Quantum computing in commercial banking: Current state, applications and strategy

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ABSTRACT,
As the world increasingly digitises, the potential for new emerging technology to transform industries becomes more apparent. Quantum computing is a revolutionary technology that utilises the principles of quantum mechanics. Commercial banking is one of the industries subject to innovation caused by quantum computing. By identifying the gap in the literature regarding the strategic integration of quantum computing in commercial banking, this research seeks to provide a broader understanding of how banks can leverage quantum computing. Through interviews with industry experts, this study gathers first-hand insights into the current state, expectations, threats, opportunities and strategies regarding quantum computing in commercial banking.

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1. INTRODUCTION

The emergence of quantum computing represents a significant technological breakthrough with the potential to revolutionise numerous sectors, including finance (Rietsche et al., 2022). As traditional computing approaches the limits of its capabilities, quantum computing offers unmatched computational power, promising to solve complex problems currently impossible for classical computers. This evolution is particularly relevant for the financial sector, where data-driven decision-making, risk assessment, and transaction processing are important aspects of business (Egger et al., 2020). Commercial banks play a crucial role in the global economy and are positioned to leverage these advancements to enhance their operations and competitive edge.

Quantum computing, at its core, utilises the principles of quantum mechanics to process information. In doing so, these computers can solve mathematical equations that cannot be solved using today's classical computers. Unlike classical computers that use bits as the smallest unit of data, quantum computers use quantum bits, or qubits, which can represent both 0 and 1 simultaneously due to a property known as superposition. This, coupled with other properties like quantum entanglement and quantum parallelism, allows quantum computers to perform multiple calculations simultaneously, greatly increasing their computational speed and efficiency (Liu, 2021).

In commercial banking, key concepts include financial modelling, portfolio optimisation, fraud detection, and customer data security. Traditional computational methods often struggle with the sheer volume and complexity of financial data in these areas. Quantum computing promises to address these challenges by providing more efficient algorithms for cryptographic security (Ying, 2010), optimising investment strategies, and enhancing predictive analytics for market trends and credit scoring (Orus, 2023).

However, the integration of quantum computing in the banking sector is still in its infancy and remains largely theoretical. Leading technology firms such as IBM, Google, and Microsoft are at the forefront of developing and commercialising quantum computing technologies, yet practical applications in banking are still emerging. Despite this, projections suggest that practical utilisation of quantum computers could begin as early as 2025. This potential has induced interest among major banking institutions like Barclays, JPMorgan, and Morgan Stanley, who are eager to explore quantum computing's computational capabilities and its transformative potential in various banking operations (Aderman, 2019). These commercial banks' primary challenge is strategically leveraging quantum computing to sustain their competitive edge in an evolving financial landscape influenced by this disruptive technology.

Despite its potential, the integration of quantum computing in the financial sector faces significant obstacles. These include the current early stage of quantum technology development, high costs, and the need for specialised skills and infrastructure. Furthermore, the theoretical fundamentals of quantum computing, such as decoherence and error rates, pose practical challenges that must be overcome to realise its full potential in commercial applications (Bhat, 2021).

For commercial banks, staying competitive in the rapidly evolving finance landscape requires the adoption of cutting-edge technologies and the ability to integrate these technologies effectively into existing systems. This requires a strategic approach to leveraging quantum computing opportunities, mitigating associated risks, and addressing implementation challenges. In doing so, utilising an adoption framework could benefit commercial banks. Implementing aspects of the Technology Adoption Cycle, combined with company specifics, will allow for greater insight into quantum computing strategy (Rogers, 2003).

The primary goal of this research is to explore how commercial banks can effectively utilise quantum computing to maintain and enhance their competitiveness in the financial sector. This includes assessing the current state and future projections of quantum computing developments in finance while identifying key areas within commercial banking that could benefit from quantum computing.– Challenges and risks associated with implementing quantum computing in commercial banking will be identified, and strategic recommendations for adopting and integrating quantum computing technologies in commercial banks will be developed.

This thesis aims to answer the primary research question: *"How can commercial banks best use quantum computing opportunities to maintain competitiveness in the evolving financial landscape?"*

To comprehensively address this question, the research will be guided by the following sub-questions:

1. *"What is the current state of quantum computing, and what are future projections?"*
2. *"What are the opportunities and applications of quantum computing in commercial banking?"*
3. *"How can commercial banks strategise to effectively leverage quantum computing to gain and sustain a competitive advantage?"*

The research will explore these sub-questions and provide a detailed analysis of how quantum computing can be strategically adopted and integrated into commercial banks' operations.

The study aims to contribute to the theoretical understanding of quantum computing applications in finance by addressing this research question. It will expand on existing theories of computational finance and technological innovation, providing empirical evidence on the potential impacts and strategic integration of quantum computing in commercial banking (Herman, 2023). This research will also contribute to the broader conversation on the relationship between quantum computing and financial services, highlighting the relationship between technological advancement and financial theory.

From a practical perspective, this research will offer actionable insights for financial institutions, like commercial banks, on utilizing quantum computing to improve operational efficiency, enhance risk management, and secure competitive advantages. The findings will guide policymakers and industry leaders in making informed decisions about investments in quantum technologies and developing a skilled workforce capable of driving this technological transition (Jenkins, 2023). Additionally, this thesis systematically explores the potential opportunities and challenges of quantum computing in commercial banking. It aims to provide commercial banks with a broader understanding of the technology, ensuring they can adapt their strategy accordingly.

2. LITERATURE REVIEW

2.1 Quantum Computing

Quantum computing has emerged as a groundbreaking field connecting quantum theory and computer science, posing a computational power and capabilities shift. The concept of quantum computers was first projected by physicist Feynman (Rietsche et al., 2022), highlighting the potential of leveraging quantum phenomena for more efficient computation. Deutsch's seminal work from 1985 further formalised the idea of quantum parallelism (Ying, 2009), where a quantum Turing machine can perform calculations on multiple inputs simultaneously. This is a feat that classical computers struggle to achieve efficiently. Quantum computing utilises quantum bits or qubits that can exist in superposition, a state where they can be both 0 and 1 simultaneously (Rietsche et al., 2022). Moreover, these qubits are subject to entanglement, which allows qubits to be interconnected, influencing one another instantaneously regardless of the distance. Another cornerstone of quantum computing is quantum interference, which enables qubits to cancel out unwanted states through constructive or destructive interference. In contrast to classical computing, quantum computing taps into the power of superposition, entanglement, and interference to perform complex calculations exponentially faster. The historical development of quantum computing dates back to the visionary ideas of physicists Feynman and Deutsch (Ying, 2009), who were known for groundbreaking discoveries such as Shor's algorithm for prime factorisation. Quantum computing technology has made significant developments, with experimental implementation of quantum processors by leading companies and recent developments showcasing the rapid progress in the field. Quantum computing holds great potential across various domains, including cryptography, optimisation, simulation, machine learning, and finance (Rietsche et al., 2022). Quantum computers have shown promise in simulating complex quantum systems more efficiently than classical computers, offering new opportunities for research in material science, chemistry, and drug development (Rietsche et al., 2022). Despite its promise, quantum computing faces challenges and limitations such as error rates, qubit coherence, scalability, and hardware constraints (Rietsche et al., 2022). Addressing these challenges will be essential for quantum computing technology's continued advancement and practical implementation.

