and we also show a real case of risk mitigation based on technology.

Key words: Quantum computing, quantum risks, quantum software engineering, quantum software development, quantum software platforms.

1 Introduction

A decade ago, quantum computing was still limited to the scientific field and to laboratories seeking practical applications of the principles of quantum mechanics. But today we live in the “quantum decade” [IBM, 2021], in which quantum computers are a reality and the advantages of their application in a wide variety of fields and activities are increasingly becoming everyday news. Thanks to this (and to the enormous media coverage of quantum computing in the last three years), today a significant part of the population is not only aware of its existence, but also has an interest in this disruptive technology that promises to change the world we live in by using the quantum advantage to analyse and understand it from a totally new perspective.

In a very succinct definition of quantum computing, we can say that it is a type of computing that takes advantage of the (“very counterintuitive”) collective properties of quantum states (superposition, entanglement, etc [Nielsen, 2010]) to perform computations. A quantum processor is “a tangible device that performs quantum information processing” [ISO, 2022] and a quantum computer can be defined as a "fully programmable quantum processor that can implement or approximate any unitary dynamics defined within its full Hilbert space" [ISO, 2022].

It is currently possible to distinguish two main paradigms for quantum computers: gate-based and adiabatic quantum computing, also known as quantum annealing. On the one hand, gate-based computing can, in theory, address all target problems (since it is Turing-complete), while quantum annealing is only used in optimization problems. On the other hand, most of the gate-based quantum computers (e.g., from IBM, IONQ, Google, Rigetti) are also known as NISQ (Noisy Intermediate-Scale Quantum) devices and are, to some extent, still limited [Grumbling, 2019], while quantum annealing computers work with an embedded solution for a specific purpose and have achieved some market penetration, as is the case of D-Wave.

A very important milestone for quantum computers was when in 2019 "quantum supremacy" was announced, a concept coined by [Preskill, 2018] to indicate the moment when "a controlled quantum system can perform tasks surpassing what can be done in the classical world". A "quantum supremacy" experiment is a task (regardless of its utility) that can be performed using an advanced quantum computer that cannot be simulated with classical computational resources" [Boixo, 2018]. At this moment there are already manufacturers such as IBM that has presented its (Osprey) quantum processor of 433 qubits, announcing that in 2023 they will release the next one (Condor) with 1,121 qubits. It has also been announced the commercialization of systems of 1 million qubits, both by PsiQuantum in 2025 (based on photons) and by Google in 2029 (based on superconducting qubit systems).

Quantum computers make possible completely new solutions in multiple business areas: economics and financial services, chemistry, medicine and healthcare, supply chain and logistics, energy, agriculture, etc. [IDB, 2019]. In the recent "State of Quantum Computing: Building a Quantum Economy" report [WEF, 2022], the World Economic Forum (WEF) identifies three key domains where quantum computing is expected to work best: Molecular simulation and discovery in materials, science, and biology; optimization and risk management in complex systems; and a bi-directional impact on existing technology areas such as AI, security and blockchain. The WEF urges governments and businesses to act now, providing for this purpose "a taxonomy to help inform stakeholders and the broader public about the areas in which quantum computing will have an impact and the opportunities and challenges that arise therewith" [WEF, 2022]. So, in addition to numerous companies, major governments have also recognized the potential of quantum technologies, investing a total of almost $30 billion [QURECA, 2022]. Overall, the global quantum technology market is projected to reach $42.4 billion by 2027 [Research, 2022], and quantum computing will lead the market at $16.1 billion by 2027 and 39.4% CAGR. In addition, according to the latest surveys, 72% of companies will have embarked on strategic planning relating to quantum computing within 1-2 years [EY, 2022].
In fact, as the Institute for Business Value points out "*quantum computing in combination with existing advanced technologies will have a dramatic impact on the evolution of science and business. By accelerating the discovery of solutions to global grand challenges, quantum computing could trigger much sharper positive disruptions than the technology waves of recent decades*" [IBM, 2021]. However, to make this a reality, neither quantum computers nor the dozens of quantum algorithms [Portugal, 2022; Barthi, 2021] that are being developed are enough, but quantum software must also be developed. The turning point, the beginning of quantum software development, as we know it today, was recorded in 2017, when:

- In March, IBM launched the Quantum Information Science Kit (QISkit) to develop quantum circuits and algorithms that could run on its Quantum Experience service quantum simulators and quantum computers (a service under that name until 2021, when IBM replaced it with two separate services, IBM Quantum Composer and IBM Quantum Lab).
- In December, Microsoft announced the release of its Quantum Development Kit (QDK) and Q# (its high-level quantum software programming language), integrated with Visual Studio for developing quantum algorithms and experimenting with its quantum simulator.

The release of these two kits for quantum software development in 2017, represents the start of tools for professional enterprise-level quantum software development. However, for these applications to be truly useful, they must be developed with careful consideration of all the risks that quantum computing presents to quantum software development. As in classic computing, risk management can play a key role in the creation and preservation of value in the context of the organisational processes [Masso, 2022]. But to address the risks of quantum computing we must go a step further and try to raise awareness of quantum software engineering (QSE), with the goal of producing quantum software with high levels of quality and productivity [Piattini, 2020a], especially if we want quantum computing to bring a new "golden age" for software [Piattini, 2020b]. The Software Engineering Institute recommends “to pay more attention to engineering for new computational models, with a focus on software systems. The software engineering community should collaborate with the quantum computing community to anticipate new architectural paradigms for quantum computing systems. The focus should be on understanding how the quantum computing model affects all layers of the software stack" [SEI, 2021]. If we do not address the risks in quantum software development, we run the risk of a "quantum winter" like the one experienced by the artificial intelligence ecosystem in the 1980s and 1990s [Lenahan, 2021a].

The key contributions of this paper are as follows:

- We present a review of the main challenges and risks of quantum computing risks
- We point out some of the most relevant risks of quantum software and its relation to Quantum Software Engineering.
- We present an example of quantum software risks mitigation using an agnostic software development platform.

The rest of this paper is organized as follows. Section 2 presents a review of the main quantum computing risks. In Section 3 delves into the risks of quantum software. Section 4 shows an example of mitigating some of these risks by implementing an agnostic architecture. Section 5 presents concluding remarks and future work.

2 Quantum Computing Risks

[Masso, 2020], a systematic literature review can be found in the field of “classical” software risk, presents the state of the art of this field, identifying gaps and opportunities for further research. In this section we will focus on collecting the contributions that exist regarding the risks posed by quantum computing and especially the few ones about quantum software.

The most comprehensive list of quantum risks published to date is that of WEF “Quantum Computing Governance Principles” [WEF, 2022] which “*provide a taxonomy to help inform stakeholders and the broader public about the areas in which quantum computing will have an impact* *and the opportunities and challenges that arise therewith*" [WEF, 2022]. The WEF organizes the risks in nine themes:

- Transformative capabilities: theme grouping risks related to unknown transformational impact, lack of clear chains of responsibility due to insufficient transformation or change management procedures, absence of a proper and comprehensive risk-assessment framework and failure to realize the full problem-solving potential of quantum computing.
- Access to hardware infrastructure: Due to the high cost and technical expertise associated with quantum computers, the uneven distribution of skills and knowledge, and the possible monopoly of knowledge of quantum computing hardware residing with only a few corporations and research institutions.
- Open innovation: risks due to the lack of collaboration, of scientific incentive to collaborate and of transparency of technological outcomes; deprioritisation of the most socially beneficial use cases, privatization of knowledge due to patents, lost in the absence of collaboration and leverage of collective intelligence across the globe, and data being shared across borders for use cases and research.
- Creating awareness: risks that may result from the lack of public engagement; misinformation about quantum computing; misrepresentation of quantum computing science and technology; protests by anti-technology groups; lack of public trust in, or understanding of, quantum computing; and all the possible risk around the quantum computing hype and distrust in its usefulness.
- Workforce development and capability-building: Lack of a trained quantum workforce; difficulty in transitioning the current workforce to a quantum workforce from both a technical and mindset perspective; difficulty in understanding the full impact of quantum computing; and lack of equitable access to quantum computing education.
- Cybersecurity: risks resulting from attacks made on communications and data stored in the cloud by breaking currently deployed public-key encryption schemes; break down validation and authorization mechanisms; destabilization of governance protocols in emerging infrastructures; malicious development of quantum computing capabilities; failure to ensure all the regulations and laws regarding privacy, data management etc.; "balkanization" of digital infrastructures; threat to certain cryptographic solutions traditionally considered resilient; etc.
- Privacy: risk of hacking of data in transit and data stored containing personal data or PII; ability to run powerful data analysis algorithms to forecast, infer or induct unconsented or unauthorized information; use of quantum technology to expand surveillance, encroach on privacy or violate civil liberties.
- Standardization: risks arising because of the lack of common and shared goals, metrics, standards, and roadmaps; rigid or premature standardization efforts; benchmarks not readily tested or biased; bias in standardization and roadmap efforts; etc.
- Sustainability: Resources and materials required to build quantum computers; risks to the environment; energy costs of operating a quantum computer, etc.

The risks associated with security are the ones that have aroused the most interest at the moment, and in fact some reviews can be found in this regard such as [Hossain, 2022] where the authors synthesize basic and primary studies related to quantum cybersecurity that can arise both as a threat and as a solution to critical cybersecurity issues; or [Arslan, 2018] where the advantages and disadvantages of the high performance that quantum computing provides is examined under the head of security. In this field, it is also important to highlight all the Post-Quantum Cryptography projects and work promoted by NIST (National Institute for Standards and Technology) [NIST, 2021].

The problems caused by a lack of talent have also been emphasized. For [EY, 2022] is one of “the two noteworthy issues top the list”, junto con integrating quantum computing into existing technology infrastructure. This is largely because the learning curve for quantum computing is significantly higher than previous ones and therefore requires much more time for the organization to have the necessary capabilities in this field [Peterssen, 2020]. This has led to initiatives such as the EU's Quantum flagship about a “Competence Framework for Quantum Technologies” [Greinert, 2021].

Also, the ethical risks have been pointed out, [Perrier, 2022] presenting the first roadmap for ethical quantum computing, [Saurabh, 2022] a literature survey about ethical and sustainable quantum computing,

On the other hand, it is also worth mentioning the risks associated with "dequantization". This fact occurs when classical quantum "inspired" algorithms are created, which although they may be a temporary solution considering the limitations of quantum hardware at present (e.g. due to the limit in the number of qubits), they eliminate the promise of exponential acceleration of several algorithms, especially those of QML (Quantum Machine Learning) [Gyurik, 2022]. Most quantum linear algebra tasks on low-dimensional data can probably be dequantified in a classical variant, however evidence suggests that the dequantization of high-dimensional problems incurs much greater difficulty [Huynh, 2023]. It should also be noted that while quantum algorithms are natively robust against small perturbations, current techniques in dequantization are not [Le Gall, 2023].

In the next section we focus on the risks derived from quantum software and its development and implementation.

3 Quantum Software Risks

Quantum computing may become the main driver of a new "golden age" of software engineering, like what other advances such as structured programming, object orientation, or DevOps, have previously brought about [Piattini, 2020a]. To this end, as Susan Stepney stated, in the 2004 report of Grand Challenges in Computing Research, “the challenge is to rework and extend the whole of classical software engineering into the quantum domain so that programmers can manipulate quantum programs with the same ease and confidence that they manipulate today’s classical programs” [Hoare, 2004].

