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Quantum Computing in the Financial Sector

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Abstract: In recent years, quantum computing has become an emerging technology and is being explored in regard to how it can disrupt industries. One industry that quantum computing could have an impact on is the financial industry. However, the currently available literature lacks a clear overview of the use cases for finance. Therefore the thesis explores the potential use cases of quantum computing in the financial industry, how such use cases could impact financial products and services, their potential value, and the challenges in implementing them. The qualitative survey method will be followed to find the answers to the stated research questions. Semi-structured, recorded, and transcribed interviews will be conducted with industry specialists. The method consists of a literature review, interview preparation, data collection, and data analysis (thematic analysis). As a result, the thesis provides a framework summarizing the potential use cases, their impact on financial services, and their value for the industry. The thesis aims to contribute to raising awareness of the potential of quantum computing and make it understandable for industry specialists how the technology could impact their companies. The contribution can be beneficial for professionals working in research and development departments of financial institutions or exploring new technologies to solve business problems.

Keywords: quantum computing, financial industry, emerging technology

CERCS: P170 Computer science, numerical analysis, systems, control

Kvantarvutus finantssektoris

Lühikokkuvõte: Viimastel aastatel on kvantarvutus muutunud kiiresti arenevaks tehnoloogiaks, seetõttu uuritakse selle võimalikku mõju erinevatele tööstusharudele. Üks tööstusharu, mida kvantarvutus mõjutada võib, on finantssektor. Samas puudub saadaolevas kirjanduses selge ülevaade kvantarvutuse võimalikest kasutusjuhtudest finantssektoris. Seega uurib antud töö kvantarvutuse võimalikke kasutusjuhte finaktsektoris, millist mõju võivad kasutusjuhud omada finantssektori toodetele ja teenustele, milline on tehnoloogia võimalik mõju antud sektorile ning millised on hetkesed väljakutsed kasutusjuhtude rakendamisel. Püstitatud uurimisküsimustele leitakse vastused järgides kvalitatiivset küsitlusmeetodit. Poolstruktureeritud, salvestatud ning transkribeeritud intervjuud viiakse läbi finantssektori spetsialistidega. Meetod koosneb kirjanduse ülevaatest, intervjuude ettevalmistamisest, andmete kogumisest ja andmeanalüüsist (temaatiline analüüs). Töö tulemuseks on raamistik, mis võtab kokku võimalikud kvantarvutuse kasutusjuhud finantssektoris, nende mõju ning väärtuse finantsteenustele. Lõputöö eesmärk on aidata kaasa kvantarvutite potentsiaali teadvustamisele ning finantssektori teadmiste laiendamisele, kuidas antud tehnoloogia võib mõjutada finantsasutusi. Panusest võivad kasu saada finantsasutuste teadus- ja arendusosakondades töötavad spetsialistid, kes tegelevad uute tehnoloogiate uurimisega äriprobleemide

lahendamiseks.

Võtmesõnad: kvantarvutus, finantssektor, arenevad tehnoloogiad

CERCS: P170 Arvutiteadus, arvutusmeetodid, süsteemid, juhtimine (automaatjuhtimisteooria)

Contents

1 Introduction

Emerging technologies are innovative, quickly growing, and potentially disrupting technologies surrounded by ambiguity [1]. Emerging technology is also an area of interest for companies, as new technologies can offer new business opportunities or pose new risks for the industries [2].

Quantum computing is one of the emerging technologies - novel, rapidly developed, potentially influential, and surrounded by uncertainties [3]. The technology is based on the principles of quantum mechanics and can potentially speed up current processes or even enable new possibilities by processing complex calculations more quickly [4]. A quantum computer could complete a calculation that may take a classical computer a billion years to complete in a much shorter time frame [4]. In 2019, Yndurain et al. [5] predicted that businesses could use quantum computing to solve specific challenges in three to five years. However, they also stated that applying the technology widely could take several years [5]. On the contrary, research conducted by consultants at McKinsey [6] suggests that the first fault-tolerant quantum systems will arrive in 2030. While the exact timing is still uncertain, multiple industries already explore the potential use cases.

The business challenges that quantum computing could solve come from industries like pharmaceutical, materials research, airline, logistics, and financial [7]. From the list, the latter might be the first to benefit from quantum computing use cases, namely because it tackles problems that, in essence, are suitable to be solved by using quantum computing [7] [8]. Thanks to its ability to process computations quicker, quantum computing could support innovation in portfolio optimization, risk analysis, and risk modeling [4]. These possibilities can help financial institutions improve their decision-making and risk management capabilities [9].

Some financial institutions, such as JPMorgan & Chase [10], CaixaBank [11], and Bank of Canada [12] are already investigating the future and discovering quantum computing's use cases for the sector. Being the first player in the field can give significant advantages over competitors [5].

As quantum computing is still in its early stages, the available literature lacks a clear overview of the use cases of quantum computing for the financial industry, the value of the use cases, the impact of the use cases, and any challenges that impede implementing the use cases in the financial industry. Therefore this thesis addresses this gap by exploring potential use cases for the financial industry through a literature review and interviews with industry specialists. This thesis aims to determine the current status, compare the use cases discussed in the literature to use cases suggested by industry specialists, and understand the value the technology can bring and its impact on the financial sector. The goal is to find answers to the following research questions:

- **RQ1.** What are the potential use cases of quantum computing in the financial industry?
- **RQ2.** How can the potential use cases of quantum computing impact financial

products and services?
- **RQ3.** What kind of value can quantum computing have on financial products and services?
- **RQ4.** Which obstacles impede implementing quantum computing use cases in the financial industry?

Starting with new technology can be difficult for businesses - especially if the technology is still developing and there is little literature available. O'Halloran in [13, p. 3] emphasizes that "the combinations of uncertainties that come with an emerging technology and a rapidly moving but fragmented landscape make it difficult for decision-makers across the private and public sectors to maintain awareness, build understanding or know when and how to act." To understand whether the new technology is worth to be explored, insights from other specialists in the industry help. The thesis aims to explore the potential use cases of quantum computing in the financial industry and understand their impact and value on the services and products in the sector. In addition, the aim is also to understand the current impediments and the time frame for implementing the use cases.

To achieve the stated goals, first, a literature review is done to explore the use cases mentioned in the currently available literature. Next, to get the perception of industry specialists, a qualitative survey method is followed. For that, the first step is the preparation for interviews. Next, interviews with industry specialists are conducted. Then, the interview results are analyzed using thematic analysis. Afterward, the results are put into a framework. The contribution of this thesis is a framework that summarizes the potential use cases of quantum computing in the financial industry, with their value and impact.

The contribution will be helpful for the financial industry, especially professionals in research and development departments of financial institutions or business development leaders exploring new technologies to solve business problems. Specialists from the financial sector can use this thesis to understand the potential of quantum computing and how their companies could be impacted.

The following is the structure of the thesis. An overview of quantum computing, its use cases, and the financial sector is given in Section 2. Section 3 explains the method in use, and Section 4 presents the outcomes of the literature review and the interviews. Section 5 discusses the findings and answers the stated research questions, while Section 6 concludes the topics discussed.

2 Background

This section overviews the main concepts, quantum computing and the financial sector, related work on the topic, and the terminology mentioned in the thesis.

2.1 Quantum Computing

This current subsection will give an overview of quantum computing. First, a brief introduction is given to the history of the technology. Next, the types of problems which could be approached with quantum computing are introduced. This is followed by a comparison of quantum and classical computing. Then, an overview of the characteristics of quantum computing and the architecture of different quantum computers is presented. Lastly, the current impediments of quantum computing are introduced.

The start of quantum computing was in the 1980s when researchers P. Benioff and R. P. Feynman discovered that the concepts of quantum physics could be applied to address complex calculation problems [14]. While the technology is still being developed, quantum computing's impact is expected to be disruptive, surpassing regular computers in certain use cases, making the calculations more effective, and enabling the processing of large amounts of data [6] [15].

Quantum computers have the potential to solve problems from complexity classes which solutions today would require extensive amounts of time, plus technical and economic resources [16]. There is a separate complexity class for such problems, BQP ("bounded-error quantum polynomial time" [17, p.67]), problems efficiently solvable by a quantum computer with answers in a bounded precision range [18]. BQP class contains all problems from class P, but also some problems from class NP and maybe some from PSPACE [17]. Class P problems are easy to solve on a classical computer [17]. However, while class NP problems are easy to verify on a classical computer, the solution is difficult to find (for example, factoring and discrete logarithm) [17]. PSPACE problems can be solved by a classical computer using "a polynomial amount of memory but possibly requiring an exponential number of steps" [17, p.67]. The illustration of the expected size of BQP class and its relation to other complexity classes be seen in Figure 1.

Will quantum computers replace classical computers? Egger et al. [19] predict that quantum computers will not replace regular computers but enable new use cases that cannot be achieved using a regular computer or would take too much time. This idea is extended in [20], where the authors explain that regular computers will continue to exist. Even if a quantum computer is used to solve the problem, the input and output data will remain classical [20]. Therefore, regular and quantum computers are expected to form a quantum computing system where the processes are run in cooperation [15].

The computation-heavy calculations have been previously tried to solve on high-performance computers (multiple supercomputers together) [3] [21]. According to [3], a

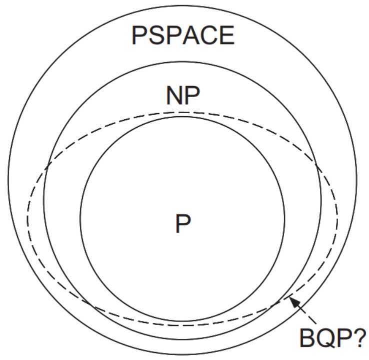

Figure 1. The Expected BQP Problem Space [18].

supercomputer is a powerful classical computer that might contain thousands of CPUs and GPUs. However, a quantum computer is not the next version of a supercomputer but another way of computing [6]. While supercomputers may be good at database sorting, they struggle with discovering hard-to-notice patterns in the data, in which quantum computers excel [3]. There is also a hope for quantum advantage, surpassing classical computers in time or precision on a quantum computer solving a real-world problem [8]. By the time of writing, the quantum advantage is not achieved yet [8]. However, in 2019, Google reported having achieved quantum supremacy, using a quantum computer to solve a problem (although not useful in the real world) faster than a classical computer [8] [15]. Reaching quantum supremacy was also claimed by a group of Chinese researchers in 2020 who reported outperforming the world's fastest supercomputer by 100 trillion times with a quantum computer [15]. In addition to quantum advantage, there is a hope that quantum computers use less energy for calculations than their classical counterparts [6].

Yndurain et al. [5, p. 2] explain that "quantum computers leverage quantum mechanical phenomena to manipulate information." For instance, superposition, entanglement, and interference are principles that give quantum computers an advantage over classical computers, as they can accelerate processes that take the classical computer an enormous amount of time or are not solvable at all [19].

Quick computations can happen thanks to how a quantum computer stores and manages information. While the classical computer stores information in bits with only one state, either 0 or 1, a quantum computer stores information in quantum bits (qubits) with states 0, 1, and a superposition [19]. Superposition in quantum physics means simultaneously being in states 0 and 1, enabling performing multiple calculations in parallel [6] [19]. However, during measurement, the qubit always falls into either 0 or 1 [22].

Entanglement is a quantum correlation, the ability of qubits to connect and interact with one another even though they might be separated in space [9] [22]. If the qubits become entangled, their states cannot be independently described, and a qubit's measurement value can be ascertained based on the other qubit [19] [23]. This unique communication means that multiple qubits can outperform the same number of classical bits, giving an advantage over classical computers [4]. Lackey et al. [4] explain that only one qubit is needed to double the computing power of a quantum computer; however, in the case of a classical computer, twice as many transistors are needed.

Interference is a feature that can reduce errors in computations [4]. Egger et al. [19, p. 2] state that interference "allows us to bias the measurement of a qubit toward the desired state, thus, controlling the probability a system of qubits collapses into particular measurement states." By increasing the likelihood that the "good" result will be seen during measurement rather than the "poor," interference can be used to find the optimal response [23]. The quantum algorithm would simply discard any computational processes producing an incorrect result [17].

Multiple companies currently develop their quantum hardware, such as Alibaba, Amazon, IBM, Google, and Microsoft [6]. Current hardware is mainly based on either superconducting qubits (IBM, Google, D-Wave, Rigetti) or trapped ion qubits (IonQ, Quantinuum, AQT) [6] [8]. However, there are also other potential technologies, for instance, qubits based on photonic systems or neutral atoms [8].

There are also different quantum models that the current quantum computers use: universal and non-universal [24]. The main universal models used today include gate-based and adiabatic models [8].

The gate-based model is also called "the quantum circuit model" [8, p.6]. On gate-based quantum computers, the quantum circuit (quantum algorithm) consists of sequences of quantum gates [6]. The quantum gates are similar to a regular computer's logic gates but are also reversible and control the states of a qubit [9] [25]. They hold all calculation-related information and allow to find the input based on the output of a gate function or a computation, leaving an option for a redo or explaining the result-getting process [9] [22]. The gate-based quantum computer offers a bigger variety of potential use cases but is also more challenging to build [8]. At the point of writing, the largest gate-based quantum computer in terms of qubits is IBM's Osprey, with 433 qubits [26]. IBM's quantum roadmap indicates the company's plans to release an 1121 qubit quantum computer Condor in 2023 [26].

The adiabatic model "puts the system into the physical conditions such that the state, which is desired as the output of the calculation, has the lowest energy among all possible states of the system" [24, p.10]. Some of the existing quantum computers "implement a specific adiabatic quantum computing algorithm for combinatorial optimization, called quantum annealing" [8, p.7].

An example of the non-universal model is quantum simulators which are built for simulating gate-based quantum machines on classical computers [8]. As stated by [8], the simulation is typically a computation-intense process, as it requires a large amount of memory. Thus it is an exponentially hard problem for classical computers [24]. However, quantum simulators are still used for the "development of algorithms, verification, and benchmarking" [8, p.7].

Over 40 years have passed since the birth of quantum computing; however, the technology is still being developed, showing that building a useful quantum computer is complex. According to Chow et al., [13, p. 19], the solution has to work "at scale and with high quality and speed" to benefit from it in real life.

Quantum hardware is one area that impedes achieving it [6]. For instance, Biondi et al. [6] mention the scalability problems of quantum computers. The current era of quantum computers is called NISQ, "noisy intermediate-scale quantum," which hints at the high error rates in current quantum computers [8, p.5] [15]. Noise can be caused by different factors, such as temperature changes or vibration [15]. For instance, for the majority of quantum computers available, the qubits require very low temperatures for stability [15]. Noise can create decoherence, external factors causing random changes in quantum states, which can result in incorrect computation results [15]. Reaching an entirely error-corrected, fault-tolerant quantum computer, which is required to deliver mathematically precise outputs, is one of the most awaited achievements in quantum computing development [6]. However, some use cases might not require a fault-tolerant quantum computer if a solution for controlling hardware errors is found [6].

Biondi et al. [6] also emphasize the difficulty of starting with quantum hardware, as it demands different kinds of resources: money, experience, and knowledge. The high entering barrier might support the use of cloud-based quantum computing, quantum hardware companies offering access to their hardware through cloud services, and as a result, it may be the main possibility for users to explore the technology during this decade [6].

Due to quantum computing being an emerging technology, a lack of talent is also apparent [13]. A minimal workforce is available who would have the necessary knowledge and skills to develop quantum technologies [13]. Rietsche et al. [15] explain that at least three different roles of people are needed: people with knowledge of mathematics and quantum physics, domain experts who would know how quantum computing could be applied in the specific domain and people who would mediate the communication between quantum computing and the domain.

Chow et al. [13, p. 4] explain that while there is a vast ongoing development, none of the quantum computers "has reached the required state, speed and quality of computation to demonstrate an advantage over classical computers in a practical, real-life application." The authors state that since the technology is still being developed, there are various guesses when the technology is ready to be used widely [13]. In a report conducted by IBM Institute for Business Value [20], it is predicted that this wide usage is not achieved at once. Instead, it will happen in waves, use case by use case.

