Quantum AI for Application in Industry
A Workflow Model

Author: Sebastian Nicolae Perijoc
University of Twente
P.O. Box 217, 7500AE Enschede
The Netherlands

ABSTRACT

In this research paper investigates the integration of Quantum Computing (QC) and Artificial Intelligence (AI) to develop a replicable workflow for quantum applications. The study addresses the significant challenges of integrating quantum algorithms into existing infrastructures and the extensive expertise required for their development and operation. The research explores and identifies the potential innovations helpful in bridging the gap between QC technologies and industrial needs. The research employs systematic literature review and case studies incorporated in a Multi-Level Perspective (MLP) approach to analyse the interactions between technological innovations and industry adoption. The paper provides a comprehensive Technological Innovation System (TIS) framework for developing quantum applications, emphasizing the synergy between AI and QC to enhance computational capabilities and address complex industrial challenges. Key components necessary for creating a comprehensive ecosystem for quantum application development, including AI hardware integration, quantum algorithm research, and error-correction advancements, are identified. The primary contribution of this study is a workflow design created to be reproducible across multiple industries. This innovative approach reduces the dependency on specialized knowledge and can accelerate the integration of quantum solutions in various industries.

Graduation Committee members:

Michel Ehrenhard
Johannes Dahlke

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1. INTRODUCTION

Quantum Computing (QC) technology provides a considerable advantage compared to classical computing due to the different system of architecture that operates on qubits instead of bits (Hassija, 2020) (Amine, 2023). The technology is expected to have a big impact for the development of Industry 4.0 as a result of the nature of the qubits that allows them to perform exponentially more calculations than the regular bits. The technology requires a specialized quantum infrastructure for the system to operate and specialized language for encoding the needed operations to be executed on a Quantum Processing Unit. Interacting with the technology was unrealistic because of the lack of hardware available which prevented development of applications. As a result of IBM's first quantum computer, the level of attention towards the technology grew exponentially (QTEdu, 2024) (Kyriaki, 2023). The interest towards Quantum Applications (QA) and how they can improve the industry has generated the search for a streamlined process of development.

In the elapsed time, with increasing investments and research made into the field, the technology is expected to be ready for market applications. The past year 2023 marked continued advances for Quantum Technologies (QT), with a range of enhanced and new QT offerings entering the market. Advances such as the transition from the Noisy Intermediate Scale Quantum (NISQ) era to the Fault Tolerant Quantum Computing (FTQC) era create the possibility for disruption as the technology is market ready for deployment of large-scale applications (McKinsey, Quantum computing: An emerging ecosystem, 2019). The expectations from the investors have been steadily increasing as the technology has been gradually developing as a result of the considerable investments (Insights, 2024). These new developments can be the signs of the technology reaching an inflection point for the applicability of the technology for real-world cases. These applications are implemented with the purpose of showcasing the quantum advantage over classical computing as a result of the parallel processing possible on the quantum bits (qubits), exponentially more powerful than the digital bits (Garrelt, 2021).

While integrating QC and AI technology into the industry promises efficiency and automation through Quantum AI Applications, they also increase the complexity of operations. Quantum algorithms differ fundamentally from classical ones, integrating these into existing workflows can be a Herculean task, demanding an overhaul of legacy systems (Bova, 2021) (Quantum, 2023). The Quantum Computing technology applicability depends on how well one can integrate with other systems and be adapted for the human factor. This adds extra requirements necessary for industry viability such as fast initialization, resource efficiency, and control without intricate expert support.

1.1. Problem Statement

The industry realized that the most optimal option is to compute quantum applications that have a proven viability and theoretical advantage, complementary with the classical computing infrastructure available (Meng-Leong, 2023). This separation of tasks helps in the efficiency of using the capabilities of each infrastructure but these different paradigms also prove to be a challenge for integration. Examples of possible applications for the technology include logistic optimizations, complex financial models, and simulation-based material design where quantum-enhanced algorithms might significantly outperform classical approaches due to their ability to calculate vast number of variables and exponentially faster than classical computing (Kyriaki, 2023) (Olawale, 2023). Existing hardware systems are available despite of the high requirements for production, maintenance and operating conditions associated with such technology. The existing supporting software cloud platforms (e.g., Microsoft Azure; AWS Braket; IBM Quiskit; Google Quantum AI; D-wave Ocean (Markets&Markets, 2024)) made access easier for such hardware. Even with the hardware problem solved, because of the high level of abstract thinking needed to extract and transform real-world problems into quantum-compatible solutions, the field of quantum applications is facing a knowledge gap. The process of developing a quantum application involves experts from different knowledge domains working long development times in highly specialized teams that can collaborate across multiple area of expertise. The access to the technology is open for the public for a cost, but as long as the pool of individuals capable of operating QC remains restricted, the perspective of an industry pull for quantum applications will remain a distant concept (EY, 2022) (McKinsey, Quantum technology report, 2023) (McKenzie, 2024) (QTEdu, 2024). Taking into consideration the aforementioned knowledge gap needed to work on quantum algorithms, as well as inherent technical challenges (e.g., Error-correction, decoherence and fragility of the quantum system, etc.), building the bridge towards industry applicability becomes a complex problem. On top of this complex issue, creating ML/AI applications in synergy adds another layer of complexity due to the fast-paced development of ever-more-performant AI solutions coupled with the evolving demands of the industries with specific requirements.

One point of interest is that currently there is no comprehensive development framework for quantum applications as mentioned by researcher within the field (Garrelt, 2021) (Andreas Bayerstadler, 2021). The primary approach is to adapt classical machine learning algorithms or their inefficient subroutines to run on quantum computers or within the framework of quantum computing theory. Building on investments to generate value is still a challenge because of the requirements for state-of-the-art hardware and infrastructure, limited awareness and adoption of quantum technologies, and a lack of interdisciplinary coordination. This raises the challenge of developing a cohesive workflow for the creation of quantum applications for the industry.

The workforce is essential in the development and integration of the technology which makes it another point of interest for the Quantum industry because of the high skills required. This makes the process lengthy and confusing because of the lack of a simplified quantum programming process that is accessible to non-professional individuals. Collaboration between industries, academia, and governments is essential for accelerating development of quantum technology to incorporate the advantages of the technology, manage intellectual property, and overcome talent gaps (Maninder, 2022). The development of the technology is predicted to be slow despite the investments made, due to the fact that, with the exception of a select group of professionals that have the necessary knowledge to operate it, the knowledge gap is still considerable (EY, 2022). Hence, a need arises for research on platforms and applications in the QC industry, and the ecosystem strategies that can be adopted by companies to fit this best to facilitate market demands. The challenge becomes to create a framework that can combine the technical knowledge difficulties that the industry is prone to with the management strategies for implementation for the wider industry. The technical requirements need to be simplified enough, taking in consideration possible future developments, to be accessible for the still-developing workforce.

Research Question:

How can a workflow model be created to assist the development of quantum solutions for the industry?

1.2. Contributions

In this study, the ecosystem emerging from the combination of AI and QC is examined within industry settings, with the scope of building a robust, flexible, reproducible workflow through a Socio-Technical Systems Design (STSD) (Gordon, 2011). Such an approach would enable a template for collaboration across the ecosystem, as described by (Leena Aarikka-Stenroos, Paavo Ritala, 2017)to develop quantum applications according to easy-to-understand guidelines. Such a template shall facilitate the efforts of closing the knowledge gap, possibly making QT more accessible towards non-experts in field such as managers, directors and executives (Maninder, 2022). According to (Meng-Leong, 2023) it is imperative to utilize AI for bridging the knowledge gap and increase accessibility to the technology that can help us encourage change and innovation. Quantum Machine Learning holds potential for significant advancements in computational capabilities, which could theoretically include noise resistant quantum circuits (Hanrui W. G., 2021). These quantum applications that run on quantum circuits generated through AI solutions can be the link for simplifying the workflow process of creating the quantum applications needed in industry. (Garrelt, 2021) (Andreas Bayerstadler, 2021).