2.2 Applications of Quantum Computing in Banking

Quantum computing has emerged as a radical technology with the potential to transform various industries, including the banking sector. The exceptional computational power and efficiency of quantum computing systems have increased interest in exploring their applications and implications for financial services within the banking system (Herman et al., 2022).

In commercial banking, key areas such as risk management, portfolio optimisation, fraud detection, and customer data security stand to benefit greatly from quantum computing. Classical computational methods often struggle with the volume and complexity of financial data, leading to inefficiencies and inaccuracies. Quantum computing can address these challenges by providing more efficient algorithms for cryptographic security, optimising investment strategies, and enhancing predictive analytics for market trends and credit scoring (Orus, 2023). The ability of quantum computers to process large datasets quickly and accurately can transform how banks manage risks and optimise portfolios, leading to better financial performance and reduced exposure to market volatility (Aderman, 2019; Herman, 2023).

Fraud detection and cybersecurity are also critical areas where quantum computing can profoundly impact. The real-time analysis capabilities of quantum computers can improve fraud detection mechanisms, enabling banks to identify and mitigate fraudulent activities more effectively. Additionally, quantum computing introduces new challenges for cybersecurity. Traditional encryption methods, which rely on the computational difficulty of specific mathematical problems, may become vulnerable to quantum attacks. This necessitates the development of quantum-resistant cryptographic algorithms to protect sensitive financial data from potential breaches (Aderman, 2019).

Transaction processing within the banking sector can also benefit from quantum computing. Increasing the efficiency and speed of complex financial transactions can significantly reduce the time and resources required for clearing and settling transactions. This improvement is particularly beneficial for tasks involving numerous variables and high computational demands, such as financial derivatives and high-frequency trading (Aderman, 2019). Quantum computing can optimise these processes, leading to faster and more reliable transaction processing, essential for maintaining competitiveness in fast-paced financial markets.

Predictive analytics and credit scoring are other areas where quantum computing can significantly contribute. By processing and analysing vast amounts of data, quantum computers can identify trends and patterns that improve the accuracy of predictions and assessments. This capability can enhance decision-making processes within banks, leading to better customer service and more reliable credit scoring systems (Herman, 2023). Generating more precise and timely insights into market trends and consumer behaviour can give banks a competitive edge in a dynamic financial environment.

The integration of quantum computing in the banking sector faces significant challenges. The technology is still in early development, with practical applications remaining largely theoretical. The high costs of quantum computing and the need for specialised skills and infrastructure pose additional barriers to widespread adoption (Bhat, 2021). Furthermore, technical challenges such as error rates and the stability of qubits must be addressed to ensure reliable quantum computations.

Commercial banks must make significant investments in research and development to harness the benefits of quantum computing. Collaborations with leading technology firms and developing a skilled workforce are crucial for building the necessary infrastructure and expertise (Jenkins, 2023). Banks must also focus on building robust cybersecurity frameworks to protect against the new threats posed by quantum technologies.

2.3 Technology Adoption Cycle

The Technology Adoption Lifecycle, conceptualised by Everett Rogers, explains how the population adopts new technologies and innovations, divided into five categories: Innovators, Early Adopters, Early Majority, Late Majority, and Laggards (Rogers, 2003). Innovators, around 2.5% of the population, take significant risks to try new technologies due to their innovative nature. Early Adopters, representing about 13.5%, are opinion leaders who adopt innovations early but carefully. The Early Majority, making up 34%, adopt new technologies before the average person, adopting only when benefits and effectiveness have been shown. The Late Majority, also 34%, are sceptical and adopt innovations after the average person. This is often due to economic need or peer pressure. Lastly, Laggards, comprising 16% of the population, are conservative individuals who resist change and adopt innovations last, typically when the technology has matured.

In the context of banks adopting quantum technology, the institution can be seen as the "individual" navigating through these stages. For instance, a bank that aligns with the Innovator category would actively innovate on quantum technology. Such a bank would invest in pilot projects and collaborate with quantum computing firms and academic institutions to stay at the forefront of technological advancements (Moore, 1991).

Understanding this lifecycle and determining which type of adopter category the company wants to pursue allows banks to strategically plan their adoption of quantum technologies, ensuring a smoother transition and broader acceptance within the financial sector.

3. METHODOLOGY

3.1 Research design

This qualitative research investigates how commercial banks can best utilise quantum computing opportunities to maintain competitiveness in the financial landscape. Qualitative research methods are used to answer questions on a particular phenomenon and integrate perspectives on this phenomenon (Hammarberg et al., 2016). Taking quantum computing as the phenomenon researched, conducting qualitative research aims to create a comprehensive theoretical context. Data collection will involve primary data in the form of interviews with experts in quantum computing and banking, as well as secondary data from desk research (Saunders et al., 2009). An inductive approach will be used based on the search for applications and opportunities of quantum computing in banking. Raw data from the desk review, complemented by interview data, are collected. From this data, opportunities and applications can be derived. This will lead to new insights. To answer how commercial banks can strategise on the emergence of quantum computing, desk research will be utilised to create an overview of strategic steps relevant to adapting emerging technologies. Interviews with field experts will be structured so that the interviewee can give their opinions on effective strategies regarding this concept, and later on, I can identify strategic steps in the desk research to get the interviewee's opinion on specific steps.

3.2 Desk research

3.2.1 Data collection

The desk research aims to identify relevant documents to support knowledge of the research question and subquestions. When dealing with a relatively new technology on which only a little information is available and understandable, it is important to base the research on a broad understanding of the topic and subtopics. Papers on quantum computing, its applications in banking, and strategies for implementing a new technology will be reviewed. Internet searches will be conducted to better understand commercial banking practices and recent strategies on quantum computing. By determining the status quo of quantum computing, banks, and their strategy, complementing this knowledge with insights from academic papers allows for a greater understanding of the topic.

3.2.2 Data analysis

The first step in analysing data is to map the current state of quantum computing. Additionally, relevant data contributing to this mapping was used as a basis for the interviews. The second set of data points collected in the research is an overview of the practices of commercial banks that are subject to quantum computing. This overview will be part of a thematic analysis that involves the identification of themes within qualitative data. The data gathered in the research is systematically analysed and organised into meaningful themes. In this paper, the themes identified will be the banking practices subject to quantum computing. This thematic analysis is part of a framework analysis that seeks to map all areas of commercial banking affected by quantum computing. After identifying these areas, the goal is to explain how these areas are subject to quantum computing and the relevance of the potential disruption by this new technology.

3.3 Interviews

3.3.1 Sampling

For the interviews, a sample of an undetermined number of participants was taken from the population. The participants were selected based on their expertise in quantum computing and commercial banking, complemented perhaps by expertise in strategy. The sampling method was non-probability sampling, as the researcher explicitly selected the participants. As the data sought to be extracted from the samples is highly specific, a clear focus needs to be used, meaning that data can only be collected from a part of the population. The sampling approach used in this research is purposive sampling, as samples are based on the individual's knowledge of the topic (Douglas, 2022). The sample size of this research was between 3 and 6. Participants in the interviews were selected based on two sets of criteria: (1) The interviewee should be working inside the environment of either quantum computing or commercial banking. (2) The interviewee must be between 21 and 67. According to these criteria, a sample was taken from the population to conduct the interview.
The table below lists the 5 participants in the research interviews. As mentioned before, all participants matched the criteria stated beforehand. Before the interviews, all participants established that they provided answers to my questions based on personal opinions and did not represent the views of their (former) employers. Therefore, the current and former employers of the interviewees are not stated in the table.