In [Zhao, 2020] and [Serrano, 2020] a comprehensive survey of the current state of the art in quantum software engineering, including all aspects of the quantum software life cycle can be found. In the "Talavera Manifesto" [Piattini, 2020c] some principles for quantum software engineering and programming are defined, most of which can be used for avoiding risks regarding quantum software quality, requiring that quantum software platforms should:

- be agnostic with respect to quantum programming languages and technologies.
- encompass the coexistence of classical and quantum computing.
- support the management of quantum software development projects.
- consider the evolution of quantum software.
- aim to deliver quantum software, if possible, with zero defects.
- assure the quality of quantum software.
- promote the reusability of quantum software.
- cover software governance and management.

A review of the main quantum software components and platforms can be found in [Serrano, 2022; Hevia, 2021a], where a set of quality requirements for the development of quantum software platforms is proposed, and [Ahmad, 2022] analyses reference architectures, frameworks, and architectural implementations of quantum software systems.

In [De Stefano, 2022] some challenges that research in quantum software engineering should face are summarized, based on a repository mining investigation, grouping them in three categories:

- Environment, both in terms of hardware and software, including software Infrastructure which in turn includes:
- Framework, challenges regarding constant changes in APIs; integration of quantum systems with traditional ones; and execution (setting up execution environments, simulators, or classical systems with which quantum programs interact, hindering their ability to execute their programs).
- Hardware Infrastructure, since quantum programming requires specialized hardware, which is under constant development; and performance since quantum hardware is limited,
- Comprehension (B), this category ranges from challenges which are inherent to the documentations of the frameworks, to challenges that are inherent to (lack of) theoretical grounds.
- Coding, i.e., challenges related to the implementation activities, the IDEs, the compilation of quantum circuits, the code quality (including debugging, testability, and readability
- Degree of Realism: the applicability of quantum programming to solve real-world problems.
- Community (E). Challenges in this category concern the lack of a community to interact with.

Training and automation can mitigate some of the risk that exists in assessing the impact of quantum computing for a use case [El Aoun, 2021]. The authors insist the AQSE (Automated Quantum Software Engineering) framework must conform to ease of use. And they propose two aspects of ease: the user interface and the level of vagueness/rigor in the problem specification.

In [Sarkar, 2022] we find a report on an empirical investigation conducted analyzing the Stack Exchange forum posts related to QSE and the GitHub issue reports, where developers raise QSE-related concerns in real world quantum computing projects. The authors founded that the three most dominant topics of posts are environment management, dependency management, and algorithm complexity. Other issues were: quantum execution results on quantum backends, learning resources, data structures and operations, quantum circuits, comparisons between quantum and classical computing and migrating classic algorithms to quantum computing.

Table 1 summarizes most of the above-mentioned risks pointing out some approaches that can be used to mitigate it. As we can see good practices in software and systems engineering (MDE, SOA, ADM, metrics, etc.) can be used to mitigate some of these risks.

Risk	**Mitigation approach**
Lack of preparation	Training, automation (AQSE)
Difficulty in use	User-friendly, Graphical User Interfaces (GUIs)
Algorithm complexity	Training, algorithm libraries
Variety of types/approaches of quantum computers	Technology agnosticism

Changes in the same quantum system	Full portability of quantum software
Diversity of programming languages	Model Driven Engineering (MDE), low code techniques
Integration of classical and quantum IT	Service Oriented Architecture (SOA), standardized APIs
Hybrid information systems construction	New hybrid software life cycles
Migration of classical software	Quantum software modernization (ADM, Architecture-Driven Modernization)
Poor quality of quantum software	New testing techniques/New software quality characteristics and metrics
Problems in execution and results/Environment management	An integrated environment for design and execution
Lack of community	Create quantum software networks and interest groups

Table 1. Main quantum software risks and mitigation approaches

4 Example of quantum software risks mitigation

For several years we have been developing the QuantumPath® platform [Hevia, 2022a] for the development of quantum software applications, focused on incorporating the best practices of software and systems engineering. With all this, we provide an ecosystem of tools, services and processes that simplify the development of quantum algorithms in the context of hybrid information systems. Other similar platforms can be found in [Serrano, 2022; Hevia, 2021a], in which they are analysed and compared both in terms of technology and quality.