This study explores the social and management problems of integration of quantum solutions and their components within the industry through a Multi-Level Perspective (MLP) (Masaharu, 2018). A notable point of interest are AI agents trained to generate Quantum Circuits without the need of specialised personnel or knowledge (Yuhuai, 2022). The workflow design incorporates the extrapolated similarities between the Classical and Quantum computing which allows for a simplified workflow useful in the technology transition process (Geels, 2002) (David P. G.-B.-P., 2022).

2. LITERATURE REVIEW

The structured Technological Innovation Systems (TIS) framework facilitates the gathering of insights from various actors, enriching the understanding of both the technical and managerial perspectives on quantum AI integration. To understand the quantum industry, the TIS framework provides a structured approach at multiple levels necessary to develop a Socio Technological Systems Design (STSD) for QA integration. To capture the intricate interactions and dependencies across these levels, the MLP is complemented by the Business Ecosystem Perspective (BEP) as mentioned in (Masaharu, 2018), emphasizing the interconnected nature of actors to reveal the dynamics and patterns of ecosystems and organizational behavior. This part is essential for identifying barriers, opportunities, and strategic considerations for adopting new technologies. The identified patterns and common problems found allow us to create a STSD that can be flexible on multiple industries. Identifying and mapping key actors (e.g., academic institutions, industry players, regulatory bodies) in the AI-quantum ecosystem provides enough information to analyze their interactions and dependencies, especially those addressing the foundational concepts of quantum computing and the evolution of AI. Industry-specific technical reports and whitepapers, particularly those published by leading tech corporations and research institutes, provide insights into the current advancements and future projections of quantum AI. Market reports about the companies pioneering Quantum and AI innovations offered in-depth information about their progress, challenges, and future directions. News articles provide timely updates on recent breakthroughs, partnerships, and quantum AI-driven initiatives in Industry 4.0.

This study employs a qualitative research methodology approach to investigate the integration of Quantum AI applications in industry settings, aiming to develop a Socio-Technical Systems Design (STSD) accessible for business purposes (Gordon, 2011). Specifically, the research is focused on hybrid quantum-classical systems to discern the functional capabilities and limitations of AI agents in translating mathematical models into quantum applications. The methods for this comprehensive study on the development of quantum applications into Industry 4.0 comprise a MLP approach to ensure the depth and accuracy of the information presented.

The scope of the study is to analyze from (MLP) the quantum-classical hybrid computing applications and their role for Industry 4.0. The research uses the insights gained from quantum applications integration case studies from the industry as a foundation. Understanding how the regimes in the quantum technology would influence the transitions of niches into the industry at large, a BEP helps to visualize how the niches from entrepreneurial ecosystem interacts with regimes and potentially transform the landscape. The map observed in **Appendix 2** shows the relationships between niche innovations and the established regime components, identifying potential points of tension, synergies, or areas for collaboration. These are necessary for a sustainable transition by highlighting potential leverage points and barriers within the multi-level system (Geels, 2002) (Gordon, 2011).

(Karl, 2011) proposes that different TIS models can be understood within an organization based on the levels of governance and functionality. This model can then be extrapolated to any organization, as the resented in **Figure 1.** the, *Functionality* is the dependent variable as TIS studies measure functionality in a predominantly qualitative manner, captured through actors' perceptions of, for example, knowledge of supply and demand, uncertainties, bottlenecks, sufficiency of guidance, availability of resources etc. The specific mix of *Governance* arrangements can be viewed as our independent variable. In the 'Who governs?' dimension, the interest is put on whether an organization, alone or in collaboration with other actors, orchestrates the governance arrangement. Of interest is at what level of governance the arrangements are orchestrated, from the local to the global. For the 'How?' dimension, we are interested in the mechanism of governance, whether regulative, market-based, normative or cognitive. In this part we include whether the target of governance is on the supply (push) or on the demand (pull) side, or both. The 'What?' dimension concerns the target of the governance arrangement in terms of key processes (Masaharu, 2018). The key processes adapted from (Karl, 2011) that are essential in technological innovation systems, which can also be converted into qualitative indicators include Knowledge development and diffusion; Influence on direction of search; Entrepreneurial Experimentation; Legitimation; Market formation; and Resource mobilization.

Developing a Socio-Technical Systems Design (STSD) framework tailored for the AI-quantum context and ensuring the TIS framework is robust (able to withstand challenges), flexible (adaptable to changes), and reproducible (can be applied in different contexts) requires both technical and management knowledge. To help alleviate the knowledge gap and provide a foundation for future quantum application, all the collated qualitative data were subsequently analyzed using the BEP to identify patterns. This structured approach ensured that our interpretations were grounded in the data, leading to the coherent presentation of insights and findings in possible industries and different applications of the current technology.

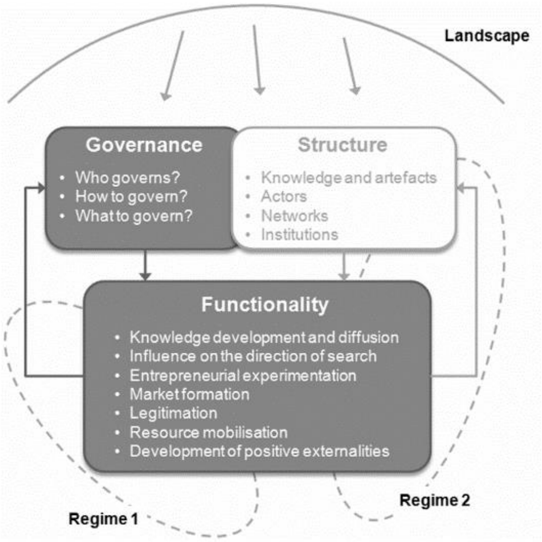


Figure 1: Schematic representation of the theoretical framework adopted from (Karl, 2011).

This approach includes the socio-technical elements crucial for the development of new quantum applications, focusing for this study on the development diffusion and the utilization of these technologies (Gordon, 2011). This process can be described as an interplay between niches, regimes, and the landscape, which is an overarching level of societal developments largely unaffected by separate changes on regime and niche levels (Karl, 2011). For developing the STSD, using the already proven methods in the use cases studies as a starting point, an analysis of patterns in the creation process of Quantum Applications is performed. Streamlining the workflow such that it can be adopted by established industries and incorporated within the existing infrastructure creates more incentive for development. Such quantum solution can create new, uncontested market spaces that could redefine competitive boundaries and identify new value opportunities. The framework proposed that used Governance and Functionality as the variables

2.1 Landscape

Strategic goals and policy directives guide research and development efforts, focusing on sectors with high potential impact. The potential economic value from quantum technology is estimated to reach $173 Billion across just five industries by 2040 (see Figure 2). Research in quantum error-mitigation proposals and demonstrations by large companies show promise of steps toward large-scale, fault-tolerant quantum applications (McKinsey, Quantum technology report, 2023) (Yunfei, 2024).

QC is in its inception phases of being introduced into the industries and new technological advances and solutions need to be developed for a more efficient integration (Andreas Bayerstadler, 2021). According to McKensey, the investments in the sector over the years resulted in 3 main technology sectors: Quantum Computing (QC), Quantum Sensing (QS) and Quantum Communications (QCom). From these, the most developed sector that shows signs that applications might become possible sooner than thought is Quantum Computing (M. P. da Silva, 2022). Comparing past reports (McKinsey, Quantum technology report, 2023) (Insights, 2024), the growing interest into the field is observed as investments reaching 6.7 billion for QC, 0.7 billion for QS and 1.2 billion for QCom respectively.