Table 1 Interview participants

Nr.	Participant's function	Expertise
1	Director commercial partnerships	Quantum computing software & hardware
2	Professor Applied Quantum Computing	knowledge across various aspects of quantum computing technologies and their theoretical foundations
3	Quantum Technology Strategist	Specialised in the strategic development, geopolitical implications, and regulatory considerations specific to quantum computing
4	Senior Managing Consultant and Quantum Ambassador	Extensive experience in applications of quantum computing and general aspects of the technology
5	Founder & Chair of quantum start-up	Relationship of quantum computing & banking, cryptography

3.3.2 Data collection

A semi-structured interview was conducted to collect the data. A semi-structured interview is a popular data collection method that has proven versatile and flexible (Kallio et al., 2016). According to Kallio et al. (2016), one of the main advantages of a semi-structured interview is successfully enabling reciprocity between the interviewer and participant, allowing the interviewer to improvise follow-up questions based on the participant's responses. The possibility of asking additional questions allows for a better understanding of principles relevant to answering the research question. The interviews will be held via Teams, Zoom, or another video conference platform. These sessions will be recorded if the interviewee grants permission. This allows for the transcription of the data.

3.3.3 Data analysis

According to a theoretical framework, the interview data will be transcribed. The transcripts will be coded according to thematic analysis, a coding method that allows the researcher to group the initial codes into potential themes (Jnanathapaswi, 2021). This would lead to the identification of quantum computing applications in specific commercial banking practices. As desk research has established potential applications of quantum computing in commercial banking, the transcripts can be coded to complement the data gathered through desk research. However, the interviewees could also mention applications for commercial banking that were not collected from the desk research. Resulting in the coding of the data being used to identify new aspects of the research. The resulting themes will be presented after identifying all quantum computing applications in commercial banking through the interviews combined with the desk research.

4. RESULTS

The following section examines the results obtained through the interviews complemented by data extracted from the desk research. The aim of doing desk research was to get secondary data about topics around the research questions and sub-questions. The data collected is exclusively non-academic, providing a greater understanding of current trends and practices within the quantum computing and banking industry. Utilising white papers, reports and articles from companies, organisations and institutions involved in the topic allows for practical insights. These practical insights allow for higher-quality interviews due to the actuality and practicality of the data. Following the analysis of the interviews, information about three main themes was identified.

4.1 Current state of quantum computing and future projections

For commercial banks investigating the potential impact and implementation of quantum computing, it is important to get an idea of the current state of quantum computing. This current state of quantum computing, complemented by future technology projections, will allow banks to inventorize the technology's possibilities for their industry.

Unlike quantum computers, which are being built, quantum computing has not shown practical applications and real-life use cases.(IP1, IP2, IP3, IP4, IP5). As highlighted by IP3 and IP5, quantum computing is currently at a stage where the technology remains theoretical, and significant advancements are needed before widespread practical use can be seen. Companies like IBM, Microsoft, and Google are already investing heavily in quantum computing (IP1 and IP4), holding on to the idea that the theoretical promises will become practical over time. (Biondi, 2021) argues that these activities from big tech will not translate into commercial results in the coming five years. The investments are based upon the solid fundamentals of quantum computing, acknowledging that development is still in the early phases. All interviewees (IP1, IP2, IP3, IP4, IP5) agree with this view and recognise that development will eventually translate into the practical flourishing of quantum computing.

Moving towards quantum computing, which provides real-world applications and use cases, key factors driving development must be identified and optimised. Desk research combined with codes from interviewees identified three main drivers of quantum computing's development.

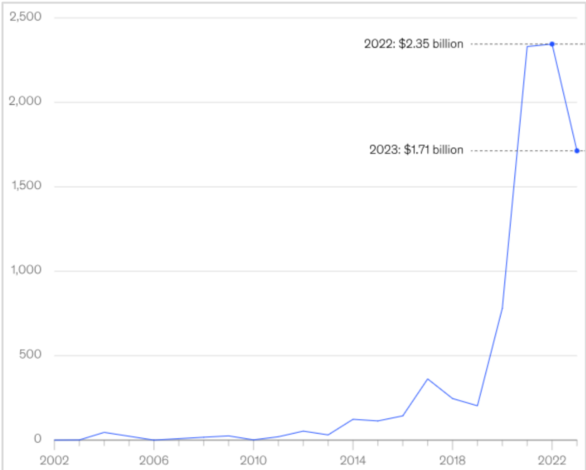
4.1.1 Technological innovation

Technological innovation refers to the technological advancements needed for quantum computing to become usable in real-world applications. “The main challenges in quantum computing are improving the quality of qubits and optimising the scalability of these computers”, was said by IP4. From a practical perspective, this means that the quality of qubits should be improved, leading to higher reliability and performance. Growing scalability capabilities, which refers to interconnecting a large number of qubits while maintaining coherence and low error rates, will allow for more computational power. (Brooks, 2023), acknowledges that these two technological factors will drive technological innovation and, therefore, quantum computing development. Before quantum computing will possibly impact the banking sector, technological advancements must be made. Financial problems, potentially being subject to quantum improvement, require more qubits and higher-quality qubits (IP4).

4.1.2 Funding and investments

Funding and investments are another key driver of quantum computing development. Although the short-term anticipated ROI is negative, companies and organisations should look ahead and invest in the technology anyway (IP5). Data from Bogobowicz (2024), reporting for McKinsey, shows the trends of investments in quantum computing over recent years. The graph below visualises the collective investments in quantum technology.

Figure 1. Total investments in quantum technology start-ups in the period 2002 to 2023



The main trend that is evident is that investment in quantum technology has shown significant growth from 2010 onwards. The significant shift in focus towards generative AI can explain the drop in investment from 2022 to 2023. Furthermore, perceptions of QC as a long-term technology whose potential in various sectors is still being understood and evaluated play a role in the drop in collective investments. The interviewees all recognise AI's hype and its implications on quantum computing (IP1, IP2, IP3, IP4, IP5). A drop in investment is one of these implications.

An interesting finding is that all interviewees foresee an emerging trend among investments in QC (IP1, IP2, IP3, IP4, IP5). They mentioned that the number of start-ups is too large currently. Over the coming years, start-ups will go bankrupt or be acquired by larger firms, causing investments in start-ups will decrease along with the number of start-ups.

This does not imply that the total investment in QC will slow down. IP3 foresees aggregate investments, public and private, to grow strongly over the coming years. All interviewees share this forecast, as they all mention that investments in QC should and are likely to grow over the coming years (IP1, IP2, IP3, IP4, IP5). Whether public or private spending will dominate investments is not clear looking forward. However, IP3 foresees China continuing its strong public investments and the US continuing its private spending trend. While total investments are close to equal between China and the US, Europe is behind regarding investment totals. (McKinsey & Company, 2024) Europe's total spending on QC lags behind these two global powers. IP5 mentioned that he thinks Europe is not investing enough in QC when looking from an international perspective and that this development will cause Europe to fall further behind in innovation. This fallback in innovation could potentially impact Europe's competitiveness in new technologies, limiting its ability to capitalise on revolutionary quantum computing applications. All developments considered, the investment growth forecast adds to the view that QC is in the initial stages of development (IP5) and shows the potential to gain track as time continues.

