



## **Quantum computing in finance: a pioneering technology or risk multiplier**

Jesse Reinikka

Haaga-Helia University of Applied Sciences

Haaga-Helia Bachelor's Degree

Bachelor's Thesis

2025

## Abstract

<b>Author(s)</b> Jesse Reinikka
<b>Degree</b> <b>Bachelor of Business Administration.</b>
<b>Report/Thesis Title</b> <b>Quantum computing in finance: a pioneering technology or risk multiplier</b>
<b>Number of pages and appendices</b> 28 + 5
<p>This thesis was motivated by the rapid evolution of quantum computing and its potential impact on financial markets. Its primary objective was to assess if quantum computing in finance would appear as a pioneering force driving innovation or function as a risk multiplier that exacerbates financial instability. Chapters 2 and 3 provide a technical foundation, detailing the distinctive features of quantum versus classical computing, current hardware developments, and key applications including optimization, stochastic modeling, machine learning, and security.</p> <p>A mixed-methods approach was employed, centered on a mixed studies review of ten publicly accessible, English language papers published within the last six years. Five keyword queries were run across Google Scholar, ScienceDirect, SpringerLink, and Web of Science. Records were filtered for open access, language, and direct relevance, then screened by title and abstract to yield fifteen candidates. A final full-text review reduced this to ten papers. Analysis identified core benefits such as near real-time risk assessment, enhanced optimization of NP-hard problems, and significant gains in predictive accuracy and critical challenges, including limited qubit counts, quantum noise, cybersecurity vulnerabilities, and regulatory gaps.</p> <p>The findings suggest that quantum computing holds transformative promise in finance through dramatic speedups and novel algorithms, yet considerable obstacles remain to practical implementation. Early adoption is deemed too risky given current hardware and regulatory constraints. However, as investments grow and the technology matures, many challenges are expected to diminish. Future research should focus on empirical validation with emerging quantum hardware, development of robust error-mitigation techniques, and creation of standardized regulatory frameworks to guide the safe integration of quantum technologies into financial practice.</p>
<b>Keywords</b> Quantum computing, financial risk, optimization, predictive analytics, scalability, regulation.

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# 1 Introduction

Financial markets today are characterized by increasing uncertainty and rapid technological change. In this dynamic landscape, institutions continuously search for innovative tools to gain a competitive edge while managing growing risks. Quantum computing is a field that leverages the abnormalities of quantum mechanics. It has emerged as a promising technology with the potential to radically change the way financial computations are performed. However, now that the tool for potential change has been found, the next question is will this technology push finance into a new era of innovation, or will it instead multiply the inherent risks already present in the market.

## 1.1 Objective and background of the thesis

The primary objective of this thesis is to explore whether quantum computing in finance will emerge as a pioneering technology to drive unprecedented innovation, or if it will function as a risk multiplier that further compounds financial instability. This study builds on a foundation of rapidly evolving research and growing interest from both academic and industry circles, as outlined in the subsequent chapters. Drawing on a broad array of literature from the fundamentals of quantum computing to its specific applications in optimization, stochastic modeling, and machine learning, this thesis seeks to provide a nuanced understanding of quantum technology's potential and pitfalls within financial contexts. Over recent years, significant investments have been made in quantum technology, sparking vigorous debate among experts about the transformative potential of these systems. While some argue that quantum computing could enable near real-time risk assessment, efficient portfolio management, and advanced predictive analytics, others warn of scalability challenges, hardware limitations, and cybersecurity concerns. These opposing perspectives form the core of this thesis.

## 1.2 Scope and limitations

The scope of the research encompasses both qualitative and quantitative analyses, synthesizing insights from academic literature and empirical studies to assess the potential of quantum computing as well as its current challenges. Key areas of investigation include the unique computational capabilities of quantum systems compared to classical methods, the promising advances in optimization, stochastic modeling, and machine learning, and the practical limitations such as hardware constraints and regulatory uncertainties.

However, there are limitations in this study. The rapid evolution of quantum technologies means that the findings, largely based on theoretical models and early empirical data, might soon require

re-evaluation with new developments. Additionally, while the study offers a comprehensive synthesis of existing research, direct empirical validation remains constrained by the current state of hardware and the preliminary nature of practical quantum applications in finance. A further limitation is that this thesis primarily focuses on the most promising benefits and the most significant risks, which necessarily leaves many gaps in the study such as niche use cases, less-explored technical challenges, and emerging regulatory considerations. These limitations stress the need for cautious interpretation of the results and point toward further research to bridge the gap between theoretical potential and real-world implementation.

## **2 Applicability of quantum computing to finance**

### **2.1 What is quantum computing**

The general problem with quantum computing is that most people don't even understand what it is. Knowing the first part of the term quantum computing helps with understanding the concept of quantum computing. In the context of quantum computing the word quantum refers to the way a quantum computer performs calculations. Today's regular computers use electronic signals and binary bits to compute, where 0 (off) and 1 (on) are used. While quantum computers make use of subatomic particles, like electrons or photons, and qubits for calculations (Investopedia April 2024). Because qubits operate uniquely from classical bits quantum computers can approach the problem in a distinct way compared to classical computers (Schneider & Smalley August 2024).

Quantum computing itself is a field of computer science that exploits the unique properties of quantum mechanics to solve problems that are far beyond the reach of today's classical computers (Schneider & Smalley August 2024). The field of quantum computing involves a wide range of disciplines consisting of computer science, physics and mathematics (Amazon Web Services s. a.). While the word quantum itself has become vaguely used in marketing various products such as detergents and food items without any scientific basis (VTT 11 February 2020). The excitement around quantum computing comes from the potential to significantly speedup problem solving capabilities and solve problems that were previously unsolvable (Schneider & Smalley August 2024).