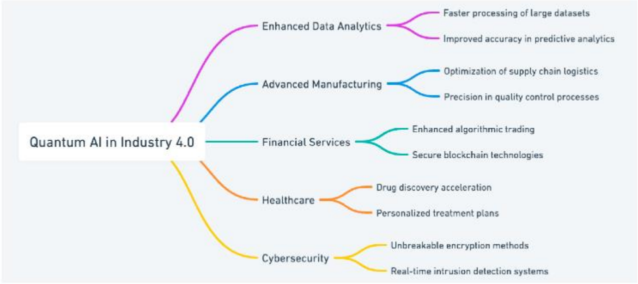


Figure 2: Simplified overview of the potential influences of quantum AI in Industry 4.0 (Meng-Leong, 2023).

The global computing increased its market size to 1.3 billion USD valuated in 2024 and is expected to grow at Compound Annual Growth Rate (CAGR) of 32.7% over the next 5 years (Markets&Markets, 2024). The barriers to entry into the field, such as a big talent gap and lack of a common structure for developing Quantum applications (Maninder, 2022), as well as a lack of noise-corrected hardware (Andreas Bayerstadler, 2021) have constrained the industry to make focused applications on Noisy Intermediate-Scale Quantum (NISQ) hardware. The NISQ hardware being able to provide error corrected results that could categorize the technology as market ready for industry implementation (Yunfei, 2024). Taking advantage of results obtained as a consequence of the investments made to overcome the hardware issues (Simon, 2024), presents opportunities for developing new ventures for Quantum applications. The focus shifting from hardware to software, the ecosystem started developing environments and tools.

The synergy between AI and QC, particularly through Quantum Machine Learning (QML), holds the potential to revolutionize industries by enhancing computational efficiency and solving complex optimization problems (Benjamin W. B., 2021). The commercial applications discussed in (Bova, 2021) allows to make an initial perspective on the possibilities of the technology in the market.

QML integrates quantum algorithms with machine learning techniques to enhance data processing and analysis capabilities. In quantum error correction, recent advancements have shown promise, with companies achieving record qubit fidelities by combining new error-correction schemes and ground-breaking architectures. The literature suggests that hybrid quantum-classical systems, which leverage the strengths of both computing paradigms, are currently the most viable approach for industrial applications (Michael, 2022).

In the evolving landscape of the Fourth Industrial Revolution, the fusion of quantum computing with artificial intelligence is poised to be a dominant force by reshaping industries and redefining paradigms. The merger of these two technologies has far-reaching implications, not just technologically but also socio-economically, demanding a fresh perspective on management and innovation. For AI applications, this means designing technology that complements human roles and organizational goals, ensuring that both technical performance and employee satisfaction are maximized. As for the quantum applications in most of the use cases studies researched, they operate on hybrid quantum-classical systems that run on Noisy Intermediate-Scale Quantum (NISQ) hardware.

2.2 Regime

(Amira, 2023)the possible challenges for the technology as well as theoretical possibilities for applicability. In (Mario, 2022) the author takes a deeper dive into the technology itself and from (Nivedita, 2020) the stages that a quantum application goes through until it is tested and implemented can be observed.

Complex technologies such as Quantum Computing encompasses a lot of knowledge domains involved in the successful operationalization of the technology. These domains need different branches of study and research to be done with the purpose of creating a quantum computer that is error tolerant. In the **Appendix 2** a detailed map of the ecosystem is shown (Andreas Bayerstadler, 2021). (Garrelt, 2021) shows that quantum community has reached a new stage of maturity and that the quantum computer as a commercial product is set to become a reality. While in (Sheir, 2022) a detailed review is performed for the QA capabilities of the QC that can be used in the industry. Niche innovations such as Noise Adaptive Search (NAS) and Noise Aware Training (NAT) discussed in (Hanrui W. D., 2021) and (Hanrui W. G., 2021) describe solutions that are closing on delivering on the promised error corrected quantum systems. The FTQC described in (Yunfei, 2024) promise significant potential for ML and data analysis and hardware results such as those described in (Morteza, 2023), (Akhtar, 2022), (M. P. da Silva, 2022)and (Simon, 2024) reinforce the idea that the industry is at a tipping point. Examining the data in (Meng-Leong, 2023) we can see trends in the technological stages that can forge the next Quantum AI applications.

Taking another look into how this technology can be simplified, (Michael, 2022) proposes solution for ISA systems that can connect the high-level language and the microarchitecture in a single framework. A similar detailed system can be observed in (Alexander, 2021), that allows for a reusable infrastructure.

2.2.1 Knowledge Development and Diffusion

In the process of understanding the regime of the technology, several aspects were researched: the technology components and their advantages, disadvantages, potential and challenges in different settings. Quantum-inspired generative models that have been applied to enhance combinatorial optimization have been explored. In the use cases studies selected it was showed that quantum approaches can integrate well with classical methods to solve complex problems more efficiently (Natasha, 2024) (Andreas Bayerstadler, 2021). (Amine, 2023) suggests potential pathways for AI to assist in developing and bridging the gap of quantum advantages for industry purposes.

Investments in quantum research and development are critical for collaboration between academia, industry, and government to facilitate resource allocation and skill development necessary for advancing the field. Start-ups and large tech companies are actively developing quantum literacy amongst the general public in order to foster the entrepreneurial spirit and initiatives, as can be observed in Figure 3 (Maninder, 2022). These initiatives are a counter-measure of the talent gap and workforce need for the development of the technology itself and possible future developments. As discussed earlier, this proves to be a challenge as discussed earlier as the knowledge domains needed to be able to work on a quantum application are still considerably high.

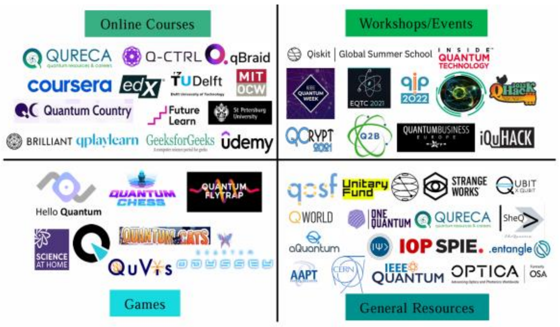


Figure 3: Educational initiatives graphs according to (Maninder, 2022).

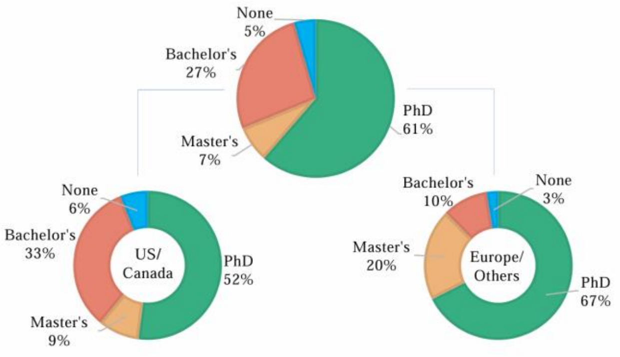


Figure 4: Educational degree requirements for various job vacancies across (a) the world, and in (b) the US/Canada and (c) Europe/rest of the world. Adopted from (Maninder, 2022).

The complex knowledge needed for creating quantum algorithms for the quantum computer to execute give rise to the need of a wide range of experts in fields like Computer Science, Mathematics, Quantum Mechanics. The stakeholders from industries within which the technology could be adapted, demand a high level of knowledge as well as observed in Figure 4. Despite the progress done to bridge the gap, the supply of skills and talent is still not satisfying the demand, as one of three jobs listed in the fields as of 2024 is still vacant according to (McKinsey, Quantum technology report, 2023). This provides a dilemma for the field: how to close the talent and knowledge gap when the increasing volume of work needed to integrate the technology within different industries adds the complexity of those knowledge domains. With the development of more complex and advanced quantum processors, more error tolerant quantum circuits and mathematically formalization systems, the need increases in the field of capable workforce. Among the skills required are included the need for identifying problems, classify solutions (e.g., Hamiltonian equations), and formulating use cases based on those real-world problems (Andreas Bayerstadler, 2021). For organizations utilizing cloud resources for quantum simulations provides additional computational power and flexibility. Syncing these cloud-based results with Omniverse ensures that all data remains accessible and integrated within the primary visualization platform.