The steady increase in investments in quantum computing signals a significant shift that commercial banks need to address strategically. Even though the outlook of return on investment might currently be negative, the growing funding highlights quantum computing's potential to transform finance, particularly in areas like data security and risk assessment. Banks should view investments in quantum computing as a long-term opportunity, expecting considerable benefits as the technology matures. Given the anticipated consolidation in the quantum computing market, banks should be selective about their investments, focusing on startups with strong business models and innovative technologies. This careful approach will help banks fully capitalise on the advancements in quantum computing.

4.1.3 Building an ecosystem

Building the ecosystem that will facilitate the development of quantum computing is essential. Although technological developments and investments are part of the ecosystem as well, the progress of QC relies on more factors. These additional factors belong to the collective ecosystem of quantum computing. Desk research combined with opinions from interviewees resulted in the identification of four additional drivers contributing to the ecosystem of quantum computing:

Knowledge in the quantum computing ecosystem encompasses the accumulation of scientific research, technical knowledge, and continuous learning. Knowledge is an important pillar of QC that must continue to expand (IP4). Key actors in this knowledge-gathering process are academia, companies, and governments.

Building upon the foundation of knowledge is developing and fostering talent in this emerging field. This increase in talent ensures an inflow of skilled and capable professionals who can push the boundaries of this new technology.

Collaboration and partnerships refer to the coordination between academia, industry players, and the government. According to IP2, IP3, and IP4, partnerships are the way for organisations wanting to innovate in this field—naturally, the coordination of knowledge and power results in greater innovation and productivity. In the quantum field, this is the same (IP5).

Awareness and adoption of quantum computing facilitate the move from a theoretical technology towards a real-world practice. Awareness and adoption refers to the processes that enable stakeholder and the broader public to become familiar with quantum computing. IP1 and IP2 are hammering on the fact that broad acknowledgement of quantum computing can take the sting out of the threads that QC hold. Shor's algorithm is the most famous quantum algorithm because it proves that QC can crack RSA, the encryption method used in most of today's data. Since all individuals and institutions are involved with (sensitive) data, recognising the impact of QC will ensure that adequate measures are taken in time (IP1, IP2, IP3, IP4, IP5).

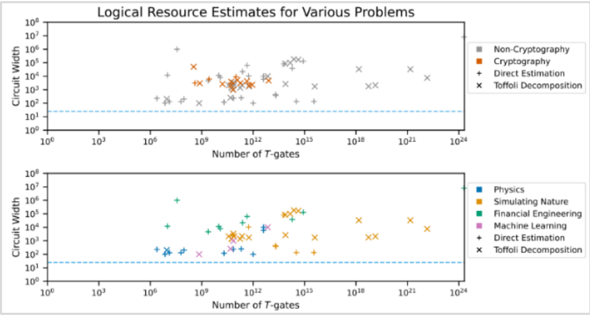
Ethics and regulations are separate aspects of QC, with regulations being the guidelines and frameworks implemented to ensure ethical and responsible development, adoption, and use of quantum computing. IP1 interestingly mentioned that there are no ethical implications of quantum computing. The argument proposed by IP1, in contrast to generative AI, is that quantum computing precisely does what has been the input. Therefore, quantum computing is not subject to ethical dilemmas.

IP2, IP3, IP4 and IP5 disagreed with this point of view. IP3, an expert on ethics and regulations within Europe, highlighted two ethical problems with quantum computing. The accessibility of quantum computing worldwide allows for ethical discussions, as countries in Africa, for example, might not have access to quantum computing. Applications of quantum computing, which promise to be revolutionary, can only be utilised in certain countries or areas. IP4 proposed that quantum computing running as a cloud service, what it is doing already, could solve this ethical problem. However, still having control over the accessibility of QC can cause countries to restrict access to the technology for certain actors from different parts of the world (IP3). The second ethical problem is the monitoring and allowance of applications of quantum algorithms. Dealing with Shor's algorithm, which has the potential to crack RSA and decrypt data, ethical dilemmas arise regarding the allowance of quantum computers being utilised for these purposes.

Governments propose and enforce regulations to eliminate or reduce ethical problems. According to (Almosallam, 2023), there are three ways to approach the governance of quantum computing, with regulations being one. Regulations are the procedural approach to eliminating ethical dilemmas and threats. The other two methods are improving technology, causing ethical problems to be obsolete and proposing behavioural measures, causing people to behave responsibly. IP3 says regulations must be imposed, regardless of technology or behaviour, preventing most ethical problems.

Mapping the ecosystem of quantum computing with drivers of innovation gives an idea of the factors impacting the development of quantum computing. To better understand the current state of quantum computing, it is essential to consider all drivers and factors influencing advancements in the emerging field. Yet, technological innovation is the main driver of emerging technologies like QC because it directly influences the creation and advancement of new capabilities that transform the industry and practices around it (IP2). The speed of technological innovation is dictating the speed of other drivers surrounding the technology. To get a better understanding of the current level of technological innovation and, therefore, the current state of quantum computing, IP4 provided a graph that indicates progress and prospects:

Figure 2. Number of qubits (y-axis) and number of gates (x-axis) needed for various applications in real-world use cases (Scholten et al., 2024)



The figure shows the technological requirements of quantum computing for various applications (Scholten et al., 2024). The first plot highlights the number of qubits in combination with the number of gates cryptography threats become realistic. According to the plot, cryptography threats arise from 10^3 to 10^4 qubits and 10^9 to 10^13 gates. Knowing that the current maximum number of qubits is 10^2 and the maximum number of gates is 10^3, cryptography threats are not yet realistic (IP4). Yet, when looking at the quantum roadmap of IBM, projections are that in 2033, there will be quantum computers with 10^3 qubits and 10^9 gates (IP4). IP4 assessed that IBM is currently at the forefront of technological innovation, meaning cryptography threats are realistic in 10-15 years.

The second plot shows the potential of quantum computing applications according to the same principles as plot 1. The trend that can be deducted from the plot is that the order of application of quantum computing starts in physics and progresses towards machine learning, nature simulation and financial engineering. Financial engineering, applying to commercial banking, is expected to become affected by QC around 10^4 till 10^5 qubits and 10^9 till 10^15 gates. IP4 believes that IBM's quantum roadmap is realistic and does not overpromise its technological advancements. Therefore, applying the quantum roadmap of IBM results in financial engineering will become possible around 10-15 years from now (IP4).

IP1, IP2, and IP3 share the same expectations about the future advancements of quantum computing. IP2 and IP3 mentioned that applications in finance will become possible ten years from now, together with cryptography threats. However, IP3 believes that in 7 years, the world could already see quantum computing playing a role in finance. He argues that there could be organisations apart from IBM that innovate faster, resulting in earlier applications of QC in finance. IP5 has a contrary belief regarding the applications of quantum computing in finance, as he argues that it will have none. He claims that he believes that there are no exponential improvements to be made in finance. He argues that classical computers will be able to solve complex financial problems as quickly as quantum computers are promised to do.