### **2.2 How quantum computing differs from classical computing**

In classical computing, a computer uses bits. Each bit contains information about whether it is 0 meaning off or 1 meaning on. When a regular computer is given a large amount of data the computer starts to process this data in the form of 1s and 0s. And if the information stays the same the result will always stay the same and give a single answer. The constraint of bits and therefore classical computers comes with complex calculations involving multiple variable changes (Ménard, Ostojic, Patel & Volz February 2020). "Each Calculation is a single path to a single result" (Ménard et al. February 2020). This method of single path to single result computing becomes very efficient when millions of these bits are placed side by side in modern devices. The biggest problem with classical computing is multipath calculations and quantum computers are being explored as a solution to this problem.

Quantum computers use qubits, which can exist in multiple different states. A qubit can exist in an unlimited range of states. Meaning a qubit can be a 1, 0, or in any state in between, a condition

known as superposition (Ménard et al. February 2020). Quantum computers can break the classical computing model of single path by using superposition because the path can branch out. Since quantum computers can calculate multiple different paths simultaneously in the same computation, their speed increases exponentially. This type of computing provides multiple different answers within the desired range, allowing the correct answer to be reached faster and more efficiently. (Ménard et al. February 2020.)

### **2.3 Hardware**

Limited hardware capabilities remain one of the most common issues when turning quantum financial theory into practice. Since the connection between quantum theory and quantum computing was discovered in the 1980s, the field has evolved rapidly (Highfield 15 June 2018). To describe this new era we are now in, John Preskill coined the term Noisy intermediate scale quantum or short NISQ. This term was made to describe the new era of quantum technology that started in 2017-2018.

NISQ era quantum computers have passed the 50-qubit barrier, and this is significant because it means we have overcome already existing supercomputers (Preskill 2018, 4–5). Recent advancements have pushed the qubit barrier further with Atom Computing announcing a record breaking 1180 qubit system exceeding the 1000-qubit barrier (Berenice October 2023). The field of quantum computing has advanced so fast that both IBM and Google have adjusted their quantum roadmaps. IBM's roadmap aims for 100 000-qubit Blue Jay system by 2033+ and Google's long-term goal is 1 million qubits (IBM s.a. a; Google s.a.).

While the qubit limit rises so do the problems. This leads us to the second biggest problem with quantum computing, qubit quality. Qubit quality refers to the control and accuracy of the qubits (Preskill 2018, 5). Trying to isolate quantum computers from outside noise to make them more accurate while making the qubits interact with each other for useful information is a gigantic task to undertake (Preskill 2018, 4). Because NISQ era quantum computers are prone to decoherence and errors, most quantum computer building strategies focus on achieving longer coherence times and error correction. For example, Google's milestone 3 is to build a long-lived logical qubit that can execute one million computational tasks with fewer than one error (Google s.a.). Advancements are accelerating and a fully fault tolerant quantum computer is believed to be possible by 2035-2040 or later (Mckinsey & Company March 2025). This would only accelerate quantum supremacy in financial use.

## **2.4 Suitability for financing**

Quantum computing is used in various scientific fields, such as advancing medicine, inventing new materials, optimizing and securing data processing. One of these areas is financial development. Since finance relies on formulas and calculations, quantum computing is perfectly suited for financial purposes (Egger et al. 2020, 1–2). While traditional computing methods are beginning to encounter significant computational challenges in asset management, investments, and retail and corporate banking. Quantum computing promises revolutionary solutions to problems that conventional computing methods are currently unable to solve.

## **2.5 Target group and beneficiaries of quantum computing**

According to Qureca, around 42 billion dollars were invested in quantum computing in 2024, aimed at advancing quantum technology. In 2023, this figure was 38.6 billion dollars. Let's take Finland's investments in quantum computing as an example. In 2023, the Finnish government granted 20.7 million euros to VTT and IQM for the construction of a new quantum computer. Business Finland added 3.3 million euros to this sum. These figures increased in 2024 to a total of 37 million euros, up from 24 million euros. The largest investors in quantum computing are the countries themselves, but significant investments have also been made by the private sector. The private sector invested 2.2 billion dollars in 2022, but this amount dropped to 1.2 billion dollars in 2023. (Qureca April 2025.) The benefits of quantum computing will be seen widely around the world, rather than by individual people, mainly due to the massive costs associated with quantum technology. However, investments in this new technology are expected to grow because of its vast potential.

### 3 Quantum computing as a market revolutionist

In section 2.4, we discussed the applicability of quantum computing in finance. This chapter delves deeper into these methods and reviews their various methodologies. These applications are distinguished from each other, but in practice, they tend to blend more. The applications of quantum computing can be roughly divided into three categories: optimization, modeling/simulation, and machine learning.

#### 3.1 Optimization

Optimization is always important when trying to achieve as much as possible with as little as possible, especially in operations aimed at generating profit. Optimization is utilized in every area of finance, and it can always be improved. Optimization presents the most promising commercial potential when using NISQ (Noisy Intermediate-Scale Quantum) hardware (Herman et al, 2022, 20). There are numerous optimization problems, but the key areas that are being targeted for improvement with quantum computers are pricing, portfolio management, risk, logistics, arbitrage, credit ratings, and predicting financial crises.

Today's computers are fine at financial optimization, however when classical algorithms encounter combinatorial and convex problems, they can't guarantee optimal solutions or can't be scalable because they take a long time to compute such as integer programming or QUBO problems (Herman et al, 2022, 20-24). They start to use algorithms that rely on approximation which are unoptimized. Quantum computing is trying to solve these specific problems that are often called NP-hard by speeding them up. The NP-hard problems are computational problems that are yes or no questions (Wikipedia 2024a). Famous NP-hard problem is traveling salesman problem where salesman needs to visit number of cities with limited amount of gasoline. Depending on the number of cities and gasoline this problem might take an infinite amount of time to answer yes or no because there is an infinite number of routes to take. (Wikipedia 2024b.) It has been proposed to tackle these combinatorial optimization problems, which are often NP-hard problems. Quantum annealing, quantum approximate optimization algorithm and variational quantum Eigensolver could be used. (Herman et al, 2022, 21-23.) Quantum annealing works on NP-hard problems like the traveling salesman problem by simulating different states and calculating which has the lowest energy (Dilmegani 1 November 2024). Lowest energy here means the optimal solution.