Despite the impediments and uncertainty, multiple researchers, such as [6], [8], [13],

[27], find that quantum computing can have a positive effect on multiple industries and the decision-makers at financial institutions need to act now [13].

2.2 The Financial Sector

The financial sector consists of institutions that provide financial services to private and business customers [28]. Egger et al. [19] split the financial sector into three: banking, insurance, and financial markets, offering products and services such as insurance, loans, and asset management [28]. There are also other areas in the financial industry, as stated in [29], but in the context of quantum computing, these three are the most relevant. In this thesis, the same categorization of the financial industry is used.

The first part of the financial industry, banking, consists of licensed institutions which deal with deposits and provide loans to consumers [30]. Examples of banking services are currency exchange and management of wealth [30]. There are also different types of banks, such as retail, commercial, investment, or central banks [30].

The insurance sector includes companies offering risk management services [31]. Both the customer and the insurance company have to manage risk [32]. While the customer is securing himself from the potential loss caused by a risk realizing, the insurance company has to find a balance between a profit and covering customers' claims [32]. Examples of insurance services are life insurance, automobile insurance, and health insurance [31] [33].

Financial markets or capital markets are "venues where funds are exchanged between buyers and sellers in the form of equity securities, bonds, or other financial assets" [34, Fig. 1]. Examples of financial markets are the stock market and the bond market [34].

The financial industry is an active but also very regulated area of science [16]. Butler [35, p.29] states that due to the regulations, the financial industry is challenged by "data governance, regulatory compliance, and risk management" topics.

Technology is an essential part of the financial sector, bringing the services closer to people, enabling complex calculations, and helping to protect customer data. For instance, examples of technology in finance are online banking and automated teller machines (ATMs). Financial sector leaders have understood that using technology smartly can give a competitive advantage. Egger et al. [19] explain that new technological solutions constantly disrupt the financial industry and introduce new players. The authors bring examples of new competitors in the financial industry in the form of FinTechs (financial technology), InsurTechs (insurance-related technology), and RegTechs (regulatory technology) [19].

The World Economic Forum [36] reports that the financial industry is more confident than before in pursuing emerging technologies. Emerging technology-related investments have helped financial companies fight new competitors and uncertainty and keep down the cost of services in recent years [36]. The list of emerging technologies in the financial industry is long, consisting of artificial intelligence (AI), cloud computing, 5G, Internet of Things (IoT), to name a few [36]. Quantum computing belongs to the list, too [36].

2.3 Related Work

Due to the great potential of quantum computing, the technology and its use cases in different fields have interested researchers, company leaders, and technology journalists. The existing related work can be clustered into the following themes: research papers, whitepapers, and reports. The current section gives a high-level overview of the related work, while a more in-depth description of the use cases is provided in Section 4.1.1.

A paper written in cooperation with JPMorgan Chase&Co by Herman et al. [8] is one of the most comprehensive articles available. The paper contains a well-detailed technical overview of the currently known algorithms and proposes use cases on how the algorithms could be used in finance. The use cases are split into three high-level categories: stochastic modeling, optimization, and machine learning [8]. In another study, [37], four different areas of quantum computing in finance are introduced: quantum optimization, quantum annealers, deep learning, and quantum amplitude estimation. The paper also includes a good overview of the problems in finance and quantum computing basics (quantum physics, hardware, and challenges) [37]. Each of the mentioned areas consists of use cases, and some of them are mentioned across multiple papers, for example, using quantum computing for optimizing portfolios ([8], [19], [37]), performing credit scoring ([8], [19], [37], [38]) and decreasing the time spent on Monte Carlo simulations ([37], [39]). A further look into the use cases is taken in a literature review, and a more detailed overview of the use cases is given in Section 4.1.1.

A paper written in 2020 by specialists at IBM Quantum [19] provides an overview of IBM's quantum algorithms. The paper summarizes quantum computing, challenges in the financial industry, and potential use cases of quantum computing with suitable algorithms [19]. The article is again informative, however, with a specific focus on IBM's achievements. This thesis takes a more high-level look at the use cases and takes into account also use cases suggested by other vendors. There are more articles, such as [40], that focus on specific algorithms of quantum computing that could be used to solve use cases in the financial industry. The authors of [40] state that current research is promising; however, further quantum computing advancements are needed to implement the use cases.

While the mentioned studies are an important base for this thesis, they do not include the business aspect: the use cases in existing research are described from the technological perspective. This thesis focuses on the business perspective by considering not only the use cases but also their value and impact on the financial services and products and the current challenges.

As quantum computing has a prospect of solving financial problems more efficiently and enabling new ways of earning money, technology and consultancy companies are also interested in discovering the use cases of quantum computing to offer quantum computing-related services to financial sector companies. A couple of companies experimenting with quantum computers, such as Microsoft [4], and EMEA [41], have conducted whitepapers featuring high-level information on how to prepare the financial institution to start exploring quantum computing with the potential use cases. Instructions mainly contain three steps: appointing people to work on quantum computing, exploring the most beneficial use cases for the company, and partnering with a quantum computing service provider [4]. Mentioned whitepapers provide a high-level overview of quantum computing applications in finance, promote the services offered, do not focus on the details of the use cases, nor are based on interviews.

Reports conducted by companies such as IBM [5], McKinsey & Company [6], and Ernst & Young [42] are also looking into the potential use cases. [6] gives an overview of the whole quantum computing ecosystem and its current status and explores the use cases in different areas. For instance, the report mentions use cases in pharmaceuticals, chemicals, automotive, and financial industries [6]. The report is based on 47 interviews with experts on quantum computing [6]. The authors also state that their work should be taken as an indication, not a comprehensive list of use cases [6]. On the other hand, IBM's report [5] discusses only the financial industry use cases of quantum computing. The report lists possibly impacted areas, provides an overview of possible benefits of quantum computing, and gives instructions on how to get started [5]. The report conducted by the specialists at Ernst & Young [42] focuses on preparing a company for the quantum future, explaining the quantum readiness in the United Kingdom, the technology's outlook, and potential use cases in different sectors. The mentioned reports are insightful and provide considerable input for this thesis. However, they either lack an in-depth overview of the financial industry, as the research did not focus explicitly on the financial sector ([6] and [42]) or insights from industry specialists ([5] and [42]).

There is a broader interest in quantum computing and its potential use cases in different industries, including the financial sector. This shows that quantum computing and its use cases are an important topic. However, as stated, current work has a technical approach for the use cases or lacks the perspective of industry specialists. Therefore, it is difficult to understand the business value of the use cases and the industry specialists' point of view. This thesis aims to fill the gap by conducting interviews with industry specialists.

2.4 Use Cases in Other Industries

A survey conducted by Ernst&Young [42] concluded that new use cases of quantum computing are announced every year, as stated in Figure 2. As quantum computing is still in ongoing development and not used widely, this thesis expects that there are undiscovered or little-mentioned use cases. The thought is also shared by some other researchers, such as [43].

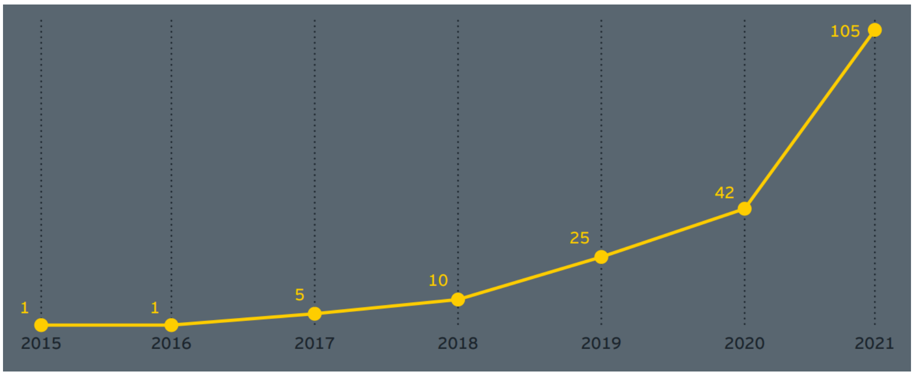

Figure 2. Timeline of Publicly Announced Quantum Computing Use Cases [42].

Biondi et al. [6] find that quantum computing use cases can impact pharmaceuticals, chemicals, automotive, and finance industries the most in the short term. Menard et al. [44] added cybersecurity to the list, also.

The process of creating new drugs is time-consuming and expensive [44]. Quantum computing could enable simulations that would help to understand how atoms interact [44]. This could improve target identification, drug design, and toxicity assessment [6]. As a result, new drugs could reach the correct patients in less time, healthcare could be more personalized, and the treatments more efficient [6] [13].

In the chemicals industry, quantum computing could improve research and development, the production of chemicals, and the optimization of the supply chain [6]. For instance, the quantum simulation could help to enhance catalyst (parts of chemical processes that speed up chemical reactions) designs, which could predict the properties of molecules more accurately [6] [45]. Advancements in catalysts could help to reduce the cost and speed of manufacturing green hydrogen [13].

The automotive industry could enhance autonomous vehicles by speeding up the training of artificial intelligence algorithms thanks to quantum computing [44]. Quantum computing has the potential to help in areas of connected driving, materials research, and route optimization [46]. Some car manufacturers, like Volkswagen and BMW, are already experimenting with use cases such as optimizing production costs [47].

In the area of cybersecurity, quantum could break the classical encryption systems by breaking the RSA public-key standard, "an asymmetric cryptography algorithm," which is widely used by modern encryption [26, para.21] [44]. Quantum computers are expected to reduce the standard's complexity from an exponential to a polynomial [48]. The problem might not be that critical at the moment, as breaking the current encryption with a quantum computer would require much computational power, which is not achieved yet [44]. At the same time, Savoie [49] emphasizes a "harvest now, decrypt later" type of threat. The term stands for the activity of attackers collecting encrypted data now to decrypt it in the future once there are powerful enough tools [49].

3 Methodology

This section provides an overview of the methodology: literature review, interview preparation, data collection, and data analysis process with justifications. The thesis aims to find answers to the research questions stated in Section 1 through a literature review and industry specialists. Industry specialists can help to explain and understand the potential use cases more in-depth from the business perspective. Such information can be collected using qualitative methods, for example, through interviews. Interviews allow for gathering detailed information from the participants, such as their opinions and feelings [50]. For that reason, it was believed that interviews would help to find the answers to the stated research questions.

Interviews were conducted based on the Empirical Standard guidelines for qualitative surveys [51]. The guidelines state that a qualitative survey considers the following criteria: an interview has one interviewee, consists of open-ended questions, is recorded, and qualitative data analysis is applied to the answers [51].

The methodology included a literature review, interview preparation, collecting data through interviews, and analyzing the collected data using thematic analysis. The process was iterative - while analyzing the results of one interview, other interviews were prepared. A high-level description of the methodology used can be seen in Table 1.

Number	1	2	3	4
Input	Research questions	Research questions	Interview guide	Interview transcripts
Step	Literature review	Interview preparation	Data collection	Data analysis
Sub-steps	-	1.Interview guide creation 2.Interviewee selection	Conducting interviews	Performing thematic analysis
Section	3.2	3.3	3.4	3.5
Output	Overview of use cases	Interview guide	Interview transcripts	Themes of findings

Table 1. Methodology.

Two artificial intelligence based tools were used to help conduct the thesis. First, ChatGPT [52] was used as one interviewee. However, no generated text is used in the thesis without a reference. ChatGPT was also used for explaining terms for the researcher to understand more complicated industry-specific terms. Second, Grammarly [53] was used to help fix punctuation and grammar mistakes in the text.

3.1 Research Questions

To understand the potential impact of quantum computing on the financial industry, the thesis aims to find answers to the following research questions:

- **RQ1. What are the potential use cases of quantum computing in the financial industry?** The first research question focuses on exploring the probable use cases of technology in the financial sector. The existing literature mentions multiple different use cases. However, as the technology is constantly improving, new use cases may appear that have not been covered by the currently available papers.

- **RQ2. How can the potential use cases of quantum computing impact financial products and services?** The second question aims to understand the impact quantum computing could have on the products and services of the financial industry. It is important to understand what changes the use cases could bring to the current and future financial services and products.
- **RQ3. What kind of value can quantum computing have on financial products and services?** The objective of the third question is to understand the value, both positive and negative, the technology could bring to the financial sector. The answers will help understand what the industry leaders must be ready for.
- **RQ4. Which obstacles impede implementing quantum computing use cases in the financial industry?** The fourth question takes an alternative approach, focusing on the impediments that decelerate implementing the use cases in the industry. The answers will give insight into which kinds of problems need to be solved before quantum computing use cases can be widely used in the financial industry.

3.2 Literature Review

It is important to take a look at the existing literature to understand what use cases have been suggested by researchers and by other quantum-interested people. During the initial phases of conducting this thesis, the currently available literature was explored to understand the larger context of the topic. It was noted that there is a considerable amount of literature available on the use cases of quantum computing in the financial industry. Thus, it was decided to perform a literature review. The literature review allowed the researcher to acquaint with the existing work on the use cases and to find gaps in the currently available materials.

Multiple databases were used, such as IEEE database [54] and arXiv database [55], to find relevant literature. For the database searches, a search string was used: **"Quantum AND (comput*) AND (finan*) AND (use case OR application*)"**. The search string's structure was created to support finding relevant articles for the current thesis. The search returned 104 articles in IEEE and 110 in arXiv. From those, relevant articles were picked through manual validation (considering titles and abstracts). Later, duplicates of articles were removed.

During the research process, it appeared that consultancy companies, such as Deloitte [56], McKinsey & Company [6], and Ernst & Young [42], have published materials on quantum computing applications in finance. However, as these do not qualify as research papers and are not included in the research databases, Google search was used to find such work. Similar keywords were used for Google search as for the database search.

While the majority of the literature was found from databases and Google search, the snowballing method was also used, finding new sources from the references of a paper [57]. To speed up the process of snowballing, ConnectedPapers helped to gain an overview of the papers [58]. ConnectedPapers is a tool that visualizes the paper's connections to other papers [58]. If ConnectedPapers revealed any new papers on the topic, the papers were added to the literature review.

Some interview participants also suggested literature that had been interesting to them. While many of the recommendations had already been covered during the initial literature review process, some new articles were found. Such articles were then worked through and, if suitable, added to the literature review.

As a result, 23 related works in total were selected for the thesis to conduct the literature review. The literature review gave a considerable contribution to finding answers for RQ1.

3.3 Interview Preparation

The interview preparation step consisted of two sub-tasks: first, preparing the interview guide and then finding potential interviewees.

3.3.1 Interview Guide

A semi-structured interview type was selected, as it is supported by the guidelines of Empirical Standards [51]. When conducting semi-structured interviews, the questions are prepared before the interview and are used to form an interview guide [59]. The guide aims to structure the interview so that the conversation is oriented towards getting the answers to the research questions [59].

The interview guide was developed based on the set of research questions, as the guide must support the researcher in getting answers to the research questions. The wording of questions was refined during the interviews. The interview guide was split into five sections: introductory, RQ1-related, RQ2-related, RQ3-related, RQ4-related, optional, and concluding questions (see Appendix I). Introductory questions warmed up the conversation and helped to understand the interviewee's professional background and relation with quantum computing. Sections dedicated to the stated research questions followed the introductory part. These sections aimed to go into more detail by focusing on different aspects of each research question. For instance, there was a separate block of questions for each research question. The helper questions aimed to go more in-depth into the topic, such as a specific use case or a potential value quantum computing could have on the financial sector. Optional questions were asked if the interviewee did not mention use cases that other researchers in existing literature have mentioned or if the interviewee did not mention his practical experience with quantum computing. Concluding questions were asked at the end of the interview to let the interviewee mention any other relevant ideas not covered by previous questions.

3.3.2 Finding Interview Participants

Finding the interview participants started with a pre-selection process. Different approaches were used to find suitable interview candidates, such as browsing the websites of quantum computing focused companies, universities, and financial institutions, looking up speakers from quantum computing conferences and events, and using LinkedIn search.

Quantum computing focused companies' and financial institutions' websites were found through Google search. The search started with companies that had had previous collaborations with financial institutions (or quantum computing companies in the case of financial institutions). Previous experience was preferred, as it was a potential cue that employees of that company would have the needed knowledge/experience to participate in the interview.