4.2 Opportunities and applications of quantum computing in commercial banking

'Quantum banking' is one of the least championed trends within financial services today. This is partly because quantum computing has not been present on a global stage yet. Nonetheless, it still has the potential to impact the financial system significantly. The vast potential of QC in commercial banking comes from its computational power and ability to process data faster. As IP1 describes, quantum computers are better at computational problems than classical computers despite having the downside of being unable to process large amounts of data (IP3). (Clere, 2023) stresses this comment by claiming that quantum computing has the potential to be 10 million times faster at computational problems than classical computers.

The transforming nature of quantum computing in banking lies in its computational ability. To determine potential applications of QC in commercial banking, practices that require large amounts of computational power have to be identified. By conducting desk research combined with input from the interviewees, three main themes within applications of QC in commercial banking were identified:

4.2.1 Optimization

Portfolio optimisation is one of the most exciting applications in quantum computing in finance(IP1, IP4 and IP5). It aims to improve the asset selection process to maximise returns while minimising risk. Portfolio optimisation is also a computationally intensive task (IP4). As the number of assets and potential combinations increases, classical computers struggle to keep pace. Quantum computers are good at processing problems dealing with low amounts of data and high computational requirements (IP1). Thus this is where quantum computing steps in. Studies like the one published in Nature in 2023 (Buonaiuto et al., 2023) demonstrate the effectiveness of the Variational Quantum Eigensolver (VQE) algorithm. This approach allows quantum computers to explore a large number of potential portfolios simultaneously, which is impossible for classical machines.

The impact of quantum computing reaches beyond just speeding up calculations. (Willingham, 2023) highlights how quantum algorithms can identify complex relationships between assets. This ability allows for creating more nuanced and potentially more profitable portfolios. Imagine investment strategies that consider regular factors like risk tolerance and account for the correlations between different asset classes (IP2). This development can lead to hyper-personalized investments, where portfolios are fitted to individual financial goals and risk profiles.

4.2.2 Financial modelling

Financial models are important when making financial decisions, predicting future market behaviour and assessing risks. However, these models currently operate within the limitations of classical computers, which struggle as the complexity of financial instruments and market dynamics increase. Traditional models rely primarily on historical data and statistical predictions, essentially making forecasts based on the past. This approach does have limitations, failing to account for unexpected events and small market shifts that can significantly impact outcomes.

Quantum computing can solve this limitation in financial modelling. Research like "Quantum Risk Analysis," published in Physical Review Letters (2022), explores the potential of quantum algorithms to tackle complex financial simulations. Quantum computers can integrate many potential market scenarios simultaneously, which is impossible for classical machines.

(Palsson et al., 2017) Refers to the concept of quantum-powered stochastic modelling. This approach aims to improve traditional statistical predictions, considering the randomness and uncertainty of financial markets. By factoring in a broader range of variables, such as social media sentiment, political events, and even global weather patterns, quantum computers can allow for a clear indication of potential risks. This will enable banks to assess creditworthiness, market volatility, and other risks more accurately. This, in turn, leads to benefits like fairer loan pricing for borrowers because they are less subject to overly cautious models. Additionally, lenders can make more informed decisions when dealing with complex markets or products. Furthermore, improving modelling creates a more stable financial system as institutions can prepare better for unexpected economic turbulence.

Another aspect of improvements in quantum computing on financial modelling is the ability to price financial instruments (IP1, IP2, IP3, IP4). Pricing complex derivatives and options relies on accurate risk assessment. (An Exploration Of Option Pricing in The Quantum Realm, 2024) stresses how quantum algorithms can revolutionise these calculations. By efficiently simulating complex financial scenarios that account for a large number of variables and potential outcomes, quantum computers can help banks price instruments more accurately. This will lead to fairer markets for all participants, from individual investors to large financial institutions. Markets will become more efficient due to accurate pricing that better represents the potential risks and rewards.

An interesting opinion from IP1 is that financial modelling by quantum computing does not have the potential for relevant speedups. Quantum computing can be superior to classical computing in modelling due to the potential energy efficiency it provides. This opinion is backed by the belief that classical computers will progress at a pace that allows them to calculate at the same speed as quantum computers when doing financial modelling.

4.2.3 Machine learning

A third application of quantum computing in banking involves the relationship between quantum computing and machine learning. Classical machine learning algorithms are powerful tools, but they struggle when the complexity of financial data increases. The interviewees did not mention machine learning itself. However, specific quantum machine learning use cases were discussed (IP4).

Machine learning algorithms are present in many aspects of modern banking practices. Examples are fraud detection, algorithmic trading, and customer segmentation. However, machine learning often reaches a bottleneck when dealing with considerable datasets or complex relationships between variables. Quantum machine learning offers a solution to such bottlenecks.

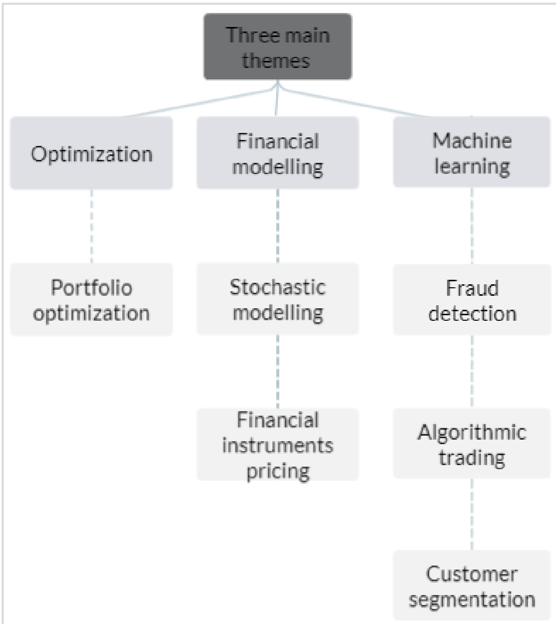
Fraud detection is the constant battle of banks trying to detect transaction anomalies. In practice, finding correct anomalies is incredibly difficult because of the overhead involved – false positives. (A New Era in Financial Crime Technology, 2023) argues that quantum machine learning allows banks to analyse extensive transaction data and provide insights that escape classical algorithms. This allows for detecting fraudulent activity with greater precision and fewer errors, protecting banks and their customers.

Algorithmic trading is another banking activity reliant on machine learning. It stands to benefit significantly from quantum computing. Current algorithms can struggle to adapt to rapidly changing market conditions and identify complex trading opportunities. All interviewees (IP1, IP2, IP3, IP4, IP5) agree that algorithmic trading has enormous potential when combined with quantum machine learning. IP3 underscores that minor improvements can result in major advantages, as a 1% increase in annual return due to technology can result in millions of additional profits. By analyzing a broader range of data points at higher speeds and making connections that classical algorithms miss, quantum machine learning can develop more sophisticated trading strategies. This development of improved trading algorithms can potentially lead to increased returns for investors.

Besides fraud detection and trading, machine learning can be used for pattern recognition and segmentation. Understanding customer needs and preferences is important for banks to offer personalised financial products and services. However, traditional machine learning can struggle with the difficulties of human behaviour. Articles (Jain, 2022) explore how quantum machine learning can improve this process. By analysing substantial amounts of customer data, including social data points and transaction patterns, quantum algorithms can identify clear customer segments. This improved approach allows banks to fit their products and services to specific customer segments. This can greatly enhance customer satisfaction and loyalty.