The second way to solve these problems is the quantum portfolio optimization algorithm. This algorithm works by reducing the problem to a second-order conic programming problem. A second-order conic programming problem or in short SOCP works by minimizing or maximizing your objective while satisfying certain constraints. This objective could be minimizing risks when choosing

stocks or maximizing profits. One special constraint the program can use is called the second order cone. This cone shape represents the relationship between variables and defines the region where the solution can exist. When the objective and constraints are chosen the program starts placing possible answers inside this cone and chooses the optimal solution to the problem while satisfying all the constraints. (Kerenidis, Prakash & Szilágyi 22 August 2019, 2–3.)

In the work Quantum Algorithms for Portfolio Optimization, they used the SOCP method and experimented with it. They used historical stock data from S&P 500 companies for each day over a period of 9 years (2007-2016). The algorithm provided a significant speedup for solving combinatorial problems related to portfolio optimization and showed theoretical efficiency in large-scale problems where the algorithm could maintain efficiency as the problem size increased. (Kerenidis, Prakash & Szilágyi 22 August 2019, 6–8.)

Future perspectives consist in solving real-life portfolio optimization problems, with higher market size, as soon as quantum devices with appropriate characteristics will be available (Buonaiuto, Gargiulo, Pietro, Esposito & Pota 2023, 12). Although these demonstrations are promising quantum algorithms show too many challenges for practical use, given the limitations of modern NISQ quantum computers. However, when such a computer becomes practical financial optimization will be one of the first areas of finance to benefit from it.

## **3.2 Stochastic modeling**

Stochastic modeling, or the dependence of random variables, refers to a phenomenon where the values of two random variables are either partially or entirely proportional to or otherwise dependent on each other. Stochastic modeling predicts outcomes under different conditions, and this information can be used when considering future plans. There are several types of stochastic modeling, but currently, one of the most important is the Monte Carlo model.

### **3.2.1 Monte Carlo**

In finance Monte Carlo method works by simulating the market movements and averaging the results over many random samples (Herman et al, 2022, 12). It's used because they are too hard to solve using analytical or numerical methods. Monte Carlo method could simulate stock price movements or value at risk where the simulation estimates the amount of value portfolio could lose in certain time frame. Currently the most common use of Monte Carlo Integration in finance is pricing financial instruments and predicting risks. The Monte Carlo simulation is a popular model because, unlike traditional stochastic modeling, the Monte Carlo simulation can predict various outcomes that include random variables. Usually getting accurate and useful results using the monte Carlo simulations means generating millions or billions of potential market trajectories and computing the

results. Generating this much complex data can take an impractical amount of time or be low in their accuracy. (Bouland, Dam, Joorati, Kerenidis & Prakash 2020, 6–8.) This is where the potential of quantum computing might shine.

Much like optimization, quantum computing promises speedups to the methods and algorithms when compared to classical computing. According to Herman et al. (2022, 12–13), efficiency in quantum algorithms has been increased by using quantum Monte Carlo integration. This has been done by using normal Monte Carlo integration and using quantum amplitude estimation together. QMCI can reduce errors at a faster rate, reducing the resources needed to achieve the same accuracy. These quantum algorithms could be used to solve real world problems like pricing derivatives and accelerating risk predictions. (Herman et al. 2022, 12–13.)

However, while these speedups sound great currently quantum computing is still stuck on theoretical models that suggest significant speedups and practical evidence and experiments are rare. Egger et al. (2019, 4–5) analyzed quantum algorithm to estimate credit risk. The tests were done on small scale due to hardware limitations and were easily simulated on classical computers. But the results showed potential improvement from a runtime of 30 minutes to near real-time when calculating one million assets. (Egger et al. 2019, 4–5.) Just imagining real-time results on massive amounts of financial data paints a pretty good picture why quantum computing is so heavily invested. But realistically right now quantum computers simply have too much noise and errors to get useful information using these methods. Much like optimization, stochastic modeling and methods such as quantum Monte Carlo could allow revolutionizing tech like real-time pricing and risk analysis, but it is too early for these methods and algorithms to become useful at scale.

### **3.3 Machine learning**

#### **3.3.1 Big data**

Making financial decisions is hard especially if you can't base it on accurate data and must guess the correct choice. The inverse is also true, and too much data becomes an even bigger problem when the data is hard to process or can't even be used because of hardware and software limits. This kind of data is called big data. Segal (15 August 2024) explains big data simply as a "Large, diverse sets of information that grow at ever-increasing rates".

#### **3.3.2 Quantum machine learning techniques**

Right now, in classical computing the use of big data and machine learning are cornerstones of any company that wants to revolutionize their finances. The ability to detect everything from trends to overall economic shifts is massive help when providing insight to investors or developing better

marketing and trading strategies. But getting effective use of big data means using machine learning.

The concept of machine learning is quite simple. Using high-performance computers to analyze massive datasets to uncover and learn patterns in the data. Big data can be structured or unstructured. Structured data is highly organized and easy to decipher. Unstructured data is basically the opposite of structured data, it can be social media posts, emails, images, books or phone data meaning it's very hard to organize and decipher into one coherent text. (Jonker & Gomstyn February 2025.)

Traditional machine learning has been used very effectively by companies like Facebook, however getting this data uses considerable computational resources, expertise and refinement. And like anything else data related classical computing has been put to its limits by the sheer scale of data volumes. With big data and machine learning there also comes responsibility to manage the data safely and ethically. Classical computing has shown dangers of this technology, and this sentiment will carry over to quantum computing.