When designing and developing QuantumPath® we try to mitigate some of the above-mentioned quantum software risks. So, for example, we have built a user-friendly interface not only for gate-based (circuits) specification, but also for annealing-based quantum system specification [Hevia, 2021b]. Agnosticism is achieved since both the circuit editor and the annealing editor generate a proprietary metalanguage that is agnostic to each manufacturer's quantum technology. The corresponding metalanguage is then transpiled at design time to the programming language supported by each manufacturer and executed in the target environment [Hevia, 2022a]. The agnosticism even reaches the "type" of quantum computing to be used (gate-based or annealing), since the platform provides a "QAgnostic QAOA®" that extends the agnostic feature regarding the execution of optimization algorithms, being possible to run the same optimization algorithms on different technologies and quantum hardware manufacturers [Hevia, 2022b]

In this paper we want to go deeper into the risks that can be mitigated by the computing vendor agnosticism of quantum software development platforms. In our opinion, all the quantum development tools, as well as the execution ecosystem, should be based on this concept: making the algorithm layer independent from the execution layer. Leaving all the details to the more internal layers of the product which, thanks to its modularity and adaptability, takes on the challenge not only of facing technological changes from a provider, but also that the platforms themselves can evolve over time or even disappear at any given time.

The problem is that IT architectures typically hardcode quantum use cases (Figure 1) so any change in quantum suppliers affects them fully.

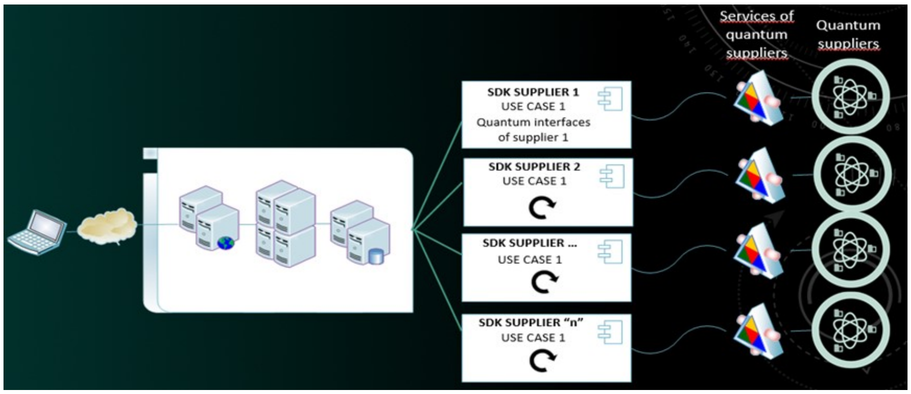

Figure 1. Classical IT architecture that implements quantum hardcoded uses cases

In QuantumPath® we follow an agnostic architecture (Figure 2), so that the impact for the user can be reduced, because:

1) All developments made with gate-based or annealing technology are not totally dependent on a specific quantum provider/QPU. They are vendor-independent designs and abstractions.
2) Both the construction of quantum assets and their exploitation in hybrid architectures are based entirely on the agnostic capacity of QuantumPath®. So, a change in quantum provider status is fully transparent to the upper layers.
3) All the added value and collateral elements of the project (documentation, publications, presentations, interactions...) remain almost intact since the context of the project has not changed.

This mitigates a whole range of risks associated with the variety of types of quantum computers; the continuous changes in the same quantum system; the wide and changing variety of suppliers; the development in different technological approaches (gate-based and annealing); the diversity of programming languages; the emerging, dispersed, proprietary technology stack for quantum software development, the development of optimization applications on different approaches and types of computers, the changes in the best (efficiency, economic) alternatives of quantum services, etc.; also facilitating the integration of classical and quantum IT and the management of hybrid information systems.