2.2.2 Entrepreneurial Activities

In the process of developing the technology and understanding different applications possible, different functionalities for industries. Exploring deeper the industries within which the technology gas an impact we can observe the following functionalities depending on the industry. These applications vary in the quantum algorithms used for development that each have different requirements to be used. Collecting information from studies about the possible capabilities we can understand how the integration of QC can change different industries.

Manufacturing

The integration of QC and AI technologies into the manufacturing sector promises substantial enhancements in efficiency and precision (Bova, 2021). By leveraging advanced optimization algorithms, Quantum AI can streamline production processes, reduce waste, and ensure higher quality control. For example, production schedules and workflows can be optimized dynamically, minimizing downtime and maximizing resource utilization. Another example is the ability of quantum system to streamline and reduce time for the development of different products that can be simulated and adjusted digitally (Andreas Bayerstadler, 2021).

Healthcare

In the healthcare industry, Quantum AI holds transformative potential by enhancing diagnostic accuracy, personalizing treatment plans, and accelerating drug discovery (Meng-Leong, 2023). The synergy of AI's data processing capabilities with the computational power of quantum computing allows for the efficient handling of complex biological datasets. AI-powered diagnostic tools can analyze medical images and patient data with a high degree of accuracy, leading to early and precise disease detection. Despite promising results in genomics and diagnostics, the transition from experimental studies to clinical applications involves overcoming numerous technical hurdles (Frederik, 2024). The drug discovery process is proven to be disrupted, as quantum computing enables the rapid simulation of molecular interactions, significantly speeding up the identification of viable drug candidates and reducing the time and cost involved in bringing new drugs to market, based specific on the folding of proteins and substances interaction (Boulebnane, 2023) (Malone, 2022).

Supply Chain and Logistics

Quantum AI can profoundly impact supply chain management and logistics by optimizing routes, improving demand forecasting, and enhancing inventory management (Andreas Bayerstadler, 2021). Logistics optimization through Quantum AI involves determining the most efficient routes and schedules for shipping, which reduces transportation costs and delivery times. This heightened efficiency in supply chain operations can lead to significant cost savings and improved customer satisfaction (Sheir, 2022).

Energy

The energy sector stands to benefit immensely from Quantum AI through optimized grid management for renewable energy sources and predictive maintenance of energy infrastructure (Meng-Leong, 2023). Quantum AI can optimize the distribution of electricity across power grids, balancing supply and demand in real-time to reduce energy waste. Additionally, Quantum AI's predictive maintenance capabilities can forecast potential failures in energy infrastructure, allowing for timely interventions that prevent downtime and maintain continuous energy supply. These advancements contribute to more sustainable and resilient energy systems (Amira, 2023).

Finance

In the financial sector, Quantum AI can revolutionize risk management, optimize trading strategies, and enhance fraud detection. By processing large volumes of financial data, Quantum AI can identify potential risks and optimize portfolios with greater accuracy, enabling better decision-making and risk mitigation (Sheir, 2022). Quantum AI can significantly improve fraud detection by recognizing unusual transaction patterns indicative of fraudulent activity, strengthening detection and protecting financial assets (Amira, 2023).

2.2.3 Guidance for Search

Individually QC and ML have their own benefits implemented to solve industry problems, but when combined, the synergy between them creates opportunities. Potential core problems to be solved include Optimization, Simulation and Data Processing. These fields present opportunities for entrepreneurs to identify need in the industry for the aforementioned services.

Optimization

Quantum-Assisted Optimization in AI Training is a hot topic in Quantum Machine Learning (QML), as it integrates quantum algorithms with machine learning techniques to speed up data processing and analysis (Andreas Bayerstadler, 2021). Quantum algorithms offer exponential speed advantages in certain types of problems, such as factorization and optimization, which are required for complex machine learning tasks (David P. G.-B.-P., 2022). QAOA and QA are used for solving complex optimization problems in logistics, finance, and manufacturing. These quantum algorithms can find optimal solutions faster, providing a significant competitive advantage. From (Kostas, 2024) we can observe that Quantum Approximate Optimization Algorithm (QAOA) and Variational Quantum Eigen-solver (VQE) are notable quantum algorithms for solving combinatorial optimization problems approximating the ground state energy of a system that behaves as a quantum equation (e.g., Hamiltonian). Quantum Annealing (QA) for Optimization uses quantum fluctuations to find the global minimum of a function, this is crucial for optimization problems encountered in industrial applications. This technique is particularly suited for solving complex, optimization problems that are typical in large-scale industrial operations that deal with uncertainty in objective functions, decision variables or constraints (Sheir, 2022) (Amira, 2023).

Simulation

Quantum neural networks extend classical neural network concepts into the quantum domain, potentially reducing computational times for training through quantum parallelism. The theoretical foundation involves using quantum circuits that mimic neural network behavior but operate under quantum mechanical principles (Sebastian, 2023). For instance, simulating molecular interactions at the quantum level can accelerate the development of new materials and pharmaceuticals (Boulebnane, 2023) (Malone, 2022) (M. P. da Silva, 2022). This approach is pivotal in developing advanced materials for use in various high-tech industries by simulating atomic and molecular interactions at the quantum level, researchers can design new materials with desired properties without the need for costly and time-consuming physical experiments (Amine, 2023) (David P. G.-B.-P., 2022).

Data Processing

Quantum Data Processing represents the capacity of quantum systems to handle vast amounts of data using the proprieties of parallelism of qubits. This involves exploring the use of these properties to enhance the performance with quantum algorithms (Kyriaki, 2023) (Amine, 2023). For example, data processing in QAOA and QA involves initializing quantum states, encoding problems into Hamiltonians equations, and iteratively optimizing parameters using classical methods. Both methods require multiple runs to gather statistical data and are challenged by noise and decoherence, necessitating error mitigation strategies and hybrid approaches integrating machine learning. Quantum Neural Networks (QNN) enhance machine learning tasks such as classification and pattern recognition. (David I. H., 2021)discusses about Quantum Intermediate Representation for Optimization (QIRO) that is a model to support quantum classical co-optimization for Multi-Level Intermediate Representation (MLIR) systems. These data systems can be adapted to incorporate the advantages of quantum computers and develop more market applications using quantum solutions.

Error Correction

The most crucial point for unlocking the quantum computer potential is to reduce the rate of error resulted from the noise that quantum computers are prone to, (Amira, 2023). This error produced in the quantum application process can be due to several factors such as decoherence, gate errors, measurement errors, quantum noise and cross talk due to the nature of how the QC is currently built. Research into how we can mitigate and eventually correct the errors, produced solution such as NAS (Hanrui W. D., 2021) for generating noise resistant quantum circuits produced out of high-level languages for coding. Also, using Noise Aware Training (NAT) (Hanrui W. G., 2021) for improving the results of Quantum Machine Learning (QML), allows for the creation of more error resilient quantum systems (Yunfei, 2024). Such developments from the software side of the industry, coupled with FTQC developments (Simon, 2024) show promising results for error corrected quantum systems that can allow for QA at industrial scale.

2.2.4 Market Formation and Resource Mobilization

Creating market demand for quantum technologies involves demonstrating the quantum advantages showcasing significant value creation opportunities (Hassija, 2020). Quantum applications in logistics optimization, financial modelling, and engineering can be explored in **Appendix 1**, which is focused on the solutions implemented in Germany. According to (Andreas Bayerstadler, 2021), the different studies for the quantum application within the industry can be observed along with their relative possible impact. This shows the successful implementation and real case impact into the different fields after the quantum solutions were implemented. It is discussed how the quantum computing ecosystem needs a structured form of creating the solutions needed to the market demands. A first stage would be the delimitation of the problem domain such that a problem can be categorized into a problem class. These problem classes can be characterized by common mathematical/business problem formulation and translated into variables and parameters for the mathematical model. The model should have clear objectives and proprieties to be able to be formulated into a quantum algorithm.