According to Pistoia et al. (September 2021, 1–2), because quantum computing algorithms are so complex and the size of data so large. Machine learning has been identified as one of the best applications of quantum computing (Pistoia et al. September 2021, 1–2). The promises machine learning depicts are indeed quite grand. Machine learning already plays a significant role in credit scoring, asset pricing, complex strategies, financial forecasting, fraud detection, stock selection and risk assessment. Now quantum computing is advancing these already useful financial tools to become more influential. There are numerous methods to unlock these benefits, but right now regression, classification, clustering, generative models and reinforcement learning are most promising (Herman et al. 2022, 28–34).

Beers (July 2024) describes regression like this, “Regression is a statistical method that's used in finance, investing, and other disciplines to attempt to determine the strength and character of the relationship between a dependent variable and one or more independent variables”. Regression involves creating models to predict continuous values based on historical data. Classically regression requires solving complex linear equations, but this can become computationally intense with large datasets. There can be exponential speedups made here with the use of quantum computing. Algorithms like the HHL algorithm use quantum states to represent data and this theoretically solves these equations exponentially faster. This method is hindered by hardware issues because it needs quantum RAM to fully use it. (Orús, Muga & Lizaso 2019, 4–5.) These methods could bring faster and more accurate forecasting, but they are still too experimental and need better hardware.

Clustering and classification are similar but have distinct differences. Belcic (October 2024) classifies classification as, “A classification model is a type of machine learning model that sorts data points into predefined groups called classes”. Clustering is classified as “Clustering is an unsupervised machine learning algorithm that organizes and classifies different objects, data points, or observations into groups or clusters based on similarities or patterns” (IBM February 2024). The key difference here is that classification involves predefined categories and clustering groups works without predefined categories making it more natural (Simplilearn 2 July 2024).

Classification works by learning labels through datasets and based on that dataset it is trying to predict the label of new data. Most common classification methods are linear classification, distance-based classifiers, support vector machines and variational quantum classifiers (Simplilearn 2 July 2024). Once again what quantum versions of these methods are trying to do is make them faster and more accurate when dealing with large and complex datasets. In finance these techniques could be useful in binary options prediction, forecasting and credit scoring.

Clustering works the same way as classification but aims differently. Clustering tries to find similarities or proximity within datasets. Quantum clustering and quantum k-means and q-means could be used here for faster and better accuracy (Simplilearn 2 July 2024). Quantum clustering benefits fraud detection, stock selection, exchange rate regimes and hedge fund clustering. Both methods hold promises in actual use, but quantum practical applications need further advancements in hardware and algorithms.

Holdsworth and Scapicchio (June 2024) describe deep learning as, “Deep learning is a subset of machine learning that uses multilayered neural networks, called deep neural networks, to simulate the complex decision-making power of the human brain”. Deep learning is mostly unsupervised learning that uses large raw datasets and this supports automation. There are multiple neural networks used in deep learning with different strengths and weaknesses ranging from prediction making to adjusting errors for better accuracy. (Holdsworth & Scapicchio June 2024.)

One of these models is called Boltzmann machines that forms a generative model from recurrent neural networks. This model is interesting in the quantum deep learning world because it has shown results. Wiebe, Kapoor and Svore (December 2014, 8) say “We show that the quantum algorithms not only lead to significantly improved models of the data, but also provide a more elegant framework in which to think about training BMs”. This kind of development is important because deep generative models’ job is to learn patterns and distributions in data and try to create new data based on that or if it’s discriminative model it tries to do the opposite by finding differences. For example, you could give a generative model pictures of animals or buildings and it could create new ones based on your training data. Discriminative models could find the differences in buildings for

example and separate them. (Google February 2025.) If you can differentiate data or generate more data, it means greater accuracy and efficiency in data use. While classical deep learning faces limitations here. Quantum is trying to transform it into a powerful tool to wield in the financial sector and beyond.

Reinforcement learning is interesting because it works like a human through trial and error. In reinforcement learning the machine makes decisions and acts as an autonomous agent responding accordingly to its environment. Reinforcement learning usually has a goal set by humans and the autonomous agent does anything it needs to achieve that goal. (Murel & Kavlakoglu March 2024.) It could be said that reinforcement learning machines are much more effective humans when it comes to data analysis. Quantum reinforcement learning uses agents that take advantage of amplitude-amplification to focus on high reward action sequences. Effectively making lucky choices faster than classical agents in luck-favoring environments. (Pistoia et al. 9 September 2021, 7.) Quantum computers have the potential to make these machines faster and more accurate, giving the user a more powerful tool when making trading or marketing decisions.

Although quantum computing's potential for machine learning in finance can't be overlooked, especially for tasks demanding exceptional amounts of computing power like clustering, regression, deep learning and reinforcement learning. It has even more requirements and limits that need to be overcome for it to become plausible and effective in practical use.

### 3.4 Encryption and security

People have always valued their security, but in this digital world we live in now people require more security out of their devices. Be it sensitive images, bank information, text messages, data or otherwise sensitive information you don't want people to have access to. There are even many laws regarding cybersecurity and that's why encryption has become an everyday phenomenon. "Encryption is the process of transforming readable plaintext into unreadable ciphertext to mask sensitive information from unauthorized users" (IBM s.a. b). Any text or numbers can be turned to ciphertext if one wants it. The simplest encryption method is the Caesar cipher where a letter of the alphabet is set number of places forward or backwards in the alphabet. For example, the letter a is b, c is d and so on. When the time comes to decipher this encrypted text, you only need to know what letter represents each other. All this is done so only authorized users can access the data.

Most modern encryptions like advanced encryption standard are virtually unbreakable through brute force. This is made possible through the sheer number of key combinations needed for the right key to be made. Brute force attacks that would take an infinite amount of time to crack on normal computers could take only minutes on a working quantum computer.