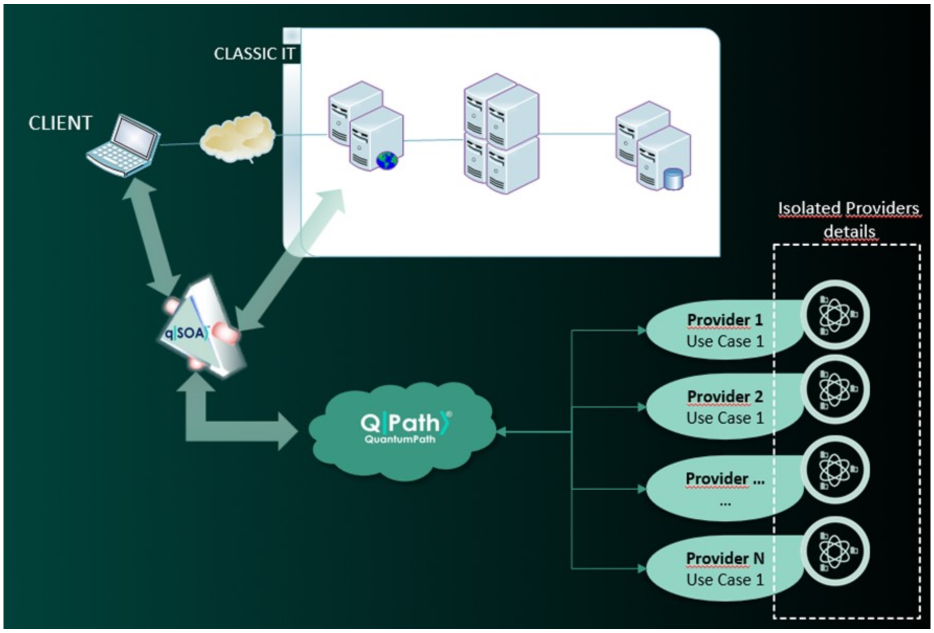

Figure 2. QuantumPath® architecture isolates the low-level's quantum provider details from the use cases.

Recently, we have been able to verify the risk mitigation that this architectural choice entails, in a real case of change in a quantum technology provider. Until 17th November 2022 Amazon Braket provided its users with access to D-Wave QPUs through its cloud services, on the same day Braket cancelled D-Wave's Braket providers, which implied the cancellation of the URNs of the D-Wave computers, as well as all API references wrapping the Braket SDK for D-Wave.

The impact on users has been mitigated allowing them to:

- Have the native D-Wave providers of QuantumPath®, if the technology is to continue to be available in the new context
- Have the local OCEAN simulators (ExactSolver, Simulated Annealer Sampler) to be able to keep the same functionality
- No re-programming of the annealing optimisation algorithms
- Retain all the solution history and telemetry
- Have a new Agnostic QAOA, which allows optimisation algorithms to be run on gate-based quantum computers
- Change management resolved with a communication to users

5 Conclusions

In the last few years dozens of quantum computers, programming languages, platforms, etc. have been emerging [Ezratty, 2022]. We are living a continuous, and often dizzying, advance in the disruptive world of quantum computing. Based on the current state-of-play, making any definitive assessments on timeframes for mainstream adoption and deployment of general-purpose quantum-computing capabilities remains challenging [Deshpande, 2022].

Therefore, in quantum computing, it is even more important than in other areas of information technology to carry out a complete risk assessment. It will be the task of the "Quantum Business Strategist" [Lenahan, 2021b] to develop a risk management strategy based on an integrated approach, which enables organisations to have a holistic view of quantum risks. These risks should also be considered in readiness model that will help an organization assess its capability of migration from classic software engineering to quantum software engineering [Akbar, 2022].

In this paper we have presented a review of the main quantum risks, especially those related to quantum software. And we have shown how, through an agnostic architecture, some of these risks can be mitigated, safeguarding the investments that users have made in the development of quantum software assets.
We are now working to mitigate further risks, especially those related to the proper functioning of quantum software, for which specific testing techniques need to be developed [Garcia, 2022] as well as new quantum software metrics.

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