(Olawale, 2023)explains the different layers of Quantum Artificial Intelligence from a physicist perspective in layman's terms while the overview presented in the (Kyriaki, 2023) helps us to gain insights for the integration of the QC with ML and developing solutions for the market. (Amine, 2023) provides a closer look into the development process of a quantum software application while (Sebastian, 2023) evaluates the results of the potential of the QML application for quantum supremacy. In (David P. G.-B.-P., 2022) and (Kostas, 2024) a systematic review for the quantum algorithms available and their usability is performed that provides enough data for understanding the algorithms. Through the development workflows described in (Nivedita, 2020), (Benjamin W. B., 2021) and (Benjamin W. , 2020) we start to understand the development lifecycle of quantum solutions that provides a foundation of understanding and implementation of a workflow design.

With the help of (Michael, 2022) we can better evaluate the requirements for bringing the technology to the market. Innovations such as (Alexander, 2021) and (David I. H., 2021) allow for improving the quantum systems infrastructure that is still in the early development stages. While solutions such as (Mario, 2022), (Yuhuai, 2022) and (Javier, 2021) provide capabilities in developing a software tool that can accelerate the process of development of QAs. These elements need to be taken in consideration when developing the workflow design as it needs to incorporate future niche innovations as well.

In order to bring the technology to the market and demonstrate the quantum supremacy, the ecosystem developed the layers of the value chain that provide services that allow for the quantum applications to be developed and connected to the wider industry. These services include different platforms and infrastructures that have been specialized for different aspects of the quantum applications process, some providing holistic solutions. The remaining steps are to use those services, tools and environments to create QA that satisfy market demands. A part of the actors in the ecosystem can be observed in the **Appendix 2**, which describes the results of the investments in developing the industry network. Among the companies in the ecosystem, there are a few of notice for the purpose of understanding the current developments into the field.

2.2.5 Legitimation

A recurring challenge across these studies is the limitation posed by current quantum hardware. NISQ devices, while promising, are constrained by noise and scale, which impacts the performance and reliability of quantum algorithms. Many quantum algorithms are still in the experimental stage and require substantial refinement before they can be widely adopted. For example, (Boulebnane, 2023) illustrates the difficulties faced by QAOA in handling complex tasks such as protein folding, indicating hurdles in applying these algorithms to real-world problems with current quantum infrastructure. Applying quantum solutions to real-world problems often reveals their complexity, the study on protein-ligand interactions demonstrates this. The study highlighting the potential benefits of quantum computing in drug design, while also pointing out the need for further algorithmic advancements to handle more complex molecular interactions effectively.

Companies need to establish the credibility and feasibility of quantum technologies which involves overcoming technical barriers and achieve industrial integration. Record qubit fidelity of 99.5 percent by QuEra, MIT, and Harvard (Natasha, 2024); and by Microsoft and Quantinuum with 99.9 percent fidelity (M. P. da Silva, 2022) were achieved by combining new error-correction schemes and innovative architectures for logical qubits. Despite the fact that the experiment done was performed only on 2 qubits and the experiment is replicable only on the trapped ion technology available at the moment, it proves the feasibility of the technology at small scale laboratory environments. This can allow for the knowledge obtained from the experiments to be slowly incorporated and extrapolated to the wider industry, marking an inflection point in the field. Shifting the focus from hardware alone to software and architecture-based schemes for error mitigation and correction promises to accelerate timelines for the advent of universal fault-tolerant quantum computers (McKinsey, Quantum computing: An emerging ecosystem, 2019).

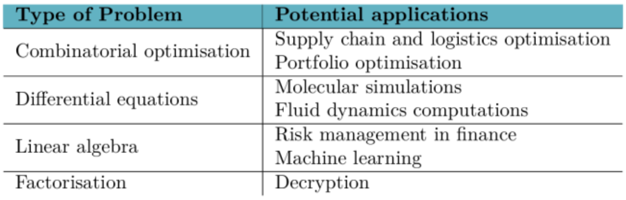
3. METHODOLOGY

The selection process of the data needed to develop the workflow design are separated in categories depending on their content and fit with the study scope. News articles, video conferences and market reports were collected to gather information on the social aspects of the Technology. A progressive search of academic databases such as Google Scholar, IEEE Xplore, and ArXiv was undertaken to identify peer-reviewed articles, conference papers, and research studies relevant to quantum computing, AI, Industry 4.0, and their interactions within the industry.

Constructing the MLP needed to develop the STSD, information related to the landscape, regime, niches and how stakeholders in the industry interact is essential. Information from veritable sources such as (McKinsey, Quantum computing: An emerging ecosystem, 2019) and (EY, 2022) help us to gather information needed to position the QC in the market. Reports such as (Insights, 2024) and (Markets&Markets, 2024) allow us to understand the trends that are necessary in describing the market situation and (McKenzie, 2024), (QTEdu, 2024) and (Quantum, 2023) give information about the social initiatives for development in the field. From the data collected the positive trends for development and challenges for implementation were identified. On top of that, sources such as (McKinsey, Quantum computing: An emerging ecosystem, 2019) and (Alex, 2022) (see **Appendix 2**), provide a comprehensive overview of the actor network within the industry.

In developing the STSD workflow for developing QA, this study employed a TIS framework to understand the different levels of the industry, from landscape forces to regime limitations as well as the niche innovations that have potential to highly impact the industry. The TIS framework was based on the work of (Karl, 2011), which has a structure that can be applied to any industry based on Governance and Functionality. This framework allows for different stakeholders to identify key factors independent of the field of knowledge. The TIS was complemented with the BEP described in (Masaharu, 2018) to analyze and identify the patterns in the industry of developing and implementing quantum solutions. (Rot, 2023) explores the business ecosystem that allows us to have a more detailed view of the policies and management challenges that the field experiences in bringing the technology to the market. Table 1 identifies the first type of problem classes that the quantum applications can have an impact. To this framework information related to the workforce extracted from (McKinsey, Quantum technology report, 2023), (EY, 2022) and (Maninder, 2022) allows us to identify the major problems from the social perspective of the technology.

For the development of a reliable STSD we examine studies that have already implemented such QA solutions such as (Andreas Bayerstadler, 2021) and (D-Waves, 2024) and (ClassiQ, 2024). From them, we identified the patterns in the workflows that help us in the creation of the design. The framework described in (Andreas Bayerstadler, 2021)used in for developing QA for the industry in a comprehensive overview of the formalization process of the problem. To understand the algorithms associated with different problems classes, (Amira, 2023) makes a good structure for understanding the issues in formalizing class problems from real world problems. For example, (Sheir, 2022) explores the use of QAOA formulations to solve optimization problems across various industries, demonstrating the versatility of these algorithms. Correlating the formulations process with the feasibility of the (D-Waves, 2024) workflow to see how universally applicable would be such a design. Additionally, the workflow patterns extracted from (Benjamin C. B., 2023), (Benjamin W. B., 2021) and (Benjamin W. , 2020) help create a comprehensive picture of the steps required for developing a quantum application.



Type of Problem	Potential applications
Combinatorial optimisation	Supply chain and logistics optimisation Portfolio optimisation
Differential equations	Molecular simulations Fluid dynamics computations
Linear algebra	Risk management in finance Machine learning
Factorisation	Decryption

Table 1: The four categories of mathematical problems where quantum computers can provide significant performance improvement. Table adopted from (Rot, 2023).