Table 1. Encryption levels (adapted from Barker January 2016, 53–54)

Security level	Algorithms	Security strength (key length)
1	AES-128, 2TDEA	Weak ( $\leq 80$ )
2	SHA-224/SHA3-224, 3TDEA	Strong (112)
3	SHA-256/SHA-256, AES-128	Stronger (128)
4	AES-192, SHA-384/SHA3-384	Very strong (192)
5	AES-256	Strongest (256)

However as shown in the above Table 1 maximum security encryption like AES256 would be acceptable to 2031 and beyond based on the NIST Special Publication (Barker January 2016, 53–54).

It will remain to be seen how secure these truly are but based on U.S national policy information on secret and top-secret level use AES algorithms would be sufficient when used with 192 or 256 key lengths (Smid August 2021).

Especially on security issue quantum computing could be likened to a nuclear option. If only one entity develops a fully working quantum computer, it would shift the balance of power in digital security and undermine widely used cryptographic systems. This is why some call it apocalypse. To diminish the likelihood of this kind of scenario readiness in post quantum cryptographic world solutions need to be made to ensure a secure future, especially in finance.

## 4 Methodology

The aim of this study is to examine whether quantum computing in finance will rise as a pioneering technology aiming to drive innovation or pose greater risks amplifying financial instability. Researching such innovative technology presented data procurement challenge. This chapter outlines how this challenge was overcome, explaining the research approach, data collection methods and analysis techniques used.

### 4.1 Research approach

Research approaches are generally categorized into quantitative and qualitative methods. “Quantitative research examines relationships between variables, which are measured numerically and analysed using a range of statistical and graphical techniques” (Saunders, Lewis & Thornhill 2016, 166). On the other hand, “Qualitative research studies participants’ meanings and the relationships between them, using a variety of data collection techniques and analytical procedures, to develop a conceptual framework and theoretical contribution” (Saunders et al. 2016, 168).

Because this research consists of both qualitative and quantitative data, a mixed-methods approach was selected. This research is primarily qualitative, aiming to explore the potential of quantum computing in finance through expert opinions, industry trends, and theoretical discussions. However quantitative elements are incorporated selectively. These numerical insights are drawn from existing research and models, to support and strengthen the findings rather than act as the main basis of analysis. Combining allows for a more comprehensive understanding of the subject.

Conducting independent research on emerging technologies, such as quantum computing in finance, presents significant challenges due to the complexity and rapid evolution of the field. To combat this issue a literature review methodology with a keyword-based data collection approach was used. Literature review works by using multiple information sources and analyzing the combined data to synthesize more cohesive answers. Doing a literary review based on multiple sources is easier and achieves the goal of this thesis while satisfying all the criteria. “A review of prior, relevant literature is an essential feature of any academic project. An effective review creates a firm foundation for advancing knowledge” (Webster & Watson 2002, 13).

After selecting a mixed-methods approach, a mixed studies review was chosen to be the most suitable literature review method out of the 14 methods analyzed by Grant and Booth. The mixed studies review was selected because it allows for the combination of different methodological approaches. “Such studies attempt to bring the ‘what works’ of the former together with the ‘how and

why does it work' of the latter to start to address the more complex issue of 'what works under which circumstances'" (Grant & Booth 2009, 98).

## 4.2 Data collection methods

Ten publicly available research papers were selected through Google Scholar, ScienceDirect, SpringerLink, and Web of Science, ensuring that all materials were freely accessible. The selection process was based on relevance to the research topic, focusing on the intersection of quantum computing in finance and financial risk management.

Criteria for the selected studies

- Publicly accessible meaning free to view and download.
- Most of the data should be published in the last one to five years.
- Directly related to quantum computing applications in finance
- Studies should be published by reputable organizations or individuals, research institutions, or industry leaders. However, some papers were not peer-reviewed.
- Contained relevant insights into the research question through empirical data, theoretical models, or case studies.

With these criteria in mind, recruitment of sources could begin. Since this study relied on existing literature, no direct participants were recruited. Instead, the research papers served as the primary data source. These papers were selected systematically using keyword-based search techniques. The search terms included "quantum computing in finance," "quantum finance risk," "quantum finance bigger crashes," "quantum computing risk measurement," "quantum computing forecasting" and multiple related variations. These terms were run across four databases Google Scholar, ScienceDirect, SpringerLink, and Web of Science.

Following the above criteria the data study could be illustrated in five steps shown below (Figure 1). The actual number of papers for each step one through three can be seen through Excel screenshots in the appendix section (Appendix 1–4).

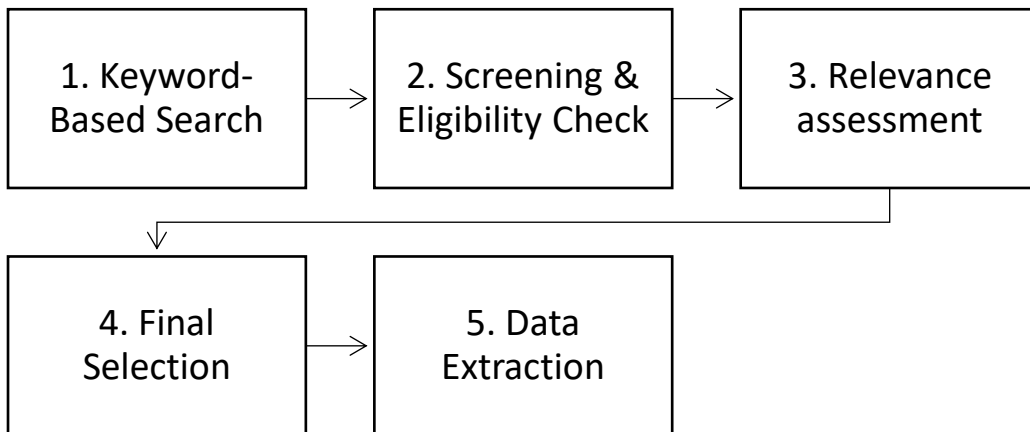


Figure 1. Illustration of data study process

Following relevance assessment, 15 papers remained (Appendix 4). These were then subjected to a final full-text review resulting in a final selection of 10 papers for the mixed studies review (Appendix 5).