Of the universities, the ones with a quantum computing department or with a research area dedicated to quantum computing were chosen for contact. Interestingly, the majority of the contacted people with an academic background stated that the research in universities is rather technical/theoretical and not that much business use case focused, which resulted in a small representation of the academia in the interviews.

Another way to find potential participants was to contact the speakers at quantum computing conferences and events. For such cases, it was determined that the presentation was either on a similar topic as this thesis or that the speaker's background or presentation indicated experience in the topic.

In LinkedIn, combinations of keywords such as "quantum computing," "finance," "quantum algorithms," "banking," and "insurance" were sought to ensure the suitable background of the interviewee. For this thesis, the LinkedIn search was the most successful way of finding interview candidates, as most of the interviewees were found using the LinkedIn search.

All candidates with a suitable background were contacted through LinkedIn or email to establish a connection and invite them to the interview.

To pick interviewees with a suitable background, the following criteria were considered during the selection process:

- **Experience.** Practical experience in quantum computing was preferred. The candidate was considered an experienced specialist if they had a combined background in quantum computing and the financial industry.
- **Expertise.** Knowledge about quantum computing and the financial industry was an important factor when picking the participants. For instance, education in the field of quantum computing or quantum physics and/or published literature on the topic was considered evidence of expertise.
- **Diversity.** To ensure a board sample, the diversity of the potential participants was taken into consideration. For example, only one person per company was invited to the interview, and specialists from different domains were preferred (for instance,

quantum hardware, quantum machine learning, banking, trading, and insurance).

3.4 Data Collection

The data collection subsection provides an overview of the participating interviewees and the process of conducting interviews.

3.4.1 Interviewees

In total, nine interviews were conducted. Despite the small sample, the diverse backgrounds of interviewees allowed for exploring the impact of quantum computing on the financial industry from multiple perspectives. For example, three participants (I-03, I-07, I-08) had a background both in finance and quantum computing. There were also two participants (I-01, I-06) with a previous experience in physics. Four out of nine participants were quantum machine learning focused (I-02, I-05, I-06, I-08), while three other interviewees (I-01, I-03, I-04) had a wider focus on the quantum algorithms. There were also quantum computing specialists (I-01, I-02, I-04, I-05, I-06) with no former experience in finance but who, as a part of their work, have learned the concepts of the financial industry. No names or other identifying information (company, for example) is used in the thesis to protect the confidentiality of the participants.

Table 2 describes the profiles of the interview participants.

Code	**Continent**	**Background**	**Role**	**Years of Experience**
I-01	Europe	Physics/Quantum Algorithms for Finance	Algorithm Developer	2
I-02	Europe	Data Science/Quantum Machine Learning	Researcher	15
I-03	Europe	Trading/Quantum Algorithms for Finance	Researcher	13
I-04	North America	Quantum Algorithms for Finance	Entrepreneur	6
I-05	Europe	Quantum Machine Learning	Technical Lead	7
I-06	North America	Physics/Quantum Machine Learning	Researcher	2
I-07	Europe	Banking/Academia	Professor	20/5
I-08	Europe	Banking/Quantum Machine Learning	Algorithm Developer	3
ChatGPT	-	Generative AI	ChatGPT	-

Table 2. Demographics of Interviewees.

In addition to human interview participants, the last interview was conducted with ChatGPT-3 to understand what an emerging technology thinks about another such technology. ChatGPT is an artificial intelligence based conversational application which is based on the GPT (Generative Pre-trained Transformer) architecture to generate human-like answers to questions asked by users [52]. ChatGPT-3.5 is the third iteration of the model [52]. The interview started with the researcher inserting a prompt in the https://chat.openai.com/ [52] webpage. The first prompt was as follows: "Hi, can I conduct an interview with you on quantum computing in the financial industry? Also, do you agree with me using the collected information in my Master Thesis?". Next, ChatGPT was asked to imagine being a researcher working in the R&D department of a financial institution by using the prompt, "Imagine you are a financial industry professional working in the research and development department of a financial institution." The interview followed the same set of questions (interview guide), and elaborating questions were asked if there was an interest from the researcher to hear more about the potential use case of quantum computing in the financial industry. The interview conducted with ChatGPT followed the same kind of data analysis process: the interview from the ChatGPT chat was saved into a text file as an interview transcript.

3.4.2 Conducting Interviews

The semi-structured interview approach was selected for the second step of methodology, data collection. A semi-structured interview has a set of prepared questions (interview guide) and a focus; however, it is not as strict as a structured interview, allowing the modification of the interview course based on the interviewee's answers [59]. Every interview had one interviewee, and the interviews were held online via Zoom, as the participants joined from various locations. Also, using Zoom allowed for the convenient recording of the interviews. The interview recordings were saved to the interviewer's local computer.

Interviews were voluntary, with no direct benefit for the participants. Also, every person with a set interview time was asked to sign a consent form before the meeting so the interview could be recorded, transcribed, and later analyzed.

The interviews started with the introduction of the researcher, the aim of the study, and the planned structure for the interview. If the participant had not signed the consent form before the meeting, verbal consent was asked during the call. After the introductory part, the interview was started, and the interview followed the set of prepared questions (interview guide). Each interview considered both the background of the participant and their answers - if the interviewee had a background or knowledge in some specific quantum computing use case, the interview guide was modified on the go to understand the topic more in-depth. Interviews were conducted during the period of February-April 2023. A detailed schedule of interviews can be found in Appendix II. The shortest interview lasted 21 minutes, and the longest interview was 52 minutes. An average interview lasted around 38 minutes.

The semi-structured interview method also has some disadvantages that need to be considered. For example, the expected interview length was set to 45 minutes. However, for some interviews, the time was too short (mainly due to a knowledgeable interviewee). Therefore some use cases were discussed only vaguely to respect the time of the participant. Also, it was mentioned by a couple of interviewees that some information related to their employer is confidential, and only a high-level overview can be shared.

3.5 Data Analysis

During the third step of methodology, data analysis, the information gathered with interviews was analyzed using thematic analysis [60].

3.5.1 Thematic Analysis

Thematic analysis is a qualitative data analysis method that allows recognition and analysis of themes in the collected data [60]. The theme is an important part of the data that answers the research question [60].

Braun and Clarke [60] divide the thematic analysis process into six steps: exploring data, generating initial codes, searching for themes, reviewing themes, naming themes, and generating the final report. In the following paragraphs, an overview of each step is given. The process of performing thematic analysis was iterative - the thematic analysis process started right after each interview.

1. **Exploring data.** The first step of thematic analysis, exploring data, included transcribing the audio recording, reading through the data, and cleaning it. Transcribing the audio data is necessary for performing thematic analysis, as thematic analysis works with textual data [60]. To save time on transcribing, automatic transcription software was preferred instead of a manual transcription process. The audio recording of the meeting was uploaded to the Otter.ai platform, where it was automatically transcribed [61]. Each interview's transcript was read through to acquaint with the data and to correct any transcription mistakes. In the case of transcription mistakes, the fixes were done manually on the Otter.ai platform, as the platform allowed the researcher to easily compare the audio file to the transcript and edit the file accordingly. This step also enabled the researcher to get to know the collected data, as all recordings were worked through during the manual touch-up process.

2. **Generating initial codes.** The next steps of thematic analysis were performed using MAXQDA software [62]. MAXQDA can be used for qualitative and mixed methods data analysis [62]. The software enables a convenient solution for coding text and data visualizations [62]. Both of these functionalities were considered important, as MAXQDA allowed to do the coding in a structured approach. At the same time, data visualization helped to keep track of the codes and present the findings in a clear and easily understandable way.

   To generate the initial codes, the corrected transcripts were exported from the Otter.ai platform to MAXQDA as text files. An inductive approach of thematic analysis was used, meaning that the initial set of codes emerged from the data [60]. The first round of coding included going through each interview once and adding the codes. A suggestion by Braun and Clarke was followed, which suggested rather have too many codes than too few codes [60]. This way, every potentially interesting theme would be coded [60]. After the first round, there were 490 coded segments, with 363 different codes. This process was repeated at least two times for each interview or until there were no new codes. The list of codes was then organized and cleaned. If multiple codes represented the same ideas, the codes were merged. If some code appeared as a subcode of another code, such categorization was created in MAXQDA.

Table 3 presents the five most occurred codes from the final list. The full list of codes can be found in [63].

#	Code	Mentioned X Times	Mentioned by X Interviewees
T6.2	Issues with Hardware	44	I-01, I-02, I-03, I-04, I-05, I-06, I-07, I-08, ChatGPT
T1.1	Interest from Institutions	19	I-01, I-02, I-04, I-05, I-06, I-07
T6.3	Barriers to Technology	18	I-02, I-06, ChatGPT
T2.1	Use Cases	17	I-01, I-02, I-03, I-04, I-05, I-06, I-07, I-08, ChatGPT
T3.1	Derivative Pricing	16	I-01, I-03, I-04, I-05, ChatGPT

Table 3. List of Generated Codes.

3. **Searching for themes.** After performing the two previous steps on every interview transcript, there was a final list of codes from which the researcher could start searching for themes. To have a visual overview of all the coded segments, a Miro [64] board was created. Miro is an online tool that enables the user to create interactive boards. Miro was preferred, as it gave a better overview for the researcher about the coded segments than MAXQDA. Also, the notes were easy to move around in Miro. This was an important functionality, as, during this step, similar codes/segments with similar codes were grouped together to see whether the similar segments could be assigned into one logical theme. To keep a distinction between different interviewees, each interviewee had its own color in Miro. A screenshot of the Miro board can be seen in Figure 3.

4. **Reviewing themes.** As the fourth step in the thematic analysis process, the possible themes were reviewed. The researcher assessed the list of codes repeatedly to see if any codes would need merging or removing. This was also necessary to understand whether the codes under the same theme are similar. The researcher also kept in mind the research questions for which answers were looked to ensure the themes would support getting answers to the questions. Not all codes fit into the themes. For instance, codes about the interviewees' reason for interest in

Figure 3. Miro Board.

quantum computing and use cases in other industries were removed as they did not relate to the research questions and thus did not help find the answers. Also, at first, it seemed that each use case would form a separate theme, such as "Quantum Data," it turned out that some such themes had too few supporting codes.

5. **Naming themes.** The fifth step is named 'defining and naming themes' in [60]. After the themes were reviewed and finalized, each theme was given a name that would capture the essence of the theme. Additionally, a description of each theme was written to provide an overview of each theme for the reader.

6. **Generating the final report.** In total, eight themes were created. Table 4 gives an overview of the generated themes. For example, the first theme (T1) captures the current state of quantum computing, both technically and in the financial industry. The second theme, however, consists of data from the interviews related to quantum as an opportunity. The theme also contains a sub-theme: T2.1 Quantum Advantage. T2.1 holds information on quantum advantage and its multiple possible forms.

The full list of themes with descriptions, relations between themes, sub-themes, and codes can be accessed in Google Sheets [63].

#	**Theme**	**Sub-theme**
T1	Current State of Quantum Computing	-
T2	Quantum as an Opportunity	T2.2 Quantum Advantage
T3	Simulation	-
T4	Optimization	-
T5	Quantum Machine Learning	-
T6	Limitations of Quantum	T6.1 Threats
T7	Change Enablers	-
T8	Time Frame of Quantum in Finance	-

Table 4. Overview of the Generated Themes.

4 Results

The following section gives an overview of the results and how they relate to the research questions. Direct quotes from the interviews are used to illustrate the results better. To protect the confidentiality of the interviewees, all identifiers were removed from the text.

The section will be divided into four to create a relation between the results and the research questions. The first part will focus on use cases of quantum computing in the financial industry (RQ1). Next, the results related to the impact of quantum computing use cases on financial products and services are introduced (RQ2). The second section is followed by results on the value the technology could have on financial products and services (RQ3). Finally, the section includes the findings on current challenges regarding implementing the use cases (RQ4).

4.1 Use Cases

Results for RQ1, use cases of quantum computing in the financial industry, are covered in the two following subsections: results from the literature review and results from the interviews.

4.1.1 Results from Literature Review

Data is an integral part of the financial sector - it is the base for millions of decisions made in the sector every day [4], decisions that also consider probabilities and assumptions [13]. Therefore, it is predicted that quantum computing will help the financial industry to increase the effectiveness and speed of making these decisions [4]. Being able to make more precise calculations and quicker decisions can be highly beneficial [20].

The existing literature mentions multiple potential use cases of quantum computing in the financial industry. The mentioned use cases can be divided into three different financial problem areas: optimization, simulation, and quantum machine learning [38]. The following sections introduce the three areas more in-depth. An overview of all the use cases mentioned in the following sections is given in Table 5. The use case was selected for introduction if at least two different analyzed sources mentioned such a use case. The following is not a comprehensive list of all the use cases of quantum computing in the financial industry but rather a look into the different areas of the potential use cases.

The first use case in the area of simulation is risk management. Risk management is one of the financial sector's primary and most complex activities [6]. This complexity arises from the different factors that affect risk [6]. Calculating risk takes much computational power [6]. Financial institutions could make faster decisions and save money by using quantum computing to do these calculations more quickly and accurately [6]. A report published by McKinsey [6] states that more precise risk calculations would enable financial institutions to decrease the buffers of capital kept for unforeseen risk management and instead use the money for investments.

Monte Carlo simulations are used to model complex systems in risk management [37]. Bova et al. [48] say that risk assessment with Monte Carlo simulations can easily grow complex, as various elements must be considered. Therefore, Monte Carlo simulations quickly become slow on a classical computer [48]. As a result, multiple banking institutions have limited the use of Monte Carlo simulations only to Value at Risk calculations [48]. Value at Risk is used to "estimate the amount of value a portfolio could lose over a particular time horizon excluding some fixed fraction of outlier events" [65, p.6]. This is where quantum computing could help by decreasing the time spent on the simulations [6].

Previous works have shown that if a "full-scale fault-tolerant" quantum computer is reached, the Monte Carlo method speedup is certain [65, p.4]. However, it might take time to reach that point, as a Monte Carlo speedup would need a lot of high-quality qubits plus big enough quantum clock speed [65]. Clock speed shows the number of cycles executed by the CPU per second [66]. Biondi et al. [6] see that optimization of the simulations could change the time spent from days to hours.

Another area of simulation is using Monte Carlo simulations for derivatives pricing [48]. A derivative is a financial agreement whose value is decided on another source, such as "an underlying asset, groups of assets or benchmark" [8] [67, Fig. 1]. Examples of derivatives are futures, options, and swaps [67]. The larger the number of underlying assets and factors, the more complex it is to find the optimal price for the derivatives, as there might be a correlation between factors that must be considered [48]. Derivative pricing is a suitable problem to be solved with the Monte Carlo method due to the "stochastic nature of the variables involved" [43, p.2].

Mugel et al. [43] state that currently, the computations done for option pricing take more than 24 hours in many cases. Bouland et al. [65] see that accomplishing Monte Carlo speedup with a quantum computer could result either in more precise or stable pricing or allow financial institutions to do the calculations in real-time.

According to [43], there are multiple optimization problems in finance with a considerable monetary value if solved. Examples of optimization problems in finance are portfolio optimization and liquidity management but also predicting financial crashes [43]. The complexity arises from the correlation between financial assets as well as between different financial institutions [43].

Portfolio optimization is one of the most apparent optimization problems in finance [8]. The goal of portfolio optimization is to conduct an optimal portfolio, a set of assets, which would fulfill the risk or return objective set by the investor [8]. The common objective is to maximize the returns based on the risk level set [8]. Examples of portfolio optimization include optimization of trading, optimization of index tracking, and optimization of collateral [6]. Biondi et al. [6] describe that a portfolio can consist of multiple different assets, leading to many possible portfolio combinations. The process requires high computing power due to the large amount of data processed [9]. Quantum computing could find more optimal portfolio combinations in a shorter time compared to currently used solutions [6].

Backes et al. [9] state that relatively accurate algorithms and models are currently used for portfolio analyses on classical computers. However, they argue that the financial sector needs new technologies for more precise predictions [9]. For example, it could be beneficial if portfolio optimization could consider the "real-life constraints, such as market volatility and customer life event changes" [5, p.3].