Three main themes were identified by combining interviewees' input with desk research. Each theme holds specific practices of commercial banks that are subject to improvement due to quantum computing. The interview participants mentioned portfolio optimisation, financial instruments pricing, fraud detection, and algorithmic trading as potential quantum computing applications in commercial banking, as stated in the related text. However, documents found in the desk research suggest stochastic modelling and customer segmentation as additional applications, which were not highlighted during the interviews. Combining interview participants' responses and desk research documents allowed for the creation of three overarching themes regarding quantum applications in commercial banking. The analysis of codes related to specific quantum applications and assigning these codes to broader themes resulted in three main themes to which specific applications could be attributed. The figure below visually represents the themes, complemented by their related applications in commercial banking processes.

Figure 3. Three main themes of applications of quantum computing in commercial banking



4.3 Strategy on quantum computing for commercial banking

While the impact of quantum computing seems far away at this point, companies are already busy thinking about or preparing for this emerging technology. Although quantum computing provides many opportunities, threats cannot be overlooked. Companies and organisations need to think ahead and strategically plan the emergence of quantum computing. By embracing a proactive approach, organisations can make themselves ‘quantum ready’ (IP5).

When asked about the strategy relevant to commercial banks, the interviewee (IP2) mentioned that it depends on the banks' perspective. He identified two sides of the implications of quantum computing: opportunities and threats. The threats, as he mentioned, refer to the ability of quantum computing to crack RSA, which is the encryption method used the most worldwide. Opportunities are chances for banks to improve their banking activities by harnessing the power of quantum computing. The difference in strategy between both sides can be described by the level of ‘necessity’. (IP1, IP2, IP3, IP4, and IP5) all argue that the necessity of an effective strategy addressing the threats of QC is high. Opportunities for QC, in essence, are optional innovations that banks can strategise towards.

4.3.1 Strategy regarding threats of quantum computing

Shor’s algorithm, combined with fully developed quantum computers, can break current encryption methods used to protect sensitive consumer and financial data. Current cryptography methods are mainly RSA and partly Elliptic Curve Cryptography (ECC). These encryption methods rely on the difficulty of factoring large numbers or solving complex mathematical problems. These difficulties make it incredibly hard for classical computers to compute these problems and crack encryption. For classical computers, calculating these problems would take millions of years (IP1). (Birch, 2023) explains that quantum computers can crack these codes in a fraction of the time it takes classical computers due to their ability to perform calculations in parallel. It would take about 8 hours to 45 minutes for a fully operational quantum computer to crack RSA encryption (IP1). This scenario, often called “harvest now, decrypt later”, is a significant threat to institutions dealing with sensitive data like commercial banks (IP1, IP2, IP3, and IP5).

The potential consequences are severe. Breaches of sensitive customer or company data could lead to large financial losses and reputational damage for banks. To mitigate this threat, banks must develop a quantum-resistant cryptography strategy.

One approach involves post-quantum cryptography (PQC) algorithms designed to protect against attacks from quantum computers (IP1, IP2, IP3, IP5). Organisations like the National Institute of Standards and Technology (NIST) are researching and standardising these PQC algorithms (Computer Security Division, Information Technology Laboratory, National Institute of Standards and Technology, U.S. Department of Commerce, z.d.). Adopting these new algorithms as early as possible is essential for banks to make their data security future-proof (IP1, IP2, IP3, IP5).

In practice, transitioning to PQC algorithms is a great challenge. All interviewees stress that banks' existing infrastructure and software may not be easily compatible with PQC algorithms. Banks should invest in research and development to ensure that the transition to this new encryption method proceeds smoothly.

Another possible alternative to PQC is Quantum Key Distribution (QKD), which uses quantum properties to establish secure, unbreakable communication for quantum computers. This encryption method is not as well-researched as PQC, and most experts prefer the promises of PQC over those of QKD (IP3).

The consensus on strategising to address quantum computing threats is that banks should have started yesterday. Banks that did not begin yesterday must strategise as soon as possible (IP1, IP2, IP3, IP4, IP5). Recognising the threat that will appear in the next 5-15 years, depending on progress made on quantum computers, is necessary for banks to survive. Transitioning to quantum-proof security when quantum computers are already full-scale can have disastrous implications for banks and individuals affected. Starting as soon as possible will prevent banks from having to ‘rush’ their transition. Rushing the entire transition will cause higher costs and more time spent.

4.3.2 Strategy regarding opportunities of quantum computing

Contrary to strategising to address quantum computing threats, having a proactive plan for the opportunities that arise is more nuanced. A bank's choice to invest in quantum computing can be fueled by the ambition to gain a competitive edge. On the other hand, a bank may opt for a more conservative approach to stay competitive as soon as quantum computing becomes practical. When strategising, the difference between a proactive and a reactive approach is an important distinction for banks to make (IP1, IP2, IP3, IP4, IP5).

Whether to be proactive or reactive in the face of quantum computing revolves around a bank’s risk tolerance and position within the Technology Adoption Cycle (Technology Adoption Lifecycle | Gainsight, 2022). Large banks, which are often categorised as innovators, can afford to take calculated risks and have the resources to broaden their scope regarding innovation (IP2, IP3, IP4, and IP5. As IP 3 described it: “When resources are small, the focus is concentrated. When resources are large, the focus is expanded”. This refers to large banks having a broader scope to innovate in emerging technologies, unlike smaller banks that do not have the resources. These innovators or first movers, like JP Morgan, can shape the quantum banking industry and potentially realise significant rewards as quantum computing matures. Smal-to-medium banks, often falling in the early adopters category, may opt for a more conservative approach. By closely monitoring the progress of quantum computing and the experiences of innovators, these banks can minimise risks while still being able to capitalising on quantum computing. These commercial banks will adopt the technology instead of developing aspects of QC at the forefront.

All interviewees agree that large banks should pursue the role of innovator, as they all think that quantum computing will play a revolutionary role in 5-15 years. IP1, IP2, IP3, and IP4’s opinions align with data from the desk research, as they also think that smaller banks are perfectly fine in their early adopter role. Having one person or a small team dedicated to staying up-to-date with QC developments and preparing for the maturing of its technology is enough for small-to-medium banks. Yet IP5 does not share that view, as he argues that there is no need for ‘playing it small’. He believes that small-to-medium banks will fall when they are only busy staying ready. Arguments for the fall of these banks are that innovators are not eager to share innovations like improved trading quantum algorithms, causing early adopters to be left with nothing. IP5 and IP1 think that banks should at least aim to be somewhere between innovators and early adopters by investigating use cases, building knowledge, and aiming for collaborations and partnerships.

5. DISCUSSION

Through performing desk research, analysing theory, and conducting interviews, this research was meant to answer the following research question:

"How can commercial banks best use quantum computing opportunities to maintain competitiveness in the evolving finance landscape?"

To enrich the research, the research question was divided into three subquestions to create a broader understanding of key concepts surrounding the topic. This section critically analyses the results, discussing the main patterns, similarities, and differences observed in the research. Additionally, the degree of alignment or divergence from existing literature is discussed.

The findings on the current state of quantum computing and its future projections indicate that while quantum computing holds immense potential for revolutionising banking operations, its practical applications remain primarily theoretical at this stage. Significant advancements are needed before the technology can become useful. Identifying the need for further advancements for this technology to mature aligns with (Rietsche et al., 2022), as this paper describes the efforts yet to be made to ensure the advancement of quantum computing.