### 4.3 Data Analysis Techniques

The analysis of collected data was conducted using a mixed-methods approach, integrating both qualitative and quantitative techniques. First, a thematic analysis was performed on the selected literature to identify recurring themes, key insights, and debates. By comparing these themes across multiple sources, the review synthesizes a coherent narrative on whether quantum computing in finance is more likely to pioneer innovation or amplify risks.

For the quantitative elements, numerical data and performance benchmarks from empirical studies were extracted and analyzed. This included, for example, the assessment of computational runtimes, qubit requirements, and accuracy metrics in risk measurement models. These figures were used to support and contextualize the qualitative findings, providing supportive perspective on the current state and potential future of quantum technologies in finance. Together, these data analysis techniques allowed for a comprehensive evaluation of the literature, ensuring that both the what works and the how and why it works aspects were adequately addressed.

## 5 Mixed studies review

Chapter 3 dived into the basics of what and where we are with quantum computing in finance. It will be used as a baseline for this study and this chapter will dwell deeper into the research question.

Recent developments in quantum computing for finance show rapidly evolving field with growing institutional and academic interest. This growing engagement is attracting researchers in computer science, physics, and other disciplines (Naik, Yeniaras, Hellstern, Prasad & Vishwakarma 2023, 2). This growing engagement from various fields comes from the disruptive potential quantum technologies are expected to bring (Orús, Muga & Lizaso 2019, 1). Herman et al. (2022, 38) also share this sentiment expecting quantum computers to surpass the processing power of traditional computers and bring about significant changes across various industries.

Herman et al. (2022, 2) observe that financial institutions are exploring quantum computing to process large-scale datasets more quickly and accurately than classical systems allow. Similarly, Wilkens and Moorhouse (2023, 2) point out that quantum technologies have seen exponential growth in research and investment, focusing on potential applications in trading and risk management. This trend shows a broader shift in the financial sector where quantum computing's potential to enhance the field is seen especially in financial analytics and decision-making.

However, while quantum computers offer benefits in potential speed ups and efficiency in handling complex data, Herman et al. (2022, 39) caution that "However, the computational complexity of a problem per se is not a guarantee that quantum computing can make a difference". This highlights that the practical impact of quantum computing depends heavily on its specific application.

So far, the community is focusing on quantum algorithms, stochastic modeling, quantum machine learning, hybrid computing solutions and real-world applications. Yet even specific financial applications face challenges, often constrained by both hardware and software limitations. Wilkens and Moorhouse (2023, 1) pointing out that even with significant progress in both hardware and software advancements quantum systems are limited by their qubit count. Beyond hardware issues like noise and qubit quality, software issues persist in the field. One critical issue is the low accuracy of modeling, which requires further research, as current models remain imprecise and have only been scaled to the largest economies (Alaminos, Belén Salas & Fernández-Gámez 2022, 2).

Quantum computing offers numerous advantages that could revolutionize financial services. Many researchers emphasize that quantum computers promise dramatic speed improvements over classical systems, enabling faster optimization, more efficient portfolio management, and accelerated

Monte Carlo simulations for derivative pricing and risk assessment. For example, one study tested how quantum algorithms for credit risk analysis would perform when applied to real world financial problems like portfolio optimization and Monte Carlo simulations. They calculated that for a portfolio with about one million assets, their quantum algorithm would take approximately 30 minutes to estimate the Value at Risk. This time could potentially be reduced to be performed in near real-time when classical simulation techniques are applied on top. (Egger, Gutiérrez, Mestre & Woerner 5 July 2019, 5.)

In addition to older algorithms like Shor's and Grover's, new quantum algorithms are being developed to further aid quantum computers benefits. While the scale of actual quantum computers is relatively limited, we can now see as a new generation of quantum algorithms that require very limited resources and are robust against errors. These new algorithms show potential even with current hardware limitations by using hybrid quantum classical approaches, such as those utilizing VQE and QAOA. (Bruno 2022, 5–9.) For example, Aboussalah, Chi and Lee's (2023, 1) real-world tests were able to reduce systemic risk by developing two-stage quantum algorithm that is more robust against financial shocks. Although currently, the field of quantum software development is still in its early stages there has been significant acceleration in the creation of quantum software tools since 2017, with numerous packages coming from various platforms including D-Wave, Google, IBM, Microsoft, and Xanadu (Bruno 2022, 9).

Substantial efforts are also made in quantum machine learning space. For finance these efforts would yield results in fraud detection, credit scoring and predictive analytics. While Classical machine learning methods encounter problems when they are challenged with intricate schemes (Naik et al. 2023, 21). Quantum machine learning could help with this Naik et al. (2023, 21) noting "For example, quantum computing allows the analysis of diverse data sources, including transaction records, social media, and public information, to identify anomalies indicative of fraudulent activity". This capability could transform cybersecurity, risk management and portfolio optimization by providing real-time insights and advanced encryption techniques (Naik et al. 2023, 23).

Strategically, the potential economic benefits are equally compelling. For instance, Herman et al. (2022, 2) observe that financial firms are turning to quantum computing to handle ever growing data volumes more quickly and accurately than classical systems can, expecting these capabilities to drive significant strategic and economic gains. However, Wilkens and Moorhouse (2023, 32–24) conclude that, although quantum risk measurement is technically feasible, today's limited qubit counts and high noise levels leave the business case weak, because classical systems already meet industry needs efficiently. These insights suggest that quantum computing is viewed not only

as a technical upgrade but also as a strategic tool to gain a competitive edge in the finance field. However, its position hinges heavily on overcoming current hardware limitations.