Biondi et al. [6] see that better optimized collateral-focused loan portfolios could mean that financial institutions could start making better offerings, decreasing interest rates, and freeing up capital.

Quantum computing could also help in detecting arbitrage opportunities [5]. Arbitrage is "making profit from differing prices in the same asset in different markets" [37, p.6]. As an example, the authors explain a process of changing one currency for a second currency, then changing the second currency for a third one and the third currency back for the initial currency and making a profit in the process [37]. The goal of financial institutions is to be fast and efficient in finding such opportunities [8]. The classical solutions for finding the opportunity are efficient [37]. However, finding "the most profitable" arbitrage opportunity is considered an NP-hard problem [68, p.2]. Rosenberg [68] suggests quantum annealers as an approach to solving the problem.

Another use case in the area of optimization problems in finance is predicting financial crashes. The problem is considered NP-hard even for small models [69]. The goal of predicting financial crashes is to understand how a change in the price of the assets could impact the financial network [69]. For example, whether a change in the price of an asset could make the market value of an institution fall [69]. Currently, the problem is solved using empirical and statistical methods [69]. However, these methods do not provide certainty in the accuracy [69]. An inability to predict the crashes in advance can have severe outcomes [69]. Both [69] and [70] suggest using quantum annealers to solve the problem instead of the classical methods to improve the predictions.

The third area besides risk management and portfolio optimization brought out by [38] is quantum machine learning. The financial industry has multiple applications of quantum machine learning, for example, customer targeting and credit scoring [20].

At the moment, credit scoring is done using complex machine learning models [43]. However, training such models can take millions of dollars [43]. Quantum machine learning promises to shorten the time spent training the models by applying quantum algorithms [6]. For instance, credit scoring can be used to predict whether the customer is going to repay the loan or not [48]. Doing precise credit scoring is important, as defaulting customers can bring a considerable financial loss for the bank [48]. At the same time, the bank will lose its profit if a loan is declined for a customer who would repay the loan [48]. The use case of credit scoring can be considered a classification problem [71]. The goal of credit scoring is to understand whether the customer is going to repay the loaned money or not [71]. The authors of [6, p.32] state that "An improvement of 1 to 2 percent in the global default rate corresponds to a savings of $17 billion to $33 billion."

Financial institutions could improve the fraud detection processes by using quantum computing [71]. In the context of fraud, the datasets are usually imbalanced, meaning that the fraud cases usually belong to the minority class [71]. The current processes for fraud detection are inaccurate with a high false positive rate [20]. Quantum computers could help to "improve pattern recognition in structured and unstructured data sets, improving the quality and speed of fraud detection" [13, p.22]. For example, fraud could be detected by using clustering, which can be used to determine if a certain point of data is abnormal [71]. As stated by [20], using quantum computers for fraud detection might not be far away, as the algorithms for improving fraud detection are compatible with near-term quantum machines. Mosteanu and Faccia [16] believe that with quantum Monte Carlo simulations, fraud detection will be the first two applications of quantum computing in the financial industry.

The customers expect personalized experience at the financial service providers [20] [5]. If institutions do not manage to provide personalized services to the customers, it can result in the loss of the customer [5]. However, building models that would consider customers' behavior and make personalized offers in real-time is computationally complex [5]. This is something quantum computing could help with by finding more subtle patterns and making more accurate predictions [5].

Some related works, such as [5], [6], and [19], mention anti-money laundering as a use case in finance for machine learning. Detecting money laundering is a part of the transactions monitoring process in the customer life cycle in finance [19]. The solutions used today are prone to false positives [19]. Quantum computing could help to detect money laundering activities more precisely [19].

Another area of the financial industry that could benefit from quantum machine learning, specifically from reinforcement learning, is algorithmic trading [71]. Algorithmic trading is an automated trading process where trading is done using an algorithm [72]. Supervised machine learning approaches are already used for the use case [71]. However, as already demonstrated, using reinforcement learning could improve the performance of algorithmic trading [71]. Pistoia et al. [71] state that before this use case could be implemented on quantum machines, the hardware challenges need to be solved.

[65] and [71] also mention risk assessment as the potential use case of quantum machine learning in the financial industry. Pistoia et al. [71] see that risk assessment could benefit from natural language processing (NLP) advancements. The authors explain that in the case of missing historical data about customers' payment behavior, natural language processing could help with the analysis process to determine a suitable payment

capacity for the customer [71]. For instance, in the case of business customers, NLP could help to "measure attitude and an entrepreneurial mindset" [71, p.8]. Or, NLP could offer new factors in risk assessment, such as analyzing "the lender's and borrower's emotions during a loan process" [71, p.8]. Chow et al. [13] believe that risk assessment can benefit from an increased number of sources for data that can be used thanks to the increased speed of processing, for instance, considering a person's social media behavior during the assessment.

Pistoia et al. [71] also suggest quantum generative AI to have an application in finance. [41, p.10] explains that the more widely used machine learning becomes, the more there is a need for "anonymous training data." Quantum generative AI could help in producing the data needed by generating new realistic data for testing more efficiently [71] [41]. This could find an application in fraud detection or help to prepare a probability distribution [71]. Additionally, [41, p.10] expects to see a "forward-looking risk management," as quantum generative AI would allow generating synthetic but realistic future data, which would help financial institutions to prepare for potential future risks better.

As stated by [6], trust and safety are the foundation of the financial sector. As with other industries, breaking currently used encryption with quantum computers is also a threat to the financial industry [6]. To continue offering secure services to customers, financial institutions have to opt for quantum-safe encryption options [6].

#	Problem Area	Use Case	Studies	Occurrences
1	**Simulation**	Risk management	[5] [6] [7] [8] [9] [13] [19] [20] [37] [38] [40] [48] [65]	13
		Derivatives Pricing	[5] [6] [8] [13] [37] [40] [48] [65] [73] [74] [75] [76]	12
2	**Optimization**	Portfolio Optimization	[6] [7] [8] [19] [20] [43] [48] [65] [77]	9
		Arbitrage	[5] [8] [37] [48] [68]	5
		Forecasting Financial Crashes	[5] [8] [43]	3
3	**Machine Learning**	Credit Scoring	[5] [6] [9] [13] [19] [20] [48] [71]	8
		Fraud Detection	[5] [6] [13] [16] [20] [65] [71]	7
		Targeting	[5] [9] [19]	3
		Anti-Money Laundering	[5] [6] [19]	3
		Algorithmic Trading	[6] [65] [71]	3
		Risk Assessment	[65] [71]	2
		Quantum generative AI	[41] [71]	2
4	**Quantum Cryptography**	Quantum Decryption	[6] [16]	2

Table 5. Use Cases Mentioned In the Literature.

Some financial institutions are already experimenting with the potential use cases of quantum computing. Table 6 presents an overview of the experimenters and the use cases. While the majority of the use cases have also been mentioned in Table 5, there are a couple of use cases that did not come up during the literature review. For example, Mastercard developing quantum-safe cards [78] or JPMorgan & Chase experimenting with quantum natural language processing to prepare summaries of financial documents for their customers [79].

#	Financial Institution	Use case(s)	Partner(s)	Source(s)
1	Ally Bank	Portfolio optimization	Microsoft Azure Quantum, Multiverse Computing	[80] [81]
2	Bank of Canada	Market simulation	Multiverse Computing	[82]
3	BBVA	Portfolio optimization, Monte Carlo speedup (derivative pricing, risk management), arbitrage, credit scoring	Multiverse Computing, Zapata Computing, Accenture, D-Wave	[83] [84] [85] [86]
4	CaixaBank	Investment portfolio hedging, portfolio optimization	D-Wave	[87]
5	Commonwealth Bank of Australia	Portfolio optimization, quantum machine learning (deep learning, fraud detection), cybersecurity	Rigetti Computing, Amazon Braket	[88]
6	Credit Agricole	Valuation of financial products, risk management	Pasqal, Multiverse Computing	[89]
7	Goldman Sachs	Monte Carlo simulations (derivative pricing)	AWS, QC Ware, IonQ, IBM	[90] [91] [92] [93]
8	HSBC	Pricing, portfolio optimization, sustainability, risk management, fraud detection	IBM	[94]
9	JPMorgan & Chase	Portfolio optimization, option pricing, risk analysis, quantum machine learning (from fraud detection to natural language processing for generating document summaries)	Q-Next, QC Ware, Quantinuum	[95] [96] [79] [97]
10	Mastercard	Optimizing customer incentive program; quantum-safe cards, fraud detection	D-Wave, JPMorgan & Chase, Citigroup Inc	[98] [78]

Table 6. An Overview of Financial Institutions Exploring Quantum Computing Use Cases.

4.1.2 Results from Interviews

The current subsection introduces the use cases mentioned by the interviewees. Table 7 gives an overview of all the use cases from the literature review as well as from the interviews. Interestingly, interviewee I-05 used the same structure for the use cases as was used in the literature review, categorizing use cases into financial problem areas. To present the results in a structured approach, the same structure is used in this subsection.

The use cases are enabled thanks to the characteristics of quantum computing. For example, the interview participants mentioned superposition (I-01, ChatGPT), entanglement (I-01, ChatGPT), interference (I-01, I-04, ChatGPT), error correction (I-01, I-04, I-06, I-08, ChatGPT), and quantum parallelism (ChatGPT).

The first class of problems is simulation. Simulation problems could be approached with quantum Monte Carlo methods, as mentioned by five interviewees (I-01, I-03, I-05, I-07, ChatGPT). For instance, one of the interviewees said, "... I think these Monte Carlo methods are really where we have to dive into and then, especially to the very complicated simulations that we do today, where you need millions or trillions of simulations, not where you do 1000 ... We need high precision with a very complicated model. That is where I think you are yearning for quantum computing." (I-01). One interviewee illustrated the importance of this use case by saying, "The problem the bankers are behind is Monte Carlo simulation. That's the hot topic." (I-07). The idea was also supported by I-01, "Monte Carlo methods are really commonly used in finance. And the slightest speedup would already have a large implication."

I-01 explained that there is a similarity between quantum computing and Monte Carlo simulation. "... A quantum computer uses these qubits, which, as long as they are in their coherent state and in their superposition state, they can represent a probability quite natively. So you can really encode a 20% probability in your quantum bit such that if you measure it 100 times, you'd expect 20% of the times zero and 80%, the one or the other way around. It doesn't really matter. And you can also entangle qubits, which makes it natively, so to speak, to connect qubits or to connect probabilities. And this is also something you have in finance, where you have a probability of one thing happening ... and that's connected to another probability. On a classical computer, it is really hard to do. But on a quantum computer, you can really bring the quantum computer into this entire probability distribution with all things linked." (I-01).

There are some experiments going on with applying quantum to the Monte Carlo method. However, "the full pipeline is just not available" (I-05). Thus, "it is people exploring. They build use cases, toy models, and toy cases. But there is this huge gap at the moment. So just toy models, which can be calculated, but the real problems, they are out of scope at the moment." (I-07). The use case could take a long time to be ready for production use. "So we have to wait. I mean, maybe 10 more years, 15 more years, before we have really fault-tolerant computers." (I-07).

One of the interviewees shared that there are no good alternatives to Monte Carlo. "Monte Carlo sampling, an algorithm for solving partial differential equations. These are very expensive. We do not have a good variational hybrid algorithm that can solve this mathematical task. And the other algorithm that we know that potentially could attack this problem, or at least to the best of our theoretical knowledge, to be able to address this problem, is just impossible to implement on computers today. They require too many qubits, and they require, again, the ability for the quantum computer to store pristine information to preserve that quantumness ..." (I-05).

Monte Carlo simulations could be used in derivative pricing and risk management, as revealed by the interviewees (derivative pricing: I-01, I-03, I-04, I-05, ChatGPT; risk management: I-01, I-07, ChatGPT). Quantum computing could help the derivative pricing process "by solving complex mathematical equations faster and more accurately than classical computers." (ChatGPT). This idea was also supported by I-04. "Derivatives pricing, you know, many large institutions spend a lot of their sources on running ... simulations of ... different strategies. I think quantum computing could come in to really reduce a lot of the resources and overheads spent on that." (I-04).

Risk management is another process in finance for which Monte Carlo could be used. "Monte Carlo is interesting for risk calculation. I mean, all banks must do risk calculations. Value at Risk, Credit Value at Risk. And these calculations take time." (I-07). Value at Risk and Credit Value at Risk are metrics often used in risk calculations [8]. "Quantum computing could help financial institutions to better manage risk by analyzing large amounts of data and identifying potential risks more quickly and accurately." (ChatGPT).

"The other class of problem is optimization. So, typically, we optimize either over continuous variables with no cost function, or that's the most typical case. In other cases, we know the cost function to some extent, but the variables are discrete, and in certain cases, instead, we don't know the cost function. We just know the cost, but we cannot access the cost function at any given point." (I-05). I-05 mentioned two use cases in optimization space: "portfolio optimization" (also mentioned by I-03, I-04, I-07, ChatGPT) and "building exchange-traded funds."

In the case of portfolio optimization, "as you increase the number of assets in a portfolio ... the problem becomes intractable, and it takes longer and longer and longer to solve it." (I-04). There are multiple approaches how to solve portfolio optimization. For instance, one of the first approaches was "quantum annealer technology from D-Wave." (I-04). However, "now, there are also methods to solve portfolio optimization problems with gate-based methods. There are hybrid algorithms like VQE, QAOA. Even quantum-inspired methods, such as Tensor Networks." (I-04). Abbreviations mentioned by I-04 stand for hybrid quantum-classical algorithms, "variational quantum eigensolver" (VQE), and "quantum approximate optimization algorithm" (QAOA) [8, p.12].

The second use case, building optimal exchange-traded funds, is another optimization problem. "Another case that is quite popular is … building exchange-traded funds. So, given an index that is made up of many sub-components, how can we build a product that can be investable that closely tracks the movement of the index? How this problem is addressed is that a financial institution is trying to find the smallest subset of … investable components of the index, creates … a weighted basket, and then offers these to investors … to minimize transaction costs and tracking error." (I-05).

The third class of problems identified by I-05 was machine learning. All participants

(I-01, I-02, I-03, I-04, I-05, I-06, I-07, I-08, and ChatGPT) identified quantum machine learning as a use case for the financial industry. Quantum machine learning could be used in areas such as "forecasting," "classification," "data generation," "separating signal from the noise," finding "hidden info in the system," or "modeling data distribution given some observation of a stochastic process" (I-05). Quantum machine learning is "still in the early stages of development" (ChatGPT), and "it is totally unclear if you will have an advantage at all" (I-07). Advancements in quantum machine learning could "improve machine learning algorithms for fraud detection, credit scoring, and other application." (ChatGPT).

Credit scoring could be an area to benefit from quantum machine learning. "Quantum computing could help financial institutions to improve credit scoring models by analyzing large amounts of data and identifying more accurate predictors of creditworthiness." (ChatGPT). Credit scoring is essentially a "classification"(I-02) problem to understand "... if somebody is going to pay or not or is going to be in default on delinquency." (I-02).

Quantum machine learning could also be used in fraud detection. The use case was mentioned by six interviewees (I-02, I-04, I-05, I-07, I-08, and ChatGPT). "Quantum computing could help financial institutions to detect fraudulent activities more quickly and accurately by analyzing large amounts of transaction data and identifying patterns and anomalies that may indicate fraud." (ChatGPT). According to I-07, fraud detection might be the most interest-provoking use case of quantum machine learning. "Some banks are exploring this quantum machine learning for fraud detection, especially." (I-07). Detecting fraud can be a challenging task, as explained by I-08: "Given the number of transactions that go on, ... per 100000, there is maybe on average one. So trying to find that one blip is a difficult challenge."

I-03 mentioned the ongoing experiments in using reinforcement learning for algorithmic trading. However, the use case is not certain. "And then you can use quantum to explore reinforcement learning and explore algorithmic trading, and then explore all the different paths that you have for deciding the venue. So deciding if the order is a market order, or if it is a limit order, which level and for how long you're going to stay, or how you will split, you have an order to execute how many levels you will split and when you send it ... it's a problem that, in principle, it looked like it fit quite well in this area because the path is exploding. So the more variables that you take into consideration, that are the problem or the variables explode, or the possibilities. But again, it is not so in principle. It looked like that will be a good case." (I-03)"

A different application of quantum machine learning could be quantum generative AI. "Another emerging area is in generative AI with quantum circuit born machines, quantum generative adversarial networks for generating synthetic data to solve certain problems." (I-04).