Furthermore, mapping the ecosystem relevant to the development of quantum computing in the banking industry is an exciting result of this research, as existing literature fails to connect different drivers and challenges of quantum computing into a comprehensive ecosystem. While Jenkins (2023) highlights the need for building an infrastructure and Bhat (2021) recognises the need for gathering knowledge and expertise, the literature does not present a complete overview of the factors driving innovation in this field.

Findings on the current state of quantum computing acknowledge that QC is still in the early stages of development. Technological innovation, meaning the advancements of hardware and software, suggests real-world use cases are still distant. Scholten et al. (2024b) underscore this finding by visualising the current progress made on the technological side of quantum developments. This paper also comes to the same conclusions, discussing the foreseen period for quantum technology to mature in different sectors and disciplines. Stakeholders, like commercial banks, can utilise these results to map the road ahead and to keep track of important drivers of QC.

The second subquestion of this research aimed to give commercial banks an idea of the threats quantum computing encompasses and which opportunities present themselves concerning this new technology:

"What are the opportunities and applications of quantum computing in commercial banking?"

The answer to this sub-question is simple. Opportunities for quantum computing in banking involve commercial activities requiring high computational power. As the literature suggests, quantum computing has many specific applications in finance and banking (Serov & Vasiliev, 2023). This research thematised all theoretical quantum computing applications and identified three general application types. A clear understanding of the three most prominent application types and specific use cases will allow commercial banks to investorise potential arguments for adoption.

The third and last research question is relevant to commercial banks choosing to pursue innovation in quantum computing:

"How can commercial banks strategise to effectively leverage quantum computing to gain and sustain a competitive advantage?"

Identifying the double-edged sword of opportunities and threats creates two ways of strategising. The main threat of quantum computing is its ability to crack current encryption methods. The strategy perceived as most useful is the one that suggests starting as soon as possible, trying to transition to a quantum-safe security protocol. The literature on cryptography is extensive, as Shor's algorithm was already found in 1994. Ying (2009) highlights the threat of quantum computing. However, the literature does not propose practical strategies that prepare an organisation for the threats of QC.

The other side of QC regards the opportunities and applications previously identified in response to subquestion two. Strategising towards the potential of quantum computing to gain a competitive advantage or remain competitive can be done proactively and reactively. The choice of strategy depends on the perception of the opportunities, resources of banks, and position in the market. Commercial banks and other financial organisations can use this framework to recognise the need for a quantum strategy and develop one specific to the organisation.

5.1 Practical Implications

From a practical viewpoint, this research's findings can contribute to commercial banks' investigation and preparation for quantum computing. Commercial banks can navigate what quantum computing encompasses for their industry and determine future projections based on the analysis of the current state of quantum computing regarding technological innovation, funding and investments and the ecosystem. Furthermore, commercial banks could use findings from this research to map the potential opportunities and threats quantum computing holds by studying the different applications presented in this research. Additionally, thinking about threats like cryptography enables commercial banks to limit their exposure to risks involved with QC. Finally, commercial banks can think about their strategy in the way presented in the research, by having an innovator or adopter mindset.

5.2 Theoretical Implications

This research aimed to create a better understanding of quantum computing, its applications, opportunities, threats, and strategies involving this new technology. Identifying the current state of quantum computing and future projections provides additional insights into the state of quantum computing proposed by Albareti et al. (2022). Identifying three main themes of quantum applications in banking contributes to Herman et al. (2022), which describe specific ranges of quantum computing applications in finance and banking. Identifying three general themes adds to this existing literature by generalizing applications and subdividing particular use cases among these themes. The findings on strategies dealing with the cryptography problems of quantum computing add another dimension to Ying's (2009) framework of the cryptography problem. The proposed strategy gives organisations a handle to act upon the cryptography problems. The discovery of strategic implications for commercial banks dealing with quantum computing builds upon the potential of quantum computing in banking described by Orus (2023). Strategising based on available resources, focus and perceived potential of quantum computing proposes ways for commercial banks to act upon the potential of quantum applications in commercial banking.

5.3 Limitations

There is room for potential limitations when researching an emerging technology like quantum computing. In addition to the inherent limitations of academic research, quantum computing is a complex and predominantly theoretical concept, which creates room for biases and uncertainties. Technological maturity is one of the principal limitations of this research because the assumption that quantum computing will progress towards practical use cases at a predictable pace is made. Quantum computing, being in the early stages of development, is subject to uncertainties. This research bases most of its opportunities, threats and strategic recommendations on this premise.

Another limitation of this research concerns the availability of empirical data. Due to the limited empirical evidence available on quantum computing, this research relies mainly on theoretical data and expert opinions. While expert opinions and theoretical data are valuable, the question is whether they can be deemed viable without real-world data and testing.

Quantum computing, working on the principles of quantum properties, is an incredibly complex technology. The depth of understanding of quantum technology and advanced computational theories may be too complex for the typical expertise in the banking sector. This complexity can limit the depth of analysis in the research.

A limitation often found in qualitative research is the conflict of interests of interview participants. The participants may have professional or financial stakes in promoting and spreading quantum computing. This potential conflict of interest could lead the interviewees to emphasise benefits while downplaying certain risks. This potential influence may skew the research towards overly optimistic projections.

An inherent risk of conducting research is researcher bias, which occurs when the researcher (sub)consciously influences which data is included or how it is interpreted. Subjective interpretations may play a role in processing the data, especially when dealing with expert opinions.

The last limitation of this research involves the relatively small sample size. Using a small number of interviewees might result in a narrow view of the topics discussed. The small sample may also exclude diverse and contrasting views, which could have changed the research's conclusions.

5.4 Future Research

Recommendations for future research are to validate the theoretical predictions of quantum computing empirically. Empirical testing and real-world experimentation will allow researchers access to data that can confirm or deny the promised benefits and challenges highlighted in theory. Empirical validation will solidify the projections of quantum computing within banking, causing stakeholders to make more informed decisions about adopting the technology.

Another suggestion for future research is to explore the use cases and applications of quantum computing in commercial banking further. Pilot testing and simulation studies can help understand the practical solutions in commercial banking scenarios, and further exploring the use cases will help to conceptualise applications in banking better.

The last proposal for future research is to investigate the strategic implications of quantum computing for organisations. Given the dual perspective on quantum computing's strategic implications for commercial banking, future research should involve holistic strategic framework development and comparative analysis. Researching holistic strategic framework development involving strategy on threats and opportunities simultaneously allows for more robust and comprehensive strategies regarding quantum computing. These improved strategies determine the optimal pathway to becoming 'quantum-ready'. Regarding further research on strategy, a comparative analysis of strategic approaches is necessary. Investigating and comparing different strategic approaches for various types of banks can give better insight into the effectiveness of certain types of strategies for different types of banks. This will help fit strategies for specific banks based on their resources, focus, and capabilities.

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APPENDIX

Appendix A- Interview guide

This semi-structured interview aims to gather information from experts in the field. As such, additional questions have been asked to provide further depth or explanation.