Quantum approaches have also shown promising results in predictive analytics and risk assessment. Traditional risk measurement methods rely on classical models that provide a 90 % quantile of potential future exposure of about 82 at one year and 134 at two years. In contrast, quantum methods using 3 qubits per risk factor produce estimates of 75 at one year and 127 at two years with errors of roughly 9 % and 5 %. With only 2 qubits, however, the error can soar to as high as 72 %. (Wilkins & Moorhouse 2023, 29–32.) These results indicate that, when properly scaled, quantum computing can offer significant accuracy improvements in risk assessment over traditional methods, however hardware limitations remain in the way of proper scaling. To transform theoretical possibilities into a practical tool for financial risk assessment and prediction purposes, significant improvements in accuracy are essential.

Despite the promising advances in quantum computing, significant challenges remain that could multiply risks in the financial sector. One major technological hurdle is scalability. Most authors caution that current quantum systems are constrained by the limited number of qubits available. For example, Wilkins and Moorhouse (2023, 1) point out that “Despite promising advances and extensive research in hard- and software developments, currently available quantum systems are still largely limited in their capability”. This means that hardware operating at around  $10^2$  qubits must scale dramatically for effective large-scale applications, a limitation further discussed in Chapter 2. For the model side Alaminos et al. (2022, 1–2) are also calling for more investigation, noting that model accuracy remains low and has only been applied to the largest economies.

Going deeper into the literature shows that the current generation of quantum annealers faces issues with both the number of physical qubits and their connectivity. Ding et al. (2023, 1–2) explain that the D-Wave 2000Q’s Chimera layout is limited by the number of physical qubits and connectivity, posing significant challenges for scaling to real-world financial problems. Bruno (2022, 3) reinforces this by emphasizing that quantum algorithms cannot be fully realized on an actual scale of less than 1,000 qubits due to inherent instability issues.

Cybersecurity also presents a major concern. Naik et al. (2023, 3) highlight major shortcomings in quantum safe encryption methods and key management protocols in quantum systems, which could leave financial infrastructures exposed to future quantum-based attacks. This lack of robust security measures could potentially expose financial institutions to quantum attacks, thereby magnifying risks.

Similarly, some authors caution that premature adoption of quantum solutions could inadvertently introduce new systemic risks. Ding et al. (2023, 1–6) warn that solving the crash-prediction problem by mapping it to QUBO and running it on today’s quantum annealers is not yet practical, stressing it remains an NP-hard challenge given current hardware limitations. However, they do present this mapping as valuable proof of concept demonstrating how quantum computation could eventually predict financial crashes (Ding et al. 2023, 1–6). In addition, Wilkens and Moorhouse (2023, 1) argue that, because established classical simulation methods already deliver risk estimates quickly and accurately, there is little compelling business case for adopting quantum-based solutions currently. Additionally, Under the third Basel accord financial institutions must compute metrics like Value-at-Risk and Conditional Value-at-Risk (Herman et al. 2022, 2). A requirement that is inherently computationally intensive on classical infrastructures so any quantum solution must integrate seamlessly with existing regulations which raises additional concerns. One study also warns that “Just as the atom bomb, technological innovations such as quantum computers, have also destructive effect over the countries in the same way” (Arslan, Ulker, Akleylek & Sagi-roglu 2023, 6).

To conclude, the experts in the field of quantum computing for finance have outlined various approaches and frameworks that not only highlight the technology's potential to drive innovation but also identify the challenges that could multiply risks. Furthermore, the key findings from this review suggest the next steps that should be explored in the future.

## 6 Conclusion and discussion

This study set out to answer the question, will quantum computing in finance emerge as a pioneering technology that drives innovation, or will it instead act as a risk multiplier, amplifying financial instability. The mixed studies review has shown that quantum computing possesses remarkable potential demonstrated by its ability to drastically reduce computational times, optimize complex financial algorithms, and improve predictive analytics. However, the research also consistently highlights critical challenges that need to be addressed before these theoretical advantages can be fully translated into practical applications.

The answers to the research question are nuanced. On one hand, quantum computing offers impressive breakthroughs, such as speed ups in computations that can achieve near real-time risk assessment and enhanced optimization capabilities that can tackle NP-hard problems. On the other hand, the current limitations in scalability, qubit quality, quantum noise, and the absence of robust regulatory frameworks clearly show that the technology's full promise is still largely out of reach. These issues are a significant barrier to widespread implementation in the financial sector.

The implications of these results do give serious consideration. First, while quantum computing appears capable of revolutionizing key financial operations like portfolio optimization, predictive analytics, and risk management. Its practical deployment will depend on substantial enhancements in hardware capability and algorithmic efficiency. This transformation could reshape market dynamics by offering competitive advantages to early adopters. However, it also poses risks, as premature or uneven implementation might worsen systemic vulnerabilities if not managed carefully.

Several limitations of this study must be acknowledged. The research relies predominantly on a mixed studies review of theoretical and simulation-based findings, which, while insightful, are not yet backed by extensive empirical data from fully operational quantum computers. Additionally, given the rapid pace of advancements in quantum technology, some findings may soon become outdated or require re-evaluation in the light of new developments. There are also limitations and possible gaps in the research due to time constraints, and how the papers were chosen.

Based on these observations, future research should focus on three key areas. First, empirical studies that test quantum computing applications on actual hardware as it becomes more available are essential. Second, further exploration into hybrid quantum–classical approaches and error correction techniques is needed to improve algorithmic accuracy and scalability. Finally, comprehensive research into regulatory and ethical frameworks is necessary to manage the disruptive potential of quantum computing in the financial sector and to ensure an equitable transition as the technology matures.

In my view, quantum computing in finance is a truly transformative technology with the potential to redefine financial operations. However, widespread early adoption at this stage is too risky due to technical, regulatory, and systemic challenges. As investments increase and technology matures, leading to reduced costs and more robust frameworks, many of the current challenges and systemic risks are likely to diminish. In fact, I believe that when these obstacles are addressed, quantum computing will become widely adopted across the financial sector, ultimately reshaping markets and decision-making processes.