Other quantum machine learning applications could be predicting "churn" or "engagement" (I-02). "Churn is the same. We are predicting if someone is leaving the company somehow. I mean, the clients and the engagement is understanding how much engaged they are to offer different products. So, for example, if they are using a lot of credit cards, and they are going through a specific path, we can offer them a loan or offer X service." (I-02). Or "identifying trading signals" (I-08). "So is this an inflection point where I should buy? Or should I sell, or should I hold on to whatever underlying asset it is that I'm focused on?" (I-08).

A non-industry-specific use case could come from quantum cryptography. "Quantum computing can help financial institutions to develop more secure cryptographic protocols to protect sensitive financial data and transactions from being hacked or intercepted. For example, quantum key distribution can be used to generate unbreakable encryption keys." (ChatGPT).

From another perspective, quantum computing could be used to form hybrid quantum-classical computing processes to eliminate some of the pains in the currently performed calculations in the financial industry. The interviewees (I-01, I-02, I-03, I-04, I-05, I-06) believed that quantum computing will not replace classical computers, but it will form a hybrid quantum-classical computing process. The hybrid approach could be explained as "you offload some of the complexity of the classical computer ... So you get something out of you quantum computer, you do some calculation on that, and that gives you a decision for what you should do next on your quantum computer." (I-01). This was further explained by I-03 "You have these bottlenecks in computation, and you can use quantum for that part." For example, this quantum approach could be used in machine learning for specific tasks in the machine learning pipeline "We just implement a quantum feature selection. So we select features better ... Feature selection in machine learning is very time-consuming. And it is very slow ... So implementing quantum feature selection for machine learning could be a huge boost." (I-02). Classical computers, on the other hand, are needed for measuring the results. "A quantum computer, I think, will always work with a classical computer combined, albeit for measuring purposes." (I-01). I-04 and I-06 predicted that in the future, a "quantum computer is like a GPU or a co-processor that should use your laptop" (I-04) that could be used to tackle computationally heavy tasks.

In conclusion, the interview results show there are many different potential use cases of quantum computing in the financial industry. Table 7 presents the overview of the use cases.

#	Problem Area	Use Case	Studies	Occurrences	Interviews
1	**Simulation**	Risk management	[5] [6] [7] [8] [9] [13] [19] [20] [37] [38] [40] [48] [65]	13	I-01, I-07, ChatGPT
		Derivatives Pricing	[5] [6] [8] [13] [37] [40] [48] [65] [73] [74] [75] [76]	12	I-01, I-03, I-04, I-05, ChatGPT
2	**Optimization**	Portfolio Optimization	[6] [7] [8] [19] [20] [43] [48] [65] [77]	9	I-03, I-04, I-05, I-07, ChatGPT
		Arbitrage	[5] [8] [37] [48] [68]	5	-
		Forecasting Financial Crashes	[5] [8] [43]	3	-
		Building Exchange-Traded Funds	-	-	I-05
3	**Machine Learning**	Credit Scoring	[5] [6] [9] [13] [19] [20] [48] [71]	8	I-02, I-08, ChatGPT
		Fraud Detection	[5] [6] [13] [16] [20] [65] [71]	7	I-02, I-04, I-05, I-08, ChatGPT
		Targeting	[5] [9] [19]	3	I-02
		Anti-Money Laundering	[5] [6] [19]	3	-
		Algorithmic Trading	[6] [65] [71]	3	I-03
		Risk Assessment	[65] [71]	2	-
		Churn Prediction	-	-	I-02
		Quantum Generative AI	[41] [71]	2	I-04
		Identifying Trading Signals	-	-	I-08
4	**Quantum Cryptography**	Quantum Decryption	[6] [16]	2	I-06, I-07, I-08, ChatGPT

Table 7. Use Cases in Literature and in Interviews.

4.2 Impact

The interviews also contained relevant information on RQ2, which was about the impact quantum computing use cases could have on the financial industry's products and services. I-05 believed that "on a very long timescale, quantum computing will be able to improve classical computation in every aspect. And any aspect ... is an interplay of three things. So, the calculation being cheaper to execute, taking less time and producing higher quality output with some intermediate things such as ... considering more data." The named improvements are important, as many financial services and products are based on complex calculations.

Doing calculations faster could have a great impact on financial products and services. "Quantum computing has the potential to revolutionize the financial industry by providing faster and more accurate solutions to complex problems that are currently difficult or impossible to solve using classical computers." (ChatGPT). Interviewees I-01, I-03, and I-04 also believed that quantum computing will enable new possibilities. "I think the value it will bring is to do calculations that are not possible." (I-01). However, it is still uncertain what these new use cases will be. "It is a bit like we are in the 60s of the previous century, and you ask, 'What is the main use case of the computer?' no one would know that it would be TikTok." (I-01).

There is hope for quantum advantage, which is achieved when a quantum computer can solve a useful problem faster or with higher precision than a classical computer [8]. It is still a question of "Where is the advantage earlier?" (I-01). It might be either in more accurate results or faster models. I-07 expressed the opinion that without advantage, there is no point in using quantum computing. "Why does it make sense to use quantum computing because quantum computing is ... more expensive, you need other people, you need other infrastructure." (I-07). However, there might be different variations of quantum advantage that would still be beneficial for the financial industry. I-02 shared an idea about "quantum economic advantage, which means that if you use quantum computing for certain cases and not classical computing, you definitely have an economic benefit, but not a quantum advantage." There could also be another kind of quantum advantage, quantum business advantage, for instance. During the interview, I-02 explained that quantum business advantage might be achieved even with quantum-inspired solutions. "If they explore all the possibilities of quantum-classical computing approaches with high-performance computing ... they can probably have similar accuracy. But the cost, the money they need to spend to reach that point, will be really expensive and complex. But if they just installed these, they can surpass their stack, their current stack of solutions. So it's a quantum business advantage." (I-02).

Quantum computing could also be a good fit for complex calculations. For example, quantum solutions are expected to be good at working with large datasets. "You can explore many different combinations at once. It is really helpful in cases where you do not necessarily have a large dataset to work with. However, the number of potential solutions or problems grows ... exponentially the more features you look at. This is where I think quantum computing really comes into play." (I-04).

It is certain that quantum computing will have a speed advantage over classical computers in the area of simulation problems when performing the Monte Carlo method. "In Monte Carlo, you know that you will have an advantage if the machines are large enough." (I-07). "Classically, you need many simulations of that probabilistic model. Sometimes millions or trillions of simulations, and on a quantum computer, you get a quadratic speed up." This means that the time spent on simulation is reduced by "the square root of the number of simulations on a classical computer" (I-01). However, "quadratic speed up is not that much. So if you need a million times fewer operations, but each of your operations takes a million times longer because of a constant factor, your quantum computer is just slower, you need to do error correction, those kinds of things, then your advantage is, zero, it's as fast, your quantum computer might use more energy, or it might be more cumbersome to set up or search, and then there's no clear advantage." (I-01). Even if the advantage is achieved, "It does not mean that all the banks are shifting to quantum to do that calculation because it might be a very specific calculation. That is where I think we will see the first advantage. A specific calculation that a bank or an insurer is doing might have an advantage. That does not mean they will change all their Monte Carlo simulations to quantum Monte Carlo." (I-01).

The impact of risk management and derivative pricing depends on the size of the financial institution. "Smaller institutions do not do all the calculations themselves. So, for example, smaller banks, they will buy the risk model from a party like Moody's or S&P, or small insurers reinsure a lot of their insurance at companies like Munich Re or Zurich Re." (I-01). For example, the use case of derivative pricing "is just a topic for the large banks. For maybe five banks worldwide." (I-07). The participant explained that the smaller banks "are buying this derivative from the five investment banks." (I-07). However, there are also use cases that might have an impact on smaller banks as well. "Monte Carlo is interesting for risk calculation. I mean, all banks must do risk calculations. Value at Risk, Credit Value at Risk. And these calculations take time. So if you are able to speed up this calculation and just quadratic speed up, it will save time to have faster results for risk management, and this will help the bank." (I-07).

The faster calculations could impact portfolio optimization too. "In portfolio optimization, there are many different combinations that if you have a big portfolio. so maybe quantum computing really is able to solve the problem in much less time. You can do more things and then try to find the advantage ... before other people. So it could give you an advantage in terms of time or the computing resources ..." (I-03). The same kind of idea was also shared by I-05, "so this is where I think much of the ... speed up will come in." However, according to I-03, the currently used heuristic algorithms are solving the problem well, meaning that there might be nothing for quantum computing to improve. "In portfolio optimization, we are using a different technique, and then we are competing with a heuristic, but ... they are solving the problem so well that there is not much more." At the same time if one would like to use more difficult scenarios of portfolio optimization, for example, considering "multi-period," "transaction cost model," "market impact model," or also the "execution," for example, "what is the liquidity or ... what is the timeframe that you have to execute" (I-03), quantum computing could help. I-07 believed that the problem is not relevant to financial institutions. "Portfolio optimization is an academically well-defined problem to induce this Markowitz problem. But in banking, people are not interested in this topic. It is not a real banking problem." (I-07).

Machine learning has multiple areas of potential impact thanks to quantum computing. "The most obvious one is the speed advantage. Can we classify this faster? Can we train faster or create an algorithm faster?" (I-08). I-07 thought differently: "In the case of quantum machine learning. People do not hope for speedup. They hope at least that there is an advantage regarding the accuracy of the models." This was supported by ChatGPT in the context of fraud detection. "Quantum computing can help financial institutions to detect fraudulent activities more quickly and accurately by analyzing large amounts of transaction data and identifying patterns and anomalies that may indicate fraud." (ChatGPT). I-07 stated that the possibility of increasing the accuracy of machine learning models and finding structures in data is not certain, "It's a very interesting topic, but it's totally unclear." There is also a hope that "the models are better able to find structures in data." (I-07). The idea was elaborated by I-08. "There may be some quantum algorithms that can be trained to the same sort of accuracy, but on less data, which is always handy because getting data can be hard because, one, it can be messy. Two, it might not go as far back as you want it to. Maybe you want a credit history for 10 years, but you can only get it for two years, for example. So any sort of advantage on those fronts is beneficial." (I-08).

A broader impact on the financial industry could come from quantum cryptography. "Quantum computing could help financial institutions to develop more secure cryptographic protocols to protect sensitive financial data and transactions from being hacked or intercepted." (ChatGPT). The impact could either be negative or positive, depending on whether the financial institution had quantum cryptography preparation. Another broader impact, not specifically for the financial services but for the entire financial industry, might come from decreased energy consumption by using quantum computing instead of the classical counterparts. The impact is not industry-specific, but if proven true, could be an argument for deciding to proceed with quantum computing implementation in financial institutions. The idea was first shared by I-01 "So maybe you can do similar calculations on a quantum computer and a classical computer. But the classical computer takes two hours, but the quantum computer takes four hours. But it is two hours on the classical computer is a supercomputer that runs in an entire data center and uses a lot of power, while a quantum computer is just a small quantum computer that uses 10 kilowatts or something like that. It is a bit slower, but you save energy. That would also be an advantage, I think." (I-01). To validate the idea, an opinion was asked from other interviewees (I-07, I-08, ChatGPT). For example, ChatGPT commented that "while quantum computing has the potential to be more energy efficient than classical computing for certain types of problems, it is not a guarantee that all quantum computing applications will be more energy efficient than their classical counterparts." I-07 and I-08 felt similarly. For instance, I-07 explained, "I am very skeptical. I noticed this argument because it is very hyped at the moment to use this argument as sustainability is very important at the moment. So it is, I think it is a kind f marketing ultimate in my perspective... But maybe I am wrong. I hope I am wrong." The participants (I-07 and I-08) explained that most of the current hardware requires low temperatures to work: "I mean, most of the technologies at the market at the moment, they work only at low temperatures. So you have this problem of cooling down the systems. And this, of course, is very expensive and energy intensive. But of course, if somebody comes around with a quantum computer at room temperature of 1000 qubits ... and you'll save energy. But at the moment, it is not." (I-07). I-08 also described that quantum computing requires a lot of energy to keep the qubits cool. "So the time spent doing your computation on a quantum computer is, I guess, cheaper per unit time versus a normal computer, especially when the normal computer generates so much heat ... But overall, there is still a lot of cooling power involved ..." (I-08).

The interviews revealed that there is some uncertainty around the size of the potential impact of quantum computing on the financial industry. For instance, I-07 believed that the "banking industry in 10 or 15 years would be totally different than today. But not because of quantum computing". When the interviewer asked for an explanation, the participant elaborated on the idea: "One reason is the financial industry is very much regulated. We have all those regulations ... The second reason is the ... when you look at disrupting effects in the past, most of them were in the interface with the customer... But quantum computing is, at the moment, not a technique that can be used at the customer interface. It is basically used in the back end of the banks ... doing some calculations for risk management for pricing, but not at the customer interface. So I do not see why doing risk calculation a little bit faster will disrupt the industry or will change the business model of the bank's a fundamental way." (I-07). ChatGPT also brought out the aspect of uncertainty "The potential impact of quantum computing on the financial industry is not fully understood, and there is a lack of clear use cases that can provide a tangible return on investment."

Table 8 overviews the impact quantum computing could have on financial services.

#	Category	Use Case	Impact	Interviewee
1	Simulation	Risk management	Faster Monte Carlo simulations	I-01, I-05, I-07
		Derivatives pricing		I-01, I-05, I-03, I-04, ChatGPT
2	Optimization	Portfolio optimization	Faster calculations; more accurate optimization	I-03, I-07
3	Machine learning	Credit scoring	Improved accuracy of models; faster training of models	I-05, I-07, I-08
		Fraud detection		
		Targeting		
		Churn prediction		
		Quantum generative AI		
		Identifying trading signals		
4	Quantum Cryptography	Quantum decryption	Positive: improved security for transactions and data, negative: a threat for current encryption solutions	ChatGPT

Table 8. Impact of the Quantum Computing Use Cases.

4.3 Value

The interviews also covered the potential value of quantum computing for financial products and services (RQ3).

Quantum computing could enable more accurate pricing. "Quantum computing can help financial institutions to price financial products more accurately and quickly." (ChatGPT). Some banks are already exploring the use case. "The banks doing this topic are Goldman and JPMorgan. They explored derivative pricing. Of course, from their perspective, advantages in derivative pricing are interesting because they can price their products faster and consult up the product better." (I-07).

Quantum computing could improve risk management and therefore result in a stronger financial system. "So we were at an insurer once talking to their risk management experts. And they were talking about all these kinds of assumptions and approximations they have to make in order to make their calculation able to run in hours instead of weeks or years if they do it all exactly. So, for example, you would want to consider nested stochastics in the indeed way of the probability distribution of one thing, and then depending on that, you have for all the outcomes a new probability distribution, and this blows up your model very fast. But it is the best way to do it. But you cannot do that today. It is really nested stochastics. And in that sense, your ... risk management will always be off. So if you can do better risk management, you can better for insurers calculate the risk that you're facing and hedge that in some sense ..." (I-01). I-01 concluded that this might "bring a stronger financial system, and it is all because we are more aware of the risk and how what risks we are facing. Financial risk, but also societal risk ... or other types of risk. If you know your risk then you can also better prepare for it."

Another example of how quantum computing could be valuable for insurance services was shared by I-05. "The insurance industry, for example, the actuarial ... develop a model of the mortality rate of how the economy is going... and then they try to estimate what are the fair plies for a certain retirement plan. And they try to reduce the chances of a pensioner going bankrupt, which means having put money, paid money into their retirement account, and then their retirement account, not being able to support him... for the rest of his life without paying him more." (I-05).