Section 1: Introduction

1.1 Engage in small talk to start of the interview
1.2 Ask the interviewee for preferences regarding language (Dutch or English)
1.3 Read the confidentiality and rights of the interviewee
1.4 Introduction Interviewer and goal of the research
1.5 Ask the interviewee to introduce himself

Section 2: General question about interviewee/expertise

2.1 What is your working experience up to this point, and how does this result in your expertise on [topic]?

2.2 How long have you been active in the field of [topic]?

Section 3: Questions about quantum computing and its current state

3.1 Despite all the news on quantum computing, where do you think quantum computing is at when discussing development?
3.2 Given that quantum computing’s promises are primarily theoretical, can it deliver on its promises?
3.3 What quantum computing applications do you consider relevant to all industries?
3.4 What are the factors that drive quantum computing’s innovation?
3.5 What is the current state of the named drivers?
3.6 Are there ethical considerations involved with the use of quantum computing?
3.7 In which form will quantum computing be used in future years? (Cloud or Physical)

Section 4: Questions about quantum computing concerning commercial banking

4.1 What makes quantum computing attractive for commercial banking?

4.2 Where does quantum computing’s impact on banking stand compared to other use cases like in chemistry?

4.3 What are the most important applications of quantum computing in commercial banking?

4.4 Are there risks involved with quantum computing being used in commercial banking?

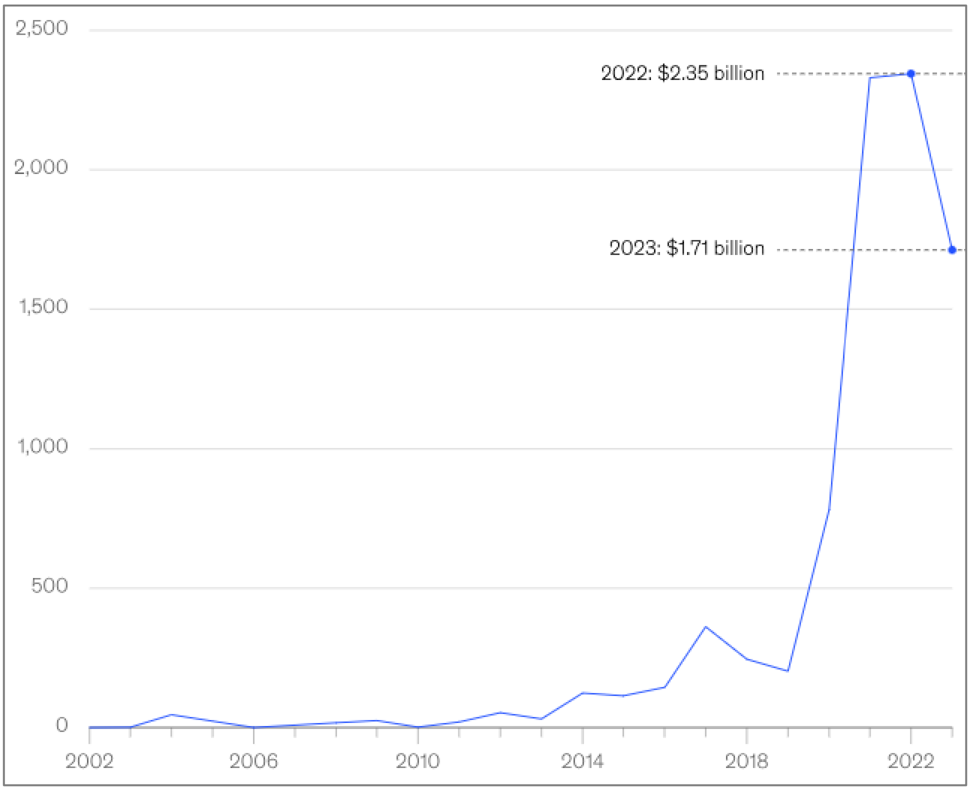
Section 5: Questions about strategy regarding quantum computing

5.1 Should banks engage in the transition/adoption of quantum computing in their business model?

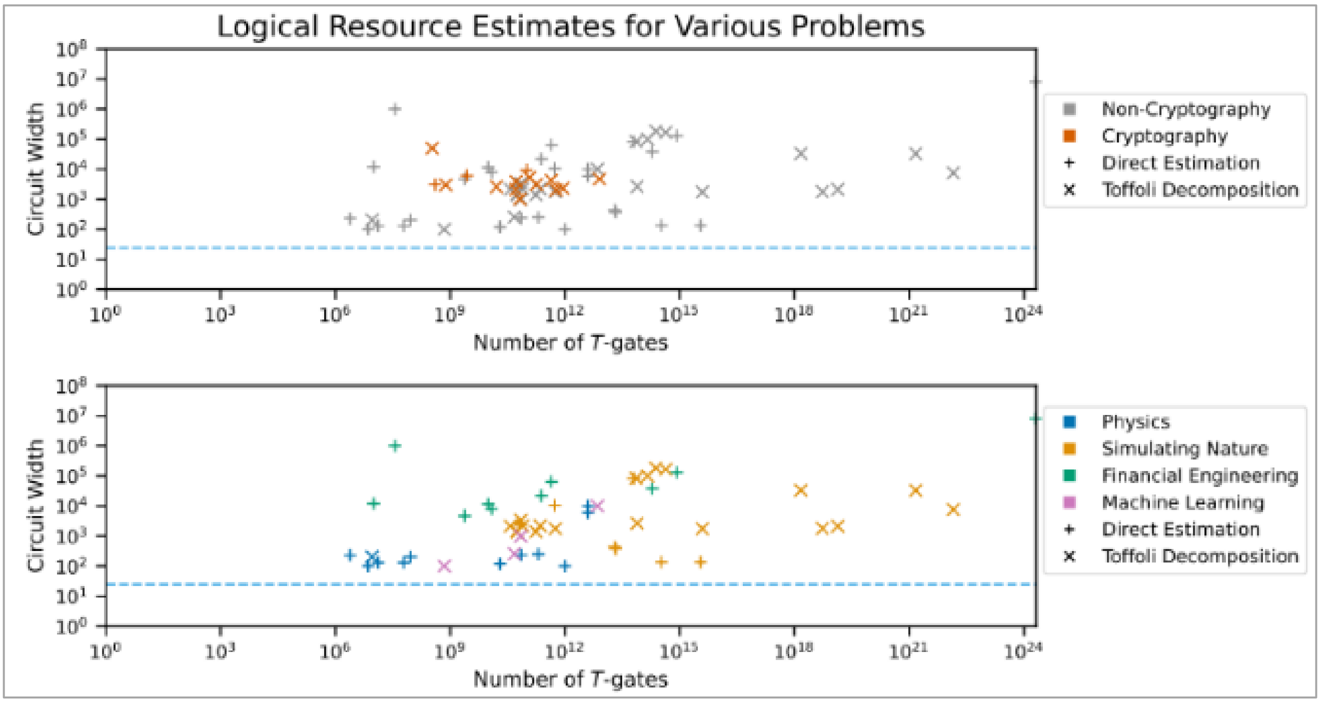
5.2 How should banks strategise towards this emerging technology?

5.3 Is first-mover advantage a strategic advantage or a costly gamble?

Appendix B- Total investments in quantum technology start-ups in the period 2002 to 2023



Appendix C- Number of qubits (Y-Axis) and number of gates (X-axis) needed for various applications in real-world use cases



Appendix D- Three main themes of applications of quantum computing in commercial banking