## 7 Reflection

I chose to research quantum computing in finance for several reasons. The topic was both fascinating and novel, and its relevance to the field of finance resonated with my interests. I was curious to explore this new technology, to understand who is currently at the forefront of its development, and to provide a glimpse into its potential for a broader audience. I hoped that through this work, I could not only deepen my own knowledge but also contribute insights that might help others grasp the implications of quantum computing and what it is about beyond hype.

The journey was not without challenges. Initially, I began this thesis in Finnish, but because most of the cutting-edge literature was in English, I had to invest extra effort in translating and sifting through the material. Defining the scope of the research was another significant hurdle. Early on, I discovered that the subject was vast and many-sided. But not knowing too much about the subject I had to just go forward with further research. About halfway through it ballooned too much. To manage this, I refined my focus by incorporating the dual perspectives of quantum computing as both a pioneering technology and a potential risk multiplier. This adjustment helped narrow down the research questions, though I had to make difficult decisions to exclude areas like flash crashes to keep the study manageable given my time constraints and personal circumstances.

Throughout the process, I encountered moments of self-doubt and frustration, especially when I realized how much there was to learn. Nonetheless, these challenges pushed me to work more consistently and adapt my approach. In the end, despite delays and obstacles, I gained a pretty good understanding of both the theoretical and practical aspects of this new technology.

Managing this thesis has been an invaluable learning experience. It has shown me that even if a project has many uncertainties, persistent effort and a willingness to refine ideas can lead to meaningful insights and a successful outcome. Overall, I believe the final result is pleasing and important for the finance sector.

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## Appendices

### Appendix 1. Screenshot of identified papers in excel

Identified	quantum computing in finance	quantum finance risk	quantum finance bigger	quantum computing risk	quantum computing forecasting	
Google scholar	310 000	269 000	15 700	228 000	92 400	915 100
Science Direct	4 326	5 291	348	15 543	8 852	30 034
Springer	4 061	6 105	77	4 973	3 618	18 834
Clarivate (web of science)	2 733	432	373	2 525	2 427	8 490
	316 794	280 828	16 498	251 041	107 297	972 458

**Appendix 2. Screenshot of filtered papers in excel**

Filtered	quantum computing in finance	quantum finance risk	quantum finance bigger	quantum computing risk	quantum computing forecasting	
Google scholar	30 700	41 700	4 550	30 400	19 900	127 250
Science Direct	1 013	993	63	3 129	1 792	6 990
Springer	4 006	6 018	77	4 936	3 584	18 621
Clarivate (web of science)	537	103	71	542	500	1 753
	36 256	48 814	4 761	39 007	25 776	154 614

**Appendix 3. Screenshot of excluded before title screening in excel**

Excluded before title screening	quantum computing in finance	quantum finance risk	quantum finance bigger	quantum computing risk	quantum computing forecasting	
Google scholar	279 300	227 300	11 150	197 600	72 500	787 850
ScienceDirect	3 313	4 298	285	12 414	7 060	27 370
Springer	55	87	0	37	34	213
Clarivate (web of science)	2 196	329	302	1 983	1 927	6 737
	284 864	232 014	11 737	212 034	81 521	822 170

**Appendix 4. Screenshot of after most relevant titles were screened in excel**

after most relevant titles were screened	quantum computing in finance	quantum finance risk	quantum finance bigger	quantum computing risk	quantum computing forecasting	
Google scholar	3	5	1		3	12
ScienceDirect			1			1
Springer	1			1		2
Clarivate (web of science)						0
	4	5	2	1	3	15

## Appendix 5. Screenshot of excel table of 10 selected papers

No.	Title	Authors	Year	Focus Area
1	Quantum Computing: a Bubble Ready to Burst or a Looming Breakthrough?	Giuseppe Bruno	2022	Quantum algorithms; NISQ-era variational methods
2	Quantum Computing Reduces Systemic Risk in Financial Networks	Amine M. Aboussalah, Cheng Chi & Chi-Guhn Lee	2023	Quantum partitioning; systemic risk optimization
3	From Portfolio Optimization to Quantum Blockchain and Security	Abha S. Naik, Esra Yeniaras, Gerhard Hellstern, Grishma Prasad & Sanjay K. L. P. Vishwakarma	2023	Portfolio optimization; quantum blockchain
4	Quantum Computing for Financial Risk Measurement	Sascha Wilkens & Joe Moorhouse	2023	Quantum amplitude estimation; risk measurement
5	A Study on the Use of Quantum Computers, Risk Assessment and Security Problems	Bilgehan Arslan, Mehtap Ulker & Seref Sagiroglu	2023	Risk assessment; security challenges
6	Forecasting Stock Market Crashes via Real-Time Recession Probabilities: A Quantum Computing Approach	David Alaminos, M. Belén Salas & Manuel A. Fernández-Gámez	2022	Stock crash forecasting; recession probabilities
7	A Survey of Quantum Computing for Finance	Dylan A. Herman, Cody Googin, Xiaoyuan Liu, Alexey Galda, Ilya Safro, Yue Sun, Marco Pistoia & Yuri Alexeev	2022	Survey: stochastic, optimization, ML in finance
8	Credit Risk Analysis Using Quantum Computers	Daniel J. Egger, Ricardo G. Gutiérrez, Jordi Cahué Mestre & Stefan Woerner	2019	Quantum amplitude estimation for credit risk
9	Towards Prediction of Financial Crashes with a D-Wave Quantum Annealer	Yongcheng Ding, Javier Gonzalez-Conde, Lucas Lamata, José D. Martín-Guerrero, Enrique Lizaso, Samuel Mugel, Xi Chen, Román Orús, Enrique Solano & Mikel Sanz	2023	Quantum annealing for financial crash prediction
10	Quantum Computing for Finance: Overview and Prospects	Román Orús, Samuel Mugel & Enrique Lizaso	2019	Quantum optimization; service design paradigms