Risk management could also benefit from considering a wider range of information in the decision-making process, which could mean better investment strategies. I-08 introduced the idea of "applications of quantum computing into ESG. Particularly for doing analysis and prediction on local weather events ... Say you want to provide a loan, or something similar to a factory, which is in a flood-prone area, you want to make sure that your underlying asset is safe and protected. And it also allows you to communicate with your customers and your clients their best effective green and ESG strategy as well." ESG, in this context, stands for environmental, social, and governance norms [99].

Use cases in the area of optimization problems could also have value for the industry. "Quantum computing could help financial institutions to optimize their portfolios by efficiently processing large amounts of data and identifying the optimal investment mix to maximize returns while minimizing risk." (ChatGPT). The idea was later elaborated by ChatGPT "... This can lead to better investment strategies and improved returns for investors." (ChatGPT).

The use case of optimizing exchange-traded funds (ETFs) could improve the ETFs offered to investors. "Another case that is quite popular is ... building exchange-traded funds. So, given an index that is made up of many sub-components, how can we build a product that can be investable that closely tracks the movement of the index? How this problem is addressed is that a financial institution is trying to find the smallest subset of ... investable components of the index, creates ... a weighted basket, and then offers these to investors ... to minimize transaction costs and tracking error." (I-05).

The use cases from the third problem area, machine learning, could have value, too. For instance, improved credit scoring could help financial institutions to understand better how the customer might behave. "Credit scoring is basically a classification if somebody is going to pay or not or is going to be in default on delinquency." (I-02). I-08 and ChatGPT listed consumer banking as the beneficiary of improved credit scoring, "doing credit analysis, it is quite a labor-intensive process. So you might want to reduce your labor costs there ... and automate more. So you can free up resources." (I-08).

Using quantum machine learning for fraud detection could make customer onboarding safer for the institution. "In the onboarding, for example, of a bank. So they are applying for something, and we detect that this person is a fraudster. Because we have processes in the past, so we train a model to understand if they have the same patterns." (I-02). Advancements in fraud detection could also be used in consumer banking. "In consumer banking is very useful to ... the use case of detecting anomalous data, and new data points. It is matched to, for example, fraud detection, and it is very typical ..." (I-05).

Another application of quantum machine learning suggested by the interviewees was predicting customer engagement. "I mean, the clients and the engagement is understanding how much engaged they are to offer different products. So, for example, if they are using a lot of credit cards, and they are going through a specific path, we can offer them a loan or offer X service." (I-02). More accurate quantum machine learning models could help to identify trading signals better and thus improve trading strategies and returns. Or "identifying trading signals" (I-08). "So is this an inflection point where I should buy? Or should I sell, or should I hold on to whatever underlying asset it is that I'm focused on?" (I-08).

Quantum generative AI could help to improve investment services by allowing financial institutions to create a proof of concept for their investment strategies. "Many financial institutions ... devote a lot of money and resources to ... generating synthetic data to validate many of their ... algorithms and their trading strategies they created in-house." (I-04).

Quantum machine learning could also have value for rating agencies and capital markets by allowing more precise forecasts and models. "Forecasting indices and macroeconomic indicators ... It is very useful for again rating agencies, for example. For all agencies that want to ... give a recommendation on how the economy as a whole is performing." (I-05). "In capital markets ... we may be interested in studying the correlation and modeling the correlations of, for example, currency and interest rates ... Or again, creating a model where certain macroeconomic factors then will influence the price of the security, and we should be able to describe the overall state of the economy as a booming economy or stagnating economy ... by creating these graphical models. In all these types of problems, we can use quantum machine learning." (I-05).

When looking at the potential value of quantum computing more broadly, it could happen that quantum computing results in financial institutions making more informed decisions. "These characteristics of quantum computing enable financial institutions to perform complex calculations and simulations more quickly and accurately than is possible with classical computers. This can help them to make better decisions, manage risk more effectively and gain competitive advantages in the financial markets." (ChatGPT).

Advancements in cryptography could also have value in the financial industry. For example, the financial industry could provide its customers with a better customer experience. "Customers can benefit from more secure transactions that can help to protect their sensitive financial data and assets from being hacked or intercepted." (ChatGPT). From a financial institution's point of view, this could lead to "increased trust in financial products and services and reduced losses due to cyber-attacks" (ChatGPT). From financial products and services, the improved cryptography could provide "secure communication, digital identity, and authentication." (ChatGPT). On the other hand, if the advancements in quantum cryptography are not taken seriously, the value on finance could be negative. "Quantum computing has the potential to break many of the encryption algorithms that are currently used to secure financial transactions and communications. This means that sensitive data could be compromised, leading to financial losses, reputational damage, and other negative impacts." (ChatGPT).

There is also potential monetary benefit involved. "We can have small advantages that in the case of the finance sector is millions of dollars sometimes." (I-02). "Imagine in the finance sector, so if you optimize 3-4-5 percent, in the precision of these models, is millions of dollars." (I-02). ChatGPT referred to a report by Boston Consulting Group which "estimates that quantum computing could generate up to $450 billion in value for the financial industry by 2030, with significant value coming from areas such as risk management, asset pricing, and fraud detection." As ChatGPT is said to be subject to generating false references, it was validated after the interview that such a report exists, and the prediction is as written [100]. The original article can be found in [101].

It is worth mentioning that some interviewees expressed that the exact value of quantum computing is unknown. It is important to work on the use cases valuable for the industry. For example, some use cases might not have a noticeable value for the banks. "Portfolio optimization is an academically well-defined problem to induce this Markowitz problem. But in banking, people are not interested in this topic. It is not a real banking problem." (I-07). The interviewee did not see quantum computing as disruptive for the financial industry. "I think just banking troubles could not be avoided if the risk models were faster. So ... I do not really see this as ... a big advantage, its disrupting advantage. It could make it seem a little bit better, of course, but ... not on a big scale." (I-07). Also, it might be that the exact value cannot be determined before implementing the use cases in production. "It is difficult to provide an exact estimate of the potential value of each use case of quantum computing in the financial industry, as the value will depend on various factors, such as the specific application, the size and complexity of the problem being solved, and the competitiveness of the market." (ChatGPT).

Table 9 presents the different areas of potential value and their relation to the use cases.

#	Category	Use Case	Value	Interviewee
1	Simulation	Risk management	Better risk management; stronger financial system	I-01
		Derivatives pricing	More accurate pricing	I-07
2	Optimization	Portfolio optimization	Better investment strategies; better returns for investors; more optimal portfolios	ChatGPT
		Building exchange-traded funds	Minimizing transaction cost; decreasing tracking error	I-05
3	Machine learning	Credit scoring	Better understanding of the customer; reducing manual work	I-02, I-08
		Fraud detection	Safer onboarding; less fraud in finance	I-02
		Targeting	Personalized offers	I-02
		Quantum generative AI	Validated algorithms and trading strategies	I-04
		Identifying trading signals	Improved investment strategies	I-08
4	Quantum Cryptography	Quantum decryption	Positive: better customer experience; more secure transactions; increased trust in financial products; negative: financial losses, reputational damage, compromised data	ChatGPT

Table 9. Value of Quantum Computing on the Financial Products and Services.

4.4 Obstacles

Implementing quantum computing use cases in the financial industry faces a myriad of challenges, as shown by the interviews. Interviewee I-05 stated that "the challenge is tantamount to the value that can be unlocked." ChatGPT said the current status of quantum computing in the financial industry is "still in its early stages, but there are many exciting developments and initiatives underway. Financial institutions are increasingly exploring the potential use cases of quantum computing, and there have been some notable experiments and proofs of concept in areas such as portfolio optimization, risk management, and option pricing. However, it is important to note that the technology is still in its infancy, and there are significant challenges that need to be overcome before quantum computing can be widely adopted in the financial industry. Some of the key challenges include developing scalable hardware and software, addressing the issue of error correction, and ensuring the security of quantum communication and cryptography."

Quantum hardware challenges were mentioned by all interviewees (I-01, I-02, I-03, I-04, I-05, I-06, I-07, I-08, ChatGPT). The currently available quantum hardware is in a "NISQ (Noisy Intermediate Scale Quantum)" (I-04) era and "at a low value" (I-06). The qubits are "prone to noise from the environment and decoherence" (I-04). The noise adds a layer of challenge, as it "limits the length of the calculations you can do." (I-01). One of the participants summarized hardware issues with the following: "I think there are three things in terms of the hardware. That is the scale of the quantum computers, the quality of the quantum computers, and the speed of the quantum computers." (I-01).

The scalability problem indicates that it is still unknown how to scale the technology and how well a bigger number of qubits would work together. However, some use cases require a large number of qubits. Interviewees (I-01, I-05, ChatGPT) mentioned that the current qubit count is limited. "You now have quantum computers with 100 or 500 qubits. But for these really complex models, you might need thousands or 10,000 qubits which then should also be stable, which is a challenge" (I-01). The interviewee also added that "There are estimates out there that for a small use case in finance, you need 10000 qubits. So with 400, it is not that useful yet." (I-01). However, having a number of qubits is not just enough. Both I-04 and I-07 stated that it is unknown whether currently working solutions will work on scaled hardware as well. "It is absolutely not clear how you can scale this if it comes to 1000 qubits. That's a very unclear scientific and technological, and engineering problem. Nobody knows if it can work out or if there is something that won't work at all. Nobody knows if it will work and, if it will, how fast." (I-07) "This particular technology works really well with 20-30 qubits. What would happen if you try to scale up to 1000 qubits or a million qubits? There are going to be scalability issues with many things." (I-04).

According to the participants, the current quantum hardware does not have the required quality. For example, I-08 brought an example of superconducting qubits technology which is sensitive to heat, light, and magnetic fields. The problem of noise was also mentioned by I-01: "There is noise in these qubits, which limits the length of calculations you can do. So you can tell I was talking about calculations that now take days, but you could do them in hours, while in one second, your qubit is no longer in superposition. So a calculation of an hour is not possible." This is called decoherence, which is when the qubits "stop behaving in this quantum way." (I-08). In addition to heat, light, and magnetic fields, decoherence can also be caused by "inherent defects that can exist in the materials" (I-08) from which qubits are built. "By discovering these defects and mitigating their effects, you can increase coherence times and increase the effectiveness of your qubits," explained I-08. Until there is a fully-fault tolerant quantum computer, there is a chance "we can get past the hardware engineering. You just have to find all kinds of workarounds. Error correction is an area of research. We are also looking at new ways just to improve existing quantum algorithms that run on these NISQ devices." (I-04). Considering the problems with errors, there are "big pushes for better error correction protocols" (I-04). I-08 had hope that "once those challenges are addressed, and quantum computers can become a larger scale, we will definitely see a boom in quantum."

Quantum computers today are also slow. In the short term, it is probable that a quantum computer will not be faster than an equivalent classical computer. "It will be very hard to do anything faster that also has a considerable business impact." (I-05). Participant I-01 shared that even personal laptops perform multiple times more calculations per second than currently available quantum computers and said: "I think quantum computers today are very slow." Also, the hardware offered by technology providers might mean waiting in a queue. "It is almost impossible to use these for banks. For example, most banks need real-time answers. And they need to train models faster. So, in that case, we cannot wait in the queue of a quantum computer for two hours." (I-02). Slowness is also a problem in quantum machine learning. For quantum machine learning, the data "needs to be turned into a quantum form" (I-05). However, at the moment, "that operation is very inefficient" (I-05).

I-06 emphasized that before developing the solutions, one has to "develop the understanding of the technology." The lack of understanding is also present in the problem space. As stated by I-03, "there is no clear problem," which is intractable on a classical computer but could be efficiently solved on a quantum computer. The idea of the struggle of picking the problem to solve is also supported by I–08 in the machine learning context, "choosing the problem is a difficult thing itself. So there's the need, there needs to be good communication amongst departments within a financial institution about what it is that a certain department is facing in terms of difficulties or problems that they want to solve, and then translating that into a proper or well-articulated data science problem that you can then start to tackle." I-04 drew a parallel to other emerging technologies, "that is a problem with many new technologies."

Other than hardware, the software side could also use some improvement. I-06 stated that the information in the literature is repetitive "It is always the same things that come up. Chemistry, cybersecurity, optimization. Everyone is talking about that. Nothing really pops up." I-03 shared that "I was expecting the software side or algorithmic side to be more developed. And it is not the case." The participant also elaborated on that idea by saying: "So we are developing new algorithms. There are not many. Actually, that is another thing that surprised me. I thought that there were more. So the ones that there are have some limitations. They are not general enough to tackle any problem." (I-03).

The interviewees also mentioned different kinds of barriers to entering quantum computing. One interviewee also considered the cost as a barrier. ChatGPT stated that "quantum computing technology is expensive to develop, maintain, and operate. The cost of implementing quantum computing solutions in the financial industry may be prohibitive for some institutions."

Another conception is that quantum computing is complex. I-02 expressed the belief of companies that in order to move to quantum computing, the company needs a "consultancy company" or "well-trained people with good skills." However, there might be a problem with having people with technical skills. As stated by ChatGPT, "There is a shortage of skilled professionals in the field of quantum computing who can develop, implement, and maintain quantum computing systems in the financial industry." This is opposed by other interviewees, "there is no lack of people with clever ideas. It is that the technology lacking" (I-01) and "You don't need to be a Ph.D. to start looking at this. You need to be a software engineer, data scientist and try it in Qiskit," to start the quantum journey (I-02). Qiskit is an "open-source software development kit" for experimenting with IBM's quantum computers and quantum simulators [102].

However, some interviewees feel the lack of relevant literature and documentation. Literature could be a big help in the process of experimenting with technology. For instance, I-06 shared that "it is also closed research because most of the time, they do not share the code. They just do not share source data. When you try to reproduce the paper, it is complicated." From one angle, it is understandable, as closed research may be important for getting a competitive advantage. On the other hand, it slows the speed of quantum innovation, as reproducing the results for validation is difficult, as one cannot be sure that the input and exact steps of processes match. So it is always a process of trial and error. It is further explained by I-02, "so I need to take a look, and then interpret what they did, and then implement myself. Sometimes you have a dead end. So you try to find something."

A separate category of obstacles is the possible threat of quantum computing. For instance, I–08 brought out that there is a similar threat with quantum machine learning as there is with classical machine learning, "there is the ethics and the inclusivity and diversity of the data that gets used when you are creating a model. So you want to make sure that our data is unbiased as possible and fair." I-07 considered quantum computing also "a security issue." This idea was supported by I-08, "There is a concept of "harvest now, decrypt later." Even if data is extremely strongly encrypted between two organizations, you could still take that encrypted data stream and hope that, in the future quantum computers are strong enough to crack it. And you can find out what was said later on." This indicates that companies are already facing a risk that could mean that "sensitive data could be compromised, leading to financial losses, reputational damage, and other negative impacts." (ChatGPT). ChatGPT also listed a competitive disadvantage, business model disruption, and regulatory non-compliance as potential risks for financial institutions. The first one focuses on the potential consequences if an institution decides not to invest in quantum technologies. "Financial institutions that do not invest in quantum computing may fall behind their competitors who are using the technology to gain a competitive advantage. This could lead to a loss of market share, decreased revenue, and other negative consequences." (ChatGPT). ChatGPT also brought out the potential disruption of business models. For example, quantum computing may "lead to the development of new financial instruments or trading strategies that traditional financial institutions may not be equipped to handle" (ChatGPT). The risk of not complying with the regulations implies the importance of implementing quantum computing use cases in accordance with the applicable regulations. Otherwise, a financial institution may face "penalties or other regulatory consequences" (ChatGPT).

However, overcoming regulatory and company constraints is a challenge in itself. ChatGPT summarized the impediment as "regulatory challenges," which include "data privacy, security, and compliance." Another interviewee shared that raising awareness is an important part of the job, "I spend a lot of my time trying to convince compliance teams and regulatory teams that what we are doing is fine. The difficulty comes in that light, is explainability, basically, so it is quite hard to explain quantum in layman's terms, especially with all the complexities you either have with a financial problem, a data science problem, or with quantum computing." (I-08). Understandably, ensuring that a quantum solution complies with the regulations can take time and thus be a considerable impediment.

After talking about the impediments, the interviewees were asked to share possible solutions to the mentioned problems. I-06 shared that "we need to work everywhere" in order to remove the impediments, meaning that every part of quantum computing still needs work.