We explore the case studies described in (Andreas Bayerstadler, 2021), (Sheir, 2022), (Malone, 2022), (Martin, 2021), (Boulebnane, 2023) and (Frederik, 2024)to understand what are the expectations of quantum applications within industry settings. Each study also tends to focus on specific industry challenges, applying quantum computing solutions to address these unique problems. A significant number of applications utilize current Noisy Intermediate-Scale Quantum (NISQ) devices for optimization problems, simulations and data processing. Some of them can be observed in **Appendix 1** which according to (Andreas Bayerstadler, 2021) reflect a shared strategy of adapting quantum computing approaches to the capabilities of existing hardware despite its limitations (Alexander, 2021). (Malone, 2022) highlights the use of NISQ-era quantum computers for drug design, showcasing how current technology is being harnessed effectively within its constraints. Algorithm development remains an ongoing challenge. Similarly, (Frederik, 2024)reviews the role of quantum computing in advancing healthcare through genomics, diagnostics, and personalized medicine.

Incorporating quantum computing into existing infrastructures necessitates a socio-technical approach that balances technological capabilities with human and organizational factors as described in (Benjamin C. B., 2023) and (Nivedita, 2020). The development process encompasses several critical stages, each essential for effectively harnessing the quantum hardware proprieties, which can be observed in Figure 5. The process starts from identifying the problem and defining its goals and requirements in the form of supported variables for implementation in high level language. These variables are used in the design phase to create a model that is translated in a quantum executable program by different software environments. With the help of the software environments, the users can further refine their model by visualizing and adapting the variables. These software environments are necessary for developing a workflow design that can be accessible and replicable for different organizations.

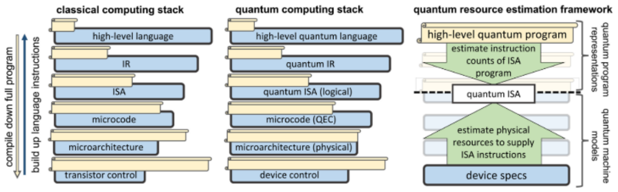


Figure 5 adopted from (Michael, 2022): The stacks for classical (left) and quantum (center) computing. At the top of the stack the program is expressed in a natural, high-level language such as C/C++ (classical) or Q# (quantum). This program is re-expressed as different program representations (manilla scrolls) in a sequence of languages (blue boxes) which are represented here as layers, with each layer being a lower-level language than that above, down to the physical signals controlling the device. A complementary viewpoint is that the instruction set available to the language at one layer can be combined to form a more elaborate instruction set for the layer above. The scrolls are shortest at the top, symbolizing that program representations are simplest when expressed in higher-level languages, while the blue boxes are smallest at the base of the stack, symbolizing that instruction sets are simplest at the lower levels. (right) quantum resource modeling framework is a modular representation of the layers of the quantum computing stack, which collects the upper layers as quantum program representations, and the lower layers as quantum machine models, with the quantum ISA connecting both. intermediate representation (IR); instruction-set architecture (ISA)).

In Figure 5 can be observed the process needed to execute a high-level quantum program, the programs instructions need to be compiled and expressed in terms of quantum Instruction-Set Infrastructure (ISA). It is appealing to support executions of programs expressed in a diverse set of high-level languages across a range of hardware back ends that may have different quantum ISAs. In analogy with classical computing, the use of a Quantum Intermediate Representation (quantum IR) that expresses high-level operations in a language-agnostic and ISA-agnostic manner, the middle optimization layer performs transformations on the quantum IR to reduce resource requirements (David I. H., 2021). In other words, these technologies can be connected through an ISA system that can allocate the computations based on the needed infrastructure to reduce resource requirements. This model of separation of tasks makes the workflow more modular that can help build the application using all solutions available. This propriety is essential in developing a workflow design that can be adapted to multiple industries.

Having the actors map in the field as shown in Appendix 2, we can better identify important players for the technology needed to have a stable ecosystem. Additionally, exploring companies with the potential to disrupt the landscape helps prepare the STSD to be adaptable for future developments as well. Design approaches as described in (Paola, 2014) were useful in identifying the socio-technical systems elements needed in developing a useful STSD that can be jointly used for different industries tackling the stakeholders, goals, requirements and resources input/output. All of these useful insights we complemented with the workflow described in (D-Waves, 2024) and (ClassiQ, 2024) for developing quantum optimization applications for the industry. This combination of theory with real-world practical methods allows us to create a robust STSD for the future development of the QAs.

4. RESULTS

Taking into consideration the synergies between the QC and AI along with the developments in qubit fidelity and simplifying the process of developing quantum applications, we can say that we are at an inflection point for the field and maybe for the industry 4.0 (Natasha, 2024).

The tested frameworks from (Andreas Bayerstadler, 2021), (D-Waves, 2024) and (ClassiQ, 2024) allows us to extrapolate the process to be more accessible for entrepreneurial activities needed in the industry. The simplified stages namely, defining the objectives and constraints; designing the task distribution and system model fitted to the problem; installing the quantum setup with the available platforms for execution; and the post processing part that helps in the interpretation of the results are the first steps in the development of quantum system. From them we can identify 4 main steps in the development process taking in considerations the solutions available. This ensures a balanced view that captures both measurable impacts and subjective experiences of stakeholders. The design workflow design presented is a simplification of the industry practices utilized by companies in the field. The ecosystem has proven that the hardware problems are manageable enough to be able to allow by companies in the field of quantum software development to create solutions that have proven industry applicability. With their workflows and complementary solutions as template, we have created the STSD to be more comprehensible from the business perspective that can rely on market solutions to create quantum applications.

Analyzing some of the most recent developments from within the ecosystem, we can observe that different solutions that can facilitate faster development of quantum applications have been created. These software platform (such as (ClassiQ, 2024))which allows users to develop quantum applications using high-level functional models, which it then converts into quantum circuits. This proves that AI agents that can automatically transform mathematical models into quantum circuits can successfully improve the rate of adoption of the technology. These circuits are automatically optimized by Q-Ctrl's infrastructure software, which enhances hardware performance as observed in Figure 6. Platforms are designed to be hardware agnostic, enabling them to run on a variety of quantum hardware providers. This integration of platforms, algorithm design and hardware optimization, provides a seamless development experience. This development experience can then be utilized in developing quantum applications that provide services to the industry.

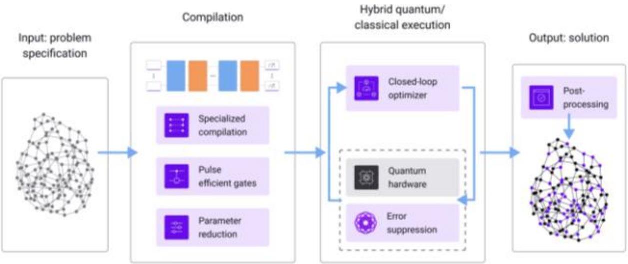


Figure 6 adapted from (Natasha, 2024): The optimization pipeline behind the quantum solver. In the input stage, a user-defined representation of the optimization problem is provided to the solver. Next, we construct the quantum model that is employed during the optimization process to construct a quantum circuit. In the compilation stage, the variational circuit is compiled to produce an optimized parametric circuit. The compiler may leverage an enhanced gate set of pre-calibrated pulse-level instructions of efficient (fast) 2-qubit gates. Finally, the optimization parameters are initialized and then passed to the closed-loop optimizer. Depending on the number of circuit parameters, a parameter reduction procedure may take place. In the hybrid execution stage, the parameterized circuits are submitted to the quantum hardware and the variational circuit parameters are optimized via a hybrid quantum-classical optimization loop. In the output stage, after final post-processing, the solution to the optimization problem is returned to the user.

Comparing (Andrew D. King, 2024) and (Natasha, 2024) for the execution of the same quantum application, which describes the simplified process needed in the development of quantum applications for optimization, their workflow and technology used signal a pattern and a shift in the industry. The described process can be observed in Figure 6 with the simplified stages of the workflow. (Natasha, 2024) demonstrated “a factor of up to 9× enhancement in the likelihood of finding the correct solution over the best published results using a trapped ion gate-model machine and over 1,500× enhancement vs published results on an annealer”. This demonstration of the capabilities of the technology proves the transition within the field from NIQS and dedicated superconducting circuits to FTQC gate-based applications run on agnostic hardware connected through cloud.