Considering the apparent problems with quantum hardware, hardware improvements were mentioned (I-01, I-06, I-07, I-08) as one of the factors that would help to accelerate progress with quantum computing in the financial industry. I-01 said, "We need better, larger systems with better qubits, which we can operate faster." I-07 shared a similar idea: "More qubits, more stable qubits, I mean, lower error rates, deeper circuits so that you can do larger calculations, more circuits." I-08 shared a thought which implies that the decoherence problems could be improved by "very novel fabrication processes." "So the processes we use to actually create a quantum chip or a quantum processing unit or GPU is, is what is necessary to sort of overcome. The challenge with these defects is that there is definitely a problem at the atomic scale in the fabrication process. So improvements in how you actually create your chips, there is definitely low-hanging fruit in terms of where you can look to explore improvements in your coherence times." (I-08).

I-02, I–03, I–05, I–06, I-08, and ChatGPT mentioned that there is a need for collaboration among financial institutions, technology providers, and academic institutions. The interviewees mentioned that better cooperation is needed for the financial institution to start believing in the technology, and there is also a need for quantum computing companies to build trust in the financial institutions. For instance, ChatGPT framed it as "quantum computing is a complex and rapidly evolving field, and it can be challenging for individual financial institutions to keep up with the latest developments and make informed decisions about how to approach the technology... By working together to share expertise and resources, financial institutions can better understand the potential applications and risks of quantum computing and develop more effective strategies for leveraging the technology in their operations." Participants (I–02, I–06, ChatGPT) also mentioned the term "quantum community" and its importance. As I–02 said: "I think we need to act more as a community." I-03 highlighted the importance of quantum computing companies building trust amongst financial institutions "First, you need to create trust."

Interviewee I-02 said that the aim should be to "move the testing and the analysis of the quantum computing approaches from the labs, universities, and startups to the market." Otherwise, "we will never know how much benefit we will have." (I-02). I-05 shared a similar idea "Some direct investments by institutions could be helpful. This institution taking an interest in quantum computing company could help make the quantum computing industry less academic, less textbook driven, and more driven by experiments." I-01 agreed that investments are crucial but thought it is also important to keep in mind that "we cannot buy a quantum computer today that works." ChatGPT added that "Continued research and development of clear use cases for quantum computing in the financial industry can help to provide a better understanding of the potential benefits and return on investment."

Governmental help could also give a boost to quantum advancements. "Having the government say derisking project and helping the industry to take a longer-term view and a more broad view of which problem should they be interested in, in tackling with quantum computing vendor will be extremely helpful." (I-05). As finance is a regulated industry, financial institutions could benefit from regulatory guidance. "Regulatory agencies can work with financial institutions to develop clear guidelines and standards for implementing new technologies in the financial industry, including quantum computing." (ChatGPT). In addition to legal standards, technical standards could help too in reducing the impediments. "Developing and adopting standards for data structures, security protocols, and programming languages can help to ease the integration of quantum computing technology with existing financial systems." (ChatGPT).

The interviewees also shared some thoughts on what the implementation strategy for the quantum computing use cases should be to avoid bigger impediments. Interviewees (I-02, I-03, I-05) agreed that the process should start with a "smaller problem" and "more quick wins." I-05 shared the same view "I am more of the view that the development of the industry will be incremental, that these build problems are, in fact, as on any technological science challenge, made up of a myriad of smaller problems. And it is not just about cracking every problem is also about being very clever about making decisions of how to plan the journey, or which problems are actually relevant to solve, and how to really design the design choices on how to build algorithms and how to build hardware. So in this view, we include the technology incrementally, and we will see that the impact of quantum computation in the finance industry will become bigger. And that is where we need the financial institution to work with us to keep benchmarking the state of the art in the industry against the problem that needs solving, the compelling industrial problems, that the finance industry is facing every day." I-05 suggested to "be part of the group of pioneers that will shape the industry" to gain from the technology.

The interviewees had different ideas about the potential timeline of quantum computing in the financial industry. I-02 thought that the progress with quantum-inspired solutions is better and that "in a few months, they will be directly in production." The same kind of idea was shared by I-03 "The first step, it will not come from quantum computing, it will be from quantum inspired things ... Not only because there is no hardware now, but also there are more developed strategies there." However, when talking about real quantum solutions, the interviewees' views differed a bit. Participants I-01 and I-04 predicted similarly that we will see something in "the next two or three years, maybe by the end of the decade." I-01 agreed, saying: "I think somewhere around ... in five or ten years, in finance, we will have some applications." ChatGPT gave two viewpoints: "It is expected that within the next five to ten years, we will see significant improvements in quantum computing hardware and software," and "Some experts believe that quantum computing could start to have a significant impact on the financial sector within the next decade. However, others caution that it may take longer for the technology to mature and that widespread adoption of quantum computing in the financial industry may still be many years away." I-07 predicted specifically the timeframe for the Monte Carlo simulation, for which "we have to wait. Maybe ten more years, 15 more years, before we have really fault-tolerant computers." I-01 added that it also depends on the use case, as some of them "might only be relevant in 20 or 30 years."

Some of the interviews also touched upon the topic of which industry will be the first one to benefit from the technology. While I-04 believed that "finance is also one of the earliest use cases with quantum computing," I-01 was not too sure. "I am not sure if I agree. I am also not sure if I disagree." (I-01). I-06 believed that the first will be in quantum materials.

Table 10 and Table 11 provide a list of impediments suggested by the interviewees. Table 12 overviews the solutions suggested by the interviewees.

#	Category	Impediment	Description	Interviewee
1	Hardware problems	Noise	Currently available hardware is in a NISQ era; hardware is prone to noise and decoherence	I-01, I-02, I-04, Chat-GPT
		Scalability problems	Unknown if current solutions will work on scaled systems	I-01, I-04, I-07
		Low qubit count	Some use cases need multiple times more qubits than it is available today	I-01, I-05, ChatGPT
		Slowness	In the near future, it will be difficult to do anything with a business value faster than done today on classical computers	I-01, I-05
2	Software problems	Lack of algorithms	There are not many quantum algorithms for finance available	I-03, I-06
3	Barriers to technology	Cost	Quantum computing is expensive to develop, maintain and operate.	I-02, Chat-GPT
		Complexity	There is a high complexity to developing and operating quantum computers, which could act as a barrier entering the technology	ChatGPT
		Lack of talent	There are not many professionals with the skills needed for developing quantum computing	I-02, Chat-GPT
		Lack of literature	There is a lack of literature, and the available literature is somewhat repetitive	I-02, I-06
4	Business constraints	Regulatory constraints	Finance is a very regulated industry. With every new technology, there are regulatory challenges, such as data privacy, security, compliance	I-08, Chat-GPT
		Company constraints	Due to lack of understanding, companies might be reluctant to implement quantum computing use cases	I-02, I-08
5	Other problems	Lack of problem	There is a lack of clear problems in finance for which to apply quantum computing.	I-03, I-04, I-08

Table 10. Impediments of Quantum Computing Use Cases in Finance (1).

#	Category	Impediment	Description	Interviewee
6	Threats	Inclusivity and diversity of quantum machine learning models	The data used for training quantum machine learning models have to be inclusive and diverse. Otherwise it creates a threat of biased models	I-08
		Harvest now, decrypt later	A threat of the theft of encrypted documents in hope to decrypt them in the future using a quantum computer	I-07, I-08, ChatGPT
		Competitive disadvantage	Financial institutions may fall behind competitors if they decide not to invest in the technology. This could lead to a loss of market share and decreased revenue	ChatGPT
		Business model disruption	Quantum could disrupt business models by creating new financial instruments or trading strategies that traditional financial institutions may not be able to handle	ChatGPT
		Regulatory non-compliance	If quantum computing is used without making sure its compliance with the regulations, financial institutions may face penalties or other consequences	ChatGPT

Table 11. Impediments of Quantum Computing Use Cases in Finance (2).

#	Solution	Description	Interviewee
1	Hardware improvements	For implementing use cases, there is a need for larger systems with better qubits that operate faster.	I-01, I-06, I-07, I-08
2	Collaboration	There is a need for knowledge sharing, which could happen through a collaboration between financial institutions, technology providers, and academic institutions.	I-02, I-03, I-05, I-06, I-08, ChatGPT
3	Testing	The industry should be driven more by experiments, not theory, to discover more use cases and to understand the value of the technology.	I-02, I-05, ChatGPT
4	Governmental help, regulatory guidance, standards	Having governmental support, regulatory guidelines, and standards for quantum computing implementation could boost the advancements of implementing quantum computing use cases in the industry.	I-05, ChatGPT
5	Starting small	The implementation of the use cases should be incremental to have quick wins more often.	I-02, I-03, I-05

Table 12. Solutions for the Impediments of Implementing Use Cases.

5 Discussion

This section discusses the results, answers research questions, places the results into a framework, considers the limitations of the thesis, and proposes ideas for future research.

The first research question was stated as: "RQ1. What are the potential use cases of quantum computing in the financial industry?" The goal of the question was to understand what kind of opportunities quantum computing could offer to the financial sector. Two approaches were used to find an answer: literature review and interviews.

The results of the thesis revealed that the use cases could be categorized by financial problem areas into three: simulation, optimization, and machine learning. This categorization was suggested in the interviews (I-05) as well as in some of the related work, such as [19], [65], and [8]. Each of the areas contains different quantum computing use cases for the financial industry.

In the first area, simulation, the two main use cases are derivative pricing and risk management. A way of approaching those problems is Monte Carlo simulations which allow the modeling of complex systems [6] [37]. The limitations in classical computers have led financial institutions to limit the Monte Carlo simulations to only a subset of calculations [48] (I-01). Quantum computing could help by speeding up the calculations [37] (I-01), (I-07).

The second area, optimization, includes use cases, such as portfolio optimization and building exchange-traded funds, as revealed by the interviews. Interestingly, the latter did not come up during the literature review. However, there were other use cases from the literature that were not mentioned by the interviewees, such as arbitrage and forecasting financial crashes.

The third problem area, machine learning, contains use cases that can be seen as machine learning problems. Use cases common in literature and interviews were credit scoring, fraud detection, targeting (called engagement prediction in interviews), algorithmic trading, and quantum generative AI. While the interviews also touched on use cases such as churn prediction and identifying trading signals, these did not come up in the literature review. However, the literature added a couple of different use cases, such as anti-money laundering and using natural language processing for risk assessment.

From the non-financial-industry-specific use cases, quantum decryption was mentioned both by related work as well as interviews. As another use case, it is expected that quantum computing could replace the current technological stack to some extent and form a quantum-classical hybrid computing workflow.

While it appeared that the use cases match to a large extent between the literature and interview results, there are also slight differences. Related work revealing use cases that were not mentioned by the interviewees could be a result of the non-exhaustive knowledge of the participants, time-bounded interviews, or it could indicate that the use cases which emerged from the interviews are the main use cases of quantum computing for the financial industry, as the interviewees were asked to share the main use cases (a sub-question in the interview guide). On the other hand, use cases not mentioned in the literature, which were mentioned by the interviewees, could be an indication that it could be a newer use case, which has not been mentioned in the literature widely, or the interviewee just had personal experience with the use case.

However, as it turned out from the interviews, there is still quite a lot of uncertainty around the technology and its use cases in the financial industry. Despite the technology promising speed-ups and enabling new use cases in the industry, the timeline is not certain. In addition, financial institutions would like to see successful case studies so that trust in the technology would increase. Even though there are some differences between the currently available literature and the results of the interviews, it seems that the main use cases of quantum computing for the financial industry are risk management, derivatives pricing, portfolio optimization, credit scoring, fraud detection, and quantum decryption. These use cases were mentioned by both related literature and the interviewees more than the others.

The second research question was focused on the impact of quantum computing applications in finance and was presented as "RQ2. How can the potential use cases of quantum computing impact financial products and services?"

Quantum computing could have various impacts on the industry's products and services. For example, the results of the interviews include the hope of achieving quantum advantage. However, if currently available literature, for example, [8] [15], mostly mentions the well-known quantum advantage (outperforming classical computers in solving time or preciseness of the results), interviewees added another layer to it. As shared by the interviewees, reaching quantum advantage might not necessarily be needed for companies to opt for quantum computing. In the conversation with I-02, two alternatives for the "classical" quantum advantage were purposed: quantum economic advantage and quantum business advantage. Neither of the terms is widely used. The quantum economic advantage was suggested as a term in [103] by Bova et al. The authors found that a company using quantum computers could be more profitable and able to invest more in market creation compared to a company using only classical computers [103]. Quantum business advantage has been mentioned and explained in [104] by Mancilla. The article brings two examples of how quantum computing could have a business benefit without a quantum advantage. First, quantum solutions could replace high-performance computing and reduce the cost and time to set up the solution [104]. Second, in some cases, quantum could outperform classical machine learning or optimization [104].

In the area of simulation, Monte Carlo simulations are said to have a quantum speedup when the quantum computers are large enough (I-07). However, the size of the impact of quantum Monte Carlo depends on the size of the financial institution. The smaller banks will not benefit from use cases such as derivative pricing, as it is a business scene for large institutions. Risk management, on the other hand, could be used more widely.

In the area of optimization, quantum computing could help to solve the optimizations more efficiently. Unfortunately, the use case of portfolio optimization appeared to be controversial, as I-07 shared that portfolio optimization "... is not a real banking problem."

Machine learning could be impacted by the increased speed of training the models or a higher precision of the machine learning models. The impact of quantum machine learning could also be the need for less training data. As introduced by the results of RQ1, the advancements of machine learning could be used in products and services such as credit scoring and fraud detection.

In addition to the other areas, there is a hope that quantum computers use less energy for calculations than their classical counterparts [6]. The idea was also proposed by I-01. However, a couple of other interviewees were skeptical (I-07, I-08, ChatGPT). Additionally, there was uncertainty regarding the impact of the technology on the industry. For example, if [6] sees quantum as a potentially disruptive technology, I-07 believes it will not happen, as the technology has very little (if any) impact on the end customer.

To summarize, the financial industry could see different kinds of impact by opting for quantum computing use cases, including: being able to solve the calculations in less time, increasing the preciseness of the calculation results, having quicker machine learning models, and finding patterns better with machine learning. Additionally, it is explored whether quantum could help to reduce the energy spent on calculations.

The third research question, "RQ3. What kind of value can quantum computing have on financial products and services?" focused on the potential value of the technology on the industry.

In the area of simulation problems, the use case of using quantum computing for derivative pricing could mean that financial institutions could price their product faster and better (also supported by [65]). Risk management, on the other hand, could have value in insurance services by allowing them to calculate the risk more precisely and to use more advanced models in risk calculations. This could result in a stronger financial system. The use cases in the optimization area could also have value on financial products and services. The use case of portfolio optimization could lead to more optimal portfolios (also supported by [6]) and improve investment strategies as well as returns. The use case of using quantum computing to conduct the exchange-traded funds better could reduce the transaction cost and tracking error for the investors. In the area of machine learning, the use cases, such as credit scoring, reduce the need for manual work and provide more accurate results (also mentioned by [6]). The use case of fraud detection, on the other hand, could improve customer onboarding processes by detecting anomalous data more precisely. This could mean that financial institutions could protect themselves better from cases of fraud. Quantum generative AI could also improve investment services by allowing to validation of the algorithms and investment strategies by using the generated synthetic data (also mentioned in [41]). Use cases such as targeting and churn prediction could potentially improve customer retention. Identifying trading signals by using quantum computing could potentially lead to better trading strategies and also better returns.

As with the use cases, there is also some uncertainty with the potential value. For example, quantum cryptography could have both positive and negative values, depending on whether a financial institution will be quantum protected or not. ChatGPT added that the final value of the technology will be understood over time "... as the value will depend on various factors ...".

Quantum computing use cases in the financial industry are expected to have value in the industry. The value is expected to be use case specific and could be in the form of better risk management, more accurate pricing, or better investments or returns.

The last research question, "RQ4. Which obstacles impede implementing quantum computing use cases in the financial industry?" took a look into the current impediments which slow down the implementation of the use cases in the industry. The interviews were insightful in terms of overviewing the current challenges and their possible solutions and also for understanding why none of the proposed use cases are used in production yet.

The most commonly mentioned impediment by the interviewees was the problem of quantum hardware. The currently available hardware is not mature. The hardware is noisy, has low qubit amounts, and is also slow. The issues of hardware are also mentioned in some of the related work, such as [6], [8], and [15]. [105] states that even a personal laptop could compete with the current quantum computers in solving calculations with the same complexity.

The software or algorithmic side is also lacking; not many promising quantum algorithms for finance are available. There are also multiple barriers to the technology. For instance, the barrier of not having access to the technology, high cost, complexity, lack of talent, and lack of literature. If the technology or knowledge is difficult to access, the implementation of use cases might take a considerable amount of time.

As stated in the introduction of the thesis, emerging technologies can enable new possibilities but also pose new threats [2]. This is also the case with quantum computing. When using quantum machine learning, the ethics, inclusivity, and diversity of the training data have to be provided. Otherwise, it might result in biased results. It is also important to ensure the technology's compliance with the regulations. If companies do not manage to pursue the new technology at the right time, it could turn into a competitive disadvantage for the financial institution. There is also the "harvest now, decrypt later" concept, which makes quantum computers a threat even now. This was also mentioned by related work, such as [49].

As shared by I-04, uncertainty and lack of a clear view are common problems for emerging technologies. This might be the reason for company constraints. A lack of understanding might make companies careful in investing in quantum computing. In addition to the company constraints, finance is a very regulated industry. Thus there are also regulations to which quantum solutions have to comply to.

The interviewees suggested some solutions for the impediments too. First, the participants saw hardware improvements as an advancement. However, as hardware improvements could be a bigger challenge, solutions such as collaboration, testing, governmental help, and starting small could also contribute to the development of quantum computing applications in finance.

If considering all the stated impediments and the surrounding uncertainty around the technology, it is understandable why some financial institutions may be reluctant to invest in technology at this point in time. Understandably, there is still uncertainty around the technology, which could make companies modest in investments. In addition, some of the financial institutions could be facing more fundamental issues than whether to invest in quantum or not, such as issues with general IT infrastructure (brought out by I-07). However, if not more, financial industry companies should at least mitigate quantum decryption risks. The potential risk is too big to ignore it. However, further investments should be in alignment with the company's strategic outlook. If innovation is a key area, quantum computing has the potential to contribute to achieving it. If not, the company could wait for a proof of concept to decide whether an investment is reasonable.

There are considerable challenges in implementing the potential use cases of quantum computing in the financial industry. Quantum hardware problems are one of the most mentioned impediments. However, there are other issues too. As said by I-06, "We need to work everywhere." The interview participants see as solutions the hardware improvements, collaboration amongst the industry, experimenting with the use cases, having governmental support, and taking use case by use case.

To provide an overview of the results of the thesis, the results are put into a framework presented below in Table 13. The framework overviews the use cases of quantum computing in the financial industry, their value, and their possible impact in an easily understandable form. The information presented in the framework is retrieved from the results of the literature review and interviews. As the impediments introduced by the interviewees were not use case specific, it was decided not to include them in the framework.

#	Category	Use Case	Impact	Value	Description
1	Simulation	Risk management	Faster Monte Carlo simulations	Better risk management; stronger financial system; faster decisions [6]; saved money [6]; moving buffers of capital into investments instead [6]	Monte Carlo simulations are common in risk management. Faster simulations could result in better risk management, faster decisions, decreased costs of running the simulations, and more accurate risk prediction could allow for a decrease in the buffers of capital. All this could result in a stronger financial system.
		Derivatives pricing	Faster Monte Carlo simulations	More accurate pricing; more stable pricing [65] ; real-time calculations [65]	Faster Monte Carlo simulations could also impact derivative pricing. This could result in more accurately and stably priced derivatives and allow financial institutions to perform the calculations in real-time.
2	Optimization	Portfolio optimization	Faster calculations; more accurate optimization; considering more factors [5]	Better investment strategies; better returns for investors; more optimal portfolios; better offerings [6]; decreased interest rates [6]; freed-up capital [6]	In the area of portfolio optimization, quantum computing could enable faster and more accurate calculations which could consider more factors. The value of this use case could appear in better investment strategies, better returns, more optimal portfolios, or even in decreased interest rates or freed-up capital.
		Arbitrage	Faster calculations; more accurate optimization [8]	Finding more optimal arbitrage options [68]; gaining competitive advantage [5]	Advancements in optimization could be used for finding arbitrage options more quickly and accurately. This could lead financial institutions to improve their arbitrage returns and outperform their competitors.
		Forecasting financial crashes	More accurate optimization [69]	Better preparation for financial crashes [69]	Quantum optimization could allow forecasting financial crashes more accurately. If the results of the calculations are improved, financial institutions could use this information to prepare for the crashes better.
		Building exchange-traded funds	Faster calculations; more accurate optimization	Minimizing transaction cost; decreasing tracking error	Optimizing exchange-traded funds with a quantum computer could mean faster and more accurate optimization. This could lead to decreased transaction costs and smaller tracking errors.
3	Machine Learning	Credit scoring	Improved accuracy of models; faster training of models	Better understanding of the customer; reducing manual work; reducing financial loss [48]; decreased investments for training models [43]; increased revenue thanks to decreased number of defaulted loans [6]	Quantum computing could enable more accurate and faster models in the area of credit scoring. This could lead financial institutions to understand the customer better, automate the credit analysis process, reduce the financial loss caused by improper scoring, spend less money on training complex models, and increase revenue from loan services thanks to the decreased number of defaulted loans.
		Fraud detection	Improved accuracy of models; faster training of models; finding patterns better [13]	Safer onboarding; less fraud in finance	The area of fraud detection could benefit from the increased accuracy and speed of the models. Additionally, quantum machine learning could help to find patterns better in financial data to detect fraudulent activities. This could reduce fraud in finance and make customer onboarding safer for financial institutions.
		Targeting	Improved accuracy of models; faster training of models; finding patterns better [5]	Better customer retention rate [5]; real-time personalized offers [5]	Targeting could benefit from quantum machine learning which could allow doing the predictions faster and more accurately. In addition, quantum machine learning might help to find subtle patterns in the data. The value of the use case is a better customer retention rate thanks to real-time personalized offers.
		Anti-money laundering (AML)	Improved accuracy of models [19];	Decrease false alerts in money-laundering tracking [19]	The current money laundering tracking is prone to mistakes (high rate of false positives [19]). Quantum could help to identify money laundering cases more accurately and faster. This could lead to reduced amounts of false alerts.
		Algorithmic trading	Improved performance [71]	Improved returns	Algorithmic trading could benefit from quantum reinforcement learning, which could improve the performance of algorithmic trading. As a result, financial institutions could improve the returns for the customers.
		Risk assessment	Improved accuracy of models; faster training of models; considering more factors [71]	Better risk assessment [71]	Risk assessment could benefit from the advancements of natural language processing. This could allow considering more factors, improve the accuracy of the models and train the models faster. As a result, financial institutions could do better risk management.
		Quantum generative AI	Improved accuracy of models; faster training of models	Validated algorithms and trading strategies; realistic data for testing [41]; forward-looking risk management [41]	Quantum generative AI could benefit from more efficient machine learning models. This could allow financial institutions to validate algorithms and trading strategies better with realistic test data. This could lead to forward-looking risk management (preparing for risk based on synthetically generated future data) [41].
		Churn prediction		Improved customer retention	Advancements in quantum machine learning could impact churn prediction with more accurate and faster models. More accurate results would allow financial institutions to know how and when to apply their customer retention processes to keep the customer from churning.
		Identifying trading signals		Better trading strategies; better returns	Quantum could enable the financial industry to identify trading signals more accurately or faster thanks to advancements in quantum machine learning. This could result in better trading strategies or better returns.
4	Quantum Cryptography	Quantum decryption	Positive: improved security for transactions and data, negative: a threat for current encryption solutions	Positive: better customer experience; more secure transactions; increased trust in financial products; negative: financial losses, reputational damage, compromised data	Quantum cryptography could have an impact on the financial industry as well. From the positive aspect, quantum cryptography could enhance the financial institution's security and thus offer a better customer experience and more secure products. From the negative aspect, quantum decryption could break current encryption algorithms and result in reputational damage and compromised data.

Table 13. Overview of the Use Cases, Their Impact, and Value.

5.1 Limitations

There are limitations to this thesis that should be addressed. First, the small number of interview participants can be considered a limitation of this paper. The number of participants may not represent the opinions of a broader group of specialists correctly. To avoid this, the sample was selected as diverse as possible. For example, people with previous experience in different sectors, such as banking, physics, and data science, were selected. Also, from the point of quantum computing, the participants had different focuses. For example, there were quantum algorithm developers, quantum machine learning researchers, a professor, and an entrepreneur, to represent the views of different larger groups.

Another possible limitation is there was only one interviewer for all the interviewees, who might have misinterpreted the answers. While it is possible to avoid this, each research question had a set of sub-questions in the interview guide, which would enable finding the answer from multiple perspectives. Also, all the interviews were recorded and transcribed, which enabled the researcher to go back and relisten the interview in case of doubt.

There is also a possible limitation of interviewees not understanding the questions. The steps for avoiding this limitation were similar to the ones mentioned before. For example, the interview guide supported the interviewee in understanding the question by answering a set of similar supporting sub-questions. Also, the interviewees were encouraged to ask questions during the interviews to avoid any misunderstandings. Multiple interviewees confirmed with the researcher after answering the question that the question was adequate.

Also, only one data collection method, semi-structured interviews, was used in this thesis. However, the semi-structured interviews were considered the best data collection for the thesis, as the aim was to understand specialists' perceptions in more detail. Other methods, such as surveys, were considered, but it was decided not to use them, as interviews allowed for collecting more data, for example, asking further questions if needed.

The literature review revealed more than expected related work on the use cases of quantum computing in the financial industry. However, due to the rapid development of the technology and the fact that 2-3 years have passed since the publishing date of some of the available works, there is hope that new use cases have been found. Also, interviews revealed the uncertainty surrounding quantum computing, which again supports the hypothesis that not all use cases have been mentioned in the currently available literature.

Finally, as quantum computing is an emerging technology, it is evident that the participants could only talk broadly about the use cases of quantum computing in the financial industry without going into details. Understandably, the companies working on quantum technologies have restricting agreements (such as non-disclosure agreements) with their employees and partners. Thus, the company information is considered confidential and cannot be shared during such interviews.

5.2 Recommendations for Further Studies

During the process of writing the thesis, a couple of recommendations for further studies were noticed. First, as it was brought up in the limitations section, the current thesis only covers the ideas of a small number of interviewees. To explore the perception of the industry specialist further, a study with more participants could be insightful.

Some ideas for further studies were also shared during the interviews by the interviewees. For example, I–08 suggested conducting a study to compare the offered quantum computers to their equivalent data centers to understand whether there is a difference in energy consumption to validate the potential use case of decreasing energy consumption by using a quantum computer. The contradicting opinions of interviewees (I-01, I-07, I-08) give reason to study this topic further to understand whether the use case would have potential.

Participant I–02 suggested taking a look into the different possible advantages of quantum computing, for example, quantum economic advantage and quantum business advantage, to understand whether companies could benefit from quantum computing before reaching the real quantum advantage.

As concluded from the interviews, there is uncertainty around quantum computing use cases for the financial industry, and the current impediments make progress challenging. Thus, every kind of contribution in the area of quantum computing is welcomed.

6 Conclusion

This thesis aimed to understand the status of quantum computing in the financial industry, the potential use cases, use cases' impact and value, and current impediments which stop applying these use cases in the industry. The thesis had four research questions:

- **RQ1.** What are the potential use cases of quantum computing in the financial industry?
- **RQ2.** How can the potential use cases of quantum computing impact financial products and services?
- **RQ3.** What kind of value can quantum computing have on financial products and services?
- **RQ4.** Which obstacles impede implementing quantum computing use cases in the financial industry?

To find answers to the stated questions, semi-structured interviews with eight industry specialists were conducted, and one additional interview was conducted with ChatGPT. The interview transcripts were analyzed using the thematic analysis method, which enabled the finding of themes from the collected data. As a result, eight different themes were found. In regards to RQ1, a literature review was also conducted to understand currently explored use cases in the literature.

As a result of the interviews and the literature review, it was revealed that the main use cases of quantum computing in the financial sector could be sorted into three financial problem categories: simulation, optimization, and machine learning. From the simulation area, the main use cases are derivative pricing and risk management. Use case portfolio optimization can be seen as the main application in the optimization area. From the machine learning problems, fraud detection and credit scoring seem the most prominent. However, there were other use cases, also non-specific use cases for the financial industry, suggested. For instance, using quantum computing for ESG or decreasing energy consumption by using quantum computing instead of high-performance computers.

Quantum computing could possibly have an impact on the financial product and services. For example, being able to solve the calculations in less time, increasing the preciseness of the calculation results, having quicker machine learning models, and finding patterns better with machine learning. Additionally, quantum could help to reduce the energy spent on calculations.

The applications of quantum computing in finance could also result in value for the financial industry. The value is expected to be use case specific, like using quantum Monte Carlo methods for risk management could result in a stronger financial system. Other forms of potential value could be more accurate pricing, improved investment strategies, or increased returns.

The thesis summarized the current challenges of quantum computing in the financial industry. The problem most commonly named by the interviewees was quantum hardware. The currently available quantum hardware is in a noisy intermediate-scale era (NISQ), which means the hardware is error-prone, making it difficult (if not possible) to implement the use cases. However, hardware is not the only problem. There are also challenges with software, business constraints, and threats. The solutions shared by the interviewees include hardware improvements, collaboration, testing, having governmental support, and starting small.

This thesis contributes with an overviewing framework of the quantum computing use cases for the financial industry. This is expected to be important for the expected target group of this thesis: specialists working in the R&D departments of financial institutions who analyze the prospects of different emerging technologies.

There are multiple approaches how to develop this thesis further. For example, to understand the ideas of a broader group, a similar study with more participants could be performed. In addition, as the interviewees mentioned, there are topics of quantum computing in the financial industry that still need further research. The different approaches of quantum advantages, such as the quantum business advantage or quantum economic advantage. Or looking into the potential use case of decreasing energy consumption by using quantum computers instead of high-performance computers.

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Appendix

I. Interview Guide

Warm-up Questions

- Do you agree with recording this interview and using your answers as input for this thesis?
- Where do you work?
- What is your position?
- How long have you been working in this position?
- What is your relationship with quantum computing?

Research Questions Related Questions

RQ1. What are the potential use cases of quantum computing in the financial industry?

- What are the main use cases of quantum computing in the financial sector?
- Which characteristics of quantum computing enable these new possibilities?

RQ2. How can the potential use cases of quantum computing impact financial products and services?

- Which financial products and processes can use case X impact?
- What impact can the use case have on financial products and processes?

RQ3. What kind of value can quantum computing have on financial products and services?

- What kind of value can the use case bring to the financial institutions?
- How big do you expect the value to be for this use case?
- How likely will the use case be used in real life?
- What is needed to implement the use case in production?

RQ4. Which obstacles impede implementing quantum computing use cases in the financial industry?

- What impediments stop implementing use case X in the financial industry?
- What is needed to solve the mentioned impediments?
- What is the time frame for overcoming the obstacles and implementing the use case?

- When should financial institutions start to look at quantum computing?

Optional Questions

- Related work also mentions X as a use case for quantum computing in the financial sector. What is your opinion on it?

Concluding Questions

- When will quantum computing be used widely in the financial sector?
- Is there anything else you would like to mention that we have not talked about?

II. Schedule of Interviews

Interview	Date	Start Time	Duration (mm:ss)
I-01	23.02.2023	11:00	43:04
I-02	01.03.2023	17:00	48:58
I-03	03.03.2023	11:00	48:20
I-04	09.03.2023	17:00	23:11
I-05	10.03.2023	13:00	41:14
I-06	27.03.2023	16:30	52:27
I-07	29.03.2023	12:00	29:31
I-08	31.03.2023	12:30	21:17
ChatGPT	03.04.2023	16:00	-

Table 14. Schedule of Interviews.

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09/05/2023