This transition allows for companies to run different quantum applications with significantly less barriers to entry and be able to adjust the model for errors with out-of-the box solutions. The knowledge gap as a result of the high-level knowledge needed to create such application is considerably simplified to coding within certain mathematical frameworks that help in formulization of the problem as observed in Table 2 (see **Appendix 3**). This problem is then executed on the quantum hardware without the user’s need for quantum knowledge. The back-end execution is performed by companies (such as IBM, Google, Microsoft or Amazon) based on the mathematical model obtained from the formalization of the problem. The end user would have to just be able to interpret then the result to extract as much value as possible.

The STSD proposed has a holistic view of the industry and is structured with the available solutions in the market that help in the development of the quantum applications for industry. Interpreting any company through a TIS structure with the governance and functionality as the dependent and independent variables and adapting their inefficient subroutines to be run on quantum solutions.

1. Define Objectives and Requirements

The initial phase involves clearly delineating the objectives and requirements of the quantum application. This includes identifying the specific problem domain, such as logistics optimization, machine learning, or complex simulations (D-Waves, 2024). Establishing high-level functional requirements and constraints is crucial. These requirements include the desired outcomes of the quantum algorithm, the performance metrics it must meet, and any hardware-specific constraints. This foundational step ensures that the subsequent phases are aligned with the overarching goals of the project. Reformulation involves expressing constraints and objectives as penalty functions suitable for quantum processing. Types of supported variables:

- Binary: Should X happen?
- Discrete: Which option to choose from X?
- Integer: Which is the optimal value for X?
- Continuous: Where should X execute?

These questions can be attributed to different quantum algorithms available corresponding to different industry. Combined with this understanding, we created Table 2 (see Appendix 3) to better group and classify the algorithms based on their possible use cases

2. Design Phase

During the design phase, ISA platforms provide the tools to create a model according to the objectives and requirements defined. The model is then established based on distribution of tasks between the quantum capabilities, ML solutions and classical calculations respectively. A schematic model can be observed in Figure 7.

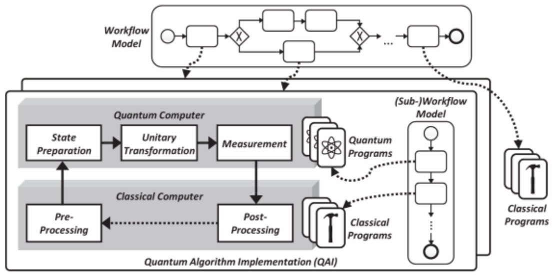


Figure 7: General structure of a Hybrid Quantum-Classical application (Sheir, 2022).

Such services that make the access to Hybrid Quantum Classical solutions easier through the combination of different ecosystems and platforms create the needed environment for developing QAs. This significantly reduces the complexity associated with gate-level programming, enabling the creation of sophisticated quantum circuits in a more intuitive and efficient manner. Such a high-level of abstraction for quantum circuit design allows the focus to shift on quantum applications development without requiring deep knowledge of quantum mechanics. The main objectives in this phase should be:

- Defining the quantum algorithms needed to fit the functionality (Andreas Bayerstadler, 2021).
- Specifying constraints and performance metrics (Kostas, 2024).
- Using ISA platform optimization tools to generate the quantum circuit (ClassiQ, 2024).

3. Quantum Simulation Setup

Hybrid solvers, which integrate both quantum and classical computational resources, are designed to tackle complex and large-scale problems that exceed the capabilities of quantum processing units (QPUs) alone. The configuration of these hybrid solvers involves setting appropriate runtimes and employing tools to manage problem size and complexity effectively. This hybrid framework facilitates the creation of customized workflows that optimize performance and streamline the development of new solutions.

The ISA platforms enable the export of circuits to formats compatible with quantum infrastructure, streamlining the transition from circuit design to simulation. (e.g. of platforms: Q-Ctrl, D-Wave, Classiq). Utilizing solutions for the ISA and Quantum cloud platforms, simulations of the designed quantum circuits are executed with high efficiency on dedicated hardware. The resulting circuit then can be scheduled for execution on a quantum computer. Following the execution phase, the results obtained from the quantum hardware require post-processing which involves classical computational techniques to interpret and validate the outcomes. This validation step is crucial to ensure that the quantum algorithm has achieved its intended objectives and that its results are reliable and actionable. This development phase includes:

- Setting up the simulation environment with quantum platforms.
- Simulation of quantum circuits with integrated solutions for validity and testing.
- Generating simulation data for further analysis, validation and refinement.

4. Visualization and Interpretation

In this phase, the supposed optimized quantum circuit is imported into a visualization environment to extract all the insights and data from the results. This simulation of the results from the quantum solution will be analyzed in different settings. By running simulations within the virtual controlled environment, researchers and end users can analyze the performance of the solution. This iterative process allows for the refinement of the quantum circuit based on the simulated outcomes, ensuring that it performs as expected when deployed in the real world.

The output of the quantum computers representing data in the form of matrixes, this represents usable data for the classical computing. This stage remains to be developed and adapted for different use cases and organizations as the quantum technology is going to be incorporated in the back-end of the processes. This presents an opportunity for the already existing ecosystems for visualization and interpretation of data within companies to integrate the results obtained from quantum systems. The data being specific for each case, the output of the quantum calculation needs to be put in the right context for interpretation.

- Defining the success/failure criteria for the results
- Reiterating the process until acceptable results are obtained
- Using the context models to evaluate the advantages/disadvantages of the model
- Creating the model for visualization software adapted to the context of the output.
- Adapting the systems to the quantum data pipeline generated

The workflow design proposed helps in streamlining the development process for quantum applications and reduces the knowledge gap needed in the development of QA by making it conceptually more accessible for people that lack quantum literacy by reducing the whole process to the four stages mentioned. Identifying the problem and its limitations from real world problems, then configuring the problem class into a quantum program that is hardware agnostic creates an ease of understanding of the stages of development. The environment setup stage will depend on the needed infrastructure that the quantum program is most efficient for execution. This distribution of tasks based on the cloud solutions infrastructure allows for a more efficient scheduling the executions of the programs. The final stage of visualization and refinement will depend on the specific solutions obtained and how they can be integrated with visualization platforms. By focusing on the intersection of technology and human factors, this approach ensures that quantum solutions advantages are accessible and useful to interdisciplinary teams, driving forward the potential of quantum computing within various industries.

5. CONCLUSION

The integration of the technology, thanks to the developments in hardware, is going to be done digitally over the cloud. The available solutions in the market have already the necessary capabilities to bridge the gap for the technical part, making the software hardware agnostic. This separation of the user from the technical part of the execution of the quantum application allows for the knowledge gap has been reduced considerably. Combined with the considerable knowledge sources and available documentation, the barriers to entry have been significantly been lowered.

In this design study we have explored the technologies and stages needed in the development process of the quantum applications, looking at different use cases and studies that tackle the development of QAs. In the development of the STSD workflow we have analyzed different studies using the TIS framework and extracted the patterns observed with the BEP. Insights from case studies and research provide critical data on the adaptability and scalability of QAs across different organizational contexts. This information is vital for developing STSDs that are flexible and capable of evolving with technological advancements and organizational changes. The STSD emphasizes the importance of technological integration while considering human and organizational factors, enhancing collaboration between different industries. The workflow design proposed takes in consideration these new advances and proposes a domain agnostic design that is replicable, adaptable and can be adopted for a wide range of QA. The design resulted provides a simplified holistic workflow design that facilitates the streamlining of the development process across industries.

6. DISCUSSION

One considerable limitation of the design is the high level of abstract thinking needed to identify, formulate and implement real case problem classes within the quantum mathematical framework. Besides the high-level skills needed for coding quantum applications each industry and organization have specific goals, requirements and limitations that would require multiple dedicated teams to organize and formulate the quantum models. These teams would work in adapting the digital infrastructure to become a Quantum-Classical Hybrid infrastructure, replacing inefficient subroutines of the system with quantum solutions.

Another considerable limitation is the lack of integrated out-of-the-box solutions for visualization and integration of the results for data analysis. These would remain to be analyzed and interpreted by the specialized team to identify the strategies for implementation. These solutions remain to be explored and developed as the market acceptance and demand grow.

Despite these limitations, this is an opportunity that allows for more entrepreneurial activities to be generated as a result of the lowered barriers to entry and diminishing knowledge gap. This is an opportunity for companies to actively take advantage of quantum technology. Adapting their systems and operations by appealing to organizations specialized in the integration with the technology will create new entrepreneurial ventures. The field of quantum applications for industrial use is at its dawn and companies that can integrate QAs will have a competitive advantage. The proposed workflow design aims to accelerate the adoption of the QC technology within entrepreneurial and industrial settings

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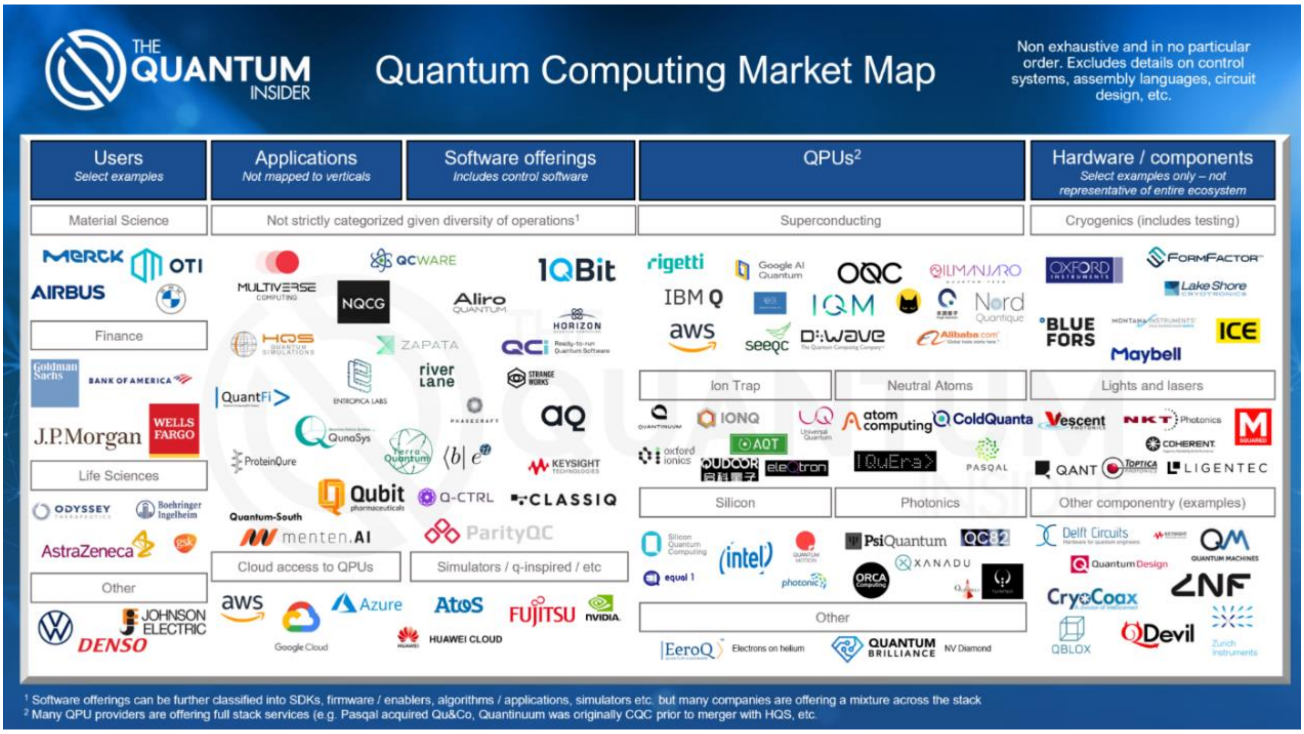
8. APPENDIX

Appendix 1:

Challenge	Problem Domain	Company	Use Case	Impact
Engineering & Design	Machine Learning	AIRBUS	QC for Surrogate Modeling of Partial Differential Equations	High
	Optimization	AIRBUS	Wingbox Design Optimization	High
		Bosch	Software Testing and Correctness Proving	Medium
	Simulation	Bosch	Design Optimizations for Electric Drives Using Numerical Simulation and Finite Element Methods	Medium
		Merck	Identification and control of Actionable Parameters for Disease Spread Control	Unknown
Material Science	Optimization	Boehringer Ingelheim	Optimized Imaging – Quantum-Inspired Imaging Techniques	Medium
	Simulation	BASF	Quantum Chemistry – Prediction of Chemical Reactivity in Molecular Quantum Chemistry	High
		Boehringer Ingelheim	Molecular Dynamics – Simulation of the Dynamics of Molecules	High
		Merck	Development of Materials and Drugs Using Quantum Simulations	Medium
		Munich Re	Battery Cover – Performance Guarantees for eVehicle Batteries	Medium
		VW	Chemistry Calculation for Battery Research	High
Production & Logistics	Machine Learning	Siemens	QaRL – Quantum-assisted Reinforcement Learning – Applicable to many Industrial Use Cases	Medium
	Optimization	BASF	Fleet Management – On-site Truck and Machine Deployment and Routing	Medium
		BMW	Robot Production Planning – Robot path Optimization for Production Robots (e.g., PVC sealing robot)	Medium
		BMW	Vehicle Feature Testing – Optimizing Test Vehicle Option Configuration	Medium
		BMW	Shift Scheduling – Optimizing Labour Shift Assignments	Medium
		Infineon	Demand Capacity Match in Supply Chain – Decide on a Production Plan given Predicted Customer Demand	Medium
		Infineon	Using Infineon Sensors and Actuators to Optimize Supply Chain Processes on the Customer Side	Medium
		Munich Re	Transportation Cover – Insurance of Time-Critical Freight	Medium
		SAP	Logistics – Truck Loading	Medium
		SAP	Supply Chain Planning – Improved and Accelerated Sizing of Orders (Lot Sizing)	High
		Siemens	QoMP – Quantum-optimized Matrix Production – Realtime Shop Floor Optimization	Medium
		VW	Vehicle Routing Problem – Optimize Vehicle Utilization in a Transport Network	High

Table adopted from (Andreas Bayerstadler, 2021): Initial Use Case Portfolio: A wide variety of optimization, simulation, and machine learning problems exist in the value-chains across the German industry. While impact in the next 5 years is low, several high-impact use cases have been identified.

Appendix 2:



Appendix 2: *Quantum Computing Market map – The Quantum Insider 2022* [51]

Appendix 3

Table 2: Overview of different algorithms and their possible applications within different industries based on (Andreas Bayerstadler, 2021) (ClassiQ, 2024) (D-Waves, 2024)

Industry	QAOA	Hamiltonian equations	QML	Grover	VQE	Industry specific
Manufacturing	Job scheduling, process optimization	Machine optimization	Anomaly detection	SAT Problems	Supply chain optimization	Any manufacturing optimization
Simulations	Fluid dynamics simulations	Combustion control	Molecule ground state calculation	Molecular Distance	Climate modeling	Environment specific simulation
Health-care	Drug component selection	Drug manufacturing optimization	Characterizing new drugs	Structure finding	Drug discovery	Personalized treatment plan
Finance	Portfolio optimization	Portfolio optimization	Fraud detection	Database search	Optimization of financial portfolios	Credit risk, Option pricing
Other	Cryptography, quantum safe encryption	Computational Fluid Dynamics simulation	Image classification	Cryptography	Materials discovery	General optimization problems