Navigating the Quantum Leap: Strategic Approaches for Pharmaceutical Companies in a Competitive R&D Environment

Thorben Schulte

Dissertation written under the supervision of professor

Peter Rajsingh

Dissertation submitted in partial fulfilment of requirements for the MSc in Business, at the Universidade Católica Portuguesa, 12/09/2024.

Abstract

Access to health and medicine are human rights guaranteed by international organizations and a pivotal theme within the Sustainable Development Goals of the United Nations. However, drug shortages are a reality that affects millions worldwide due to inefficiency in Research & Development regarding the pharmaceutical industry. Quantum computing is rising as a solution to faster drug discovery, although guidelines for its strategic implementation by pharma companies in a competitive scenario are lacking. Considering this issue, this thesis applies a mixed-method approach to uncover the current state of quantum computing integration via a SWOT Analysis and evaluate whether investing in it is a viable strategy based on game theory. This study reveals different levels of quantum computing implementation among top pharmaceutical companies. Moreover, it was shown that if the first mover advantage is very high, then it is more likely that other companies will also invest. This research suggests that pharma companies should adapt to quantum computing technology based on company size. Larger companies may benefit from quantum computing investment by its better capabilities to adapt to market conditions, while smaller companies should build dynamic capabilities or niche applications, which will give them an advantage in specific areas and thus competitive strength.

Keywords: Quantum computing, Pharmaceutical industry, Research & Development, Game Theory

Title: “Navigating the Quantum Leap: Strategic Approaches for Pharmaceutical Companies in a Competitive R&D Environment”

Author: Thorben Schulte

Resumo

O acesso à saúde e aos medicamentos é um direito humano garantido por organizações internacionais e um tema central nos Objectivos de Desenvolvimento Sustentável das Nações Unidas. No entanto, a escassez de medicamentos é uma realidade que afecta milhões de pessoas em todo o mundo devido à ineficiência da Investigação & Desenvolvimento da indústria farmacêutica. A computação quântica está a surgir como uma solução para a descoberta mais rápida de medicamentos, embora faltem orientações para a sua implementação estratégica pelas empresas farmacêuticas num cenário competitivo. À luz desta questão, esta dissertação aplica uma abordagem de métodos mistos para entender o estado atual da integração da computação quântica através de uma análise SWOT e avaliar se investir nela é uma estratégia viável baseada na teoria dos jogos. Este estudo revela diferentes níveis de implementação da computação quântica entre as principais empresas farmacêuticas. Além disso, foi demonstrado que, se o *first-move advantage* for muito elevada, é mais provável que outras empresas também invistam. Esta dissertação sugere que as empresas farmacêuticas devem adaptar-se à tecnologia de computação quântica com base na dimensão da empresa. As empresas de maior dimensão podem beneficiar do investimento em computação quântica devido às suas melhores capacidades de adaptação às condições do mercado, enquanto as empresas de menor dimensão devem desenvolver capacidades dinâmicas ou aplicações de nicho, o que lhes dará vantagem em áreas específicas e, por conseguinte, força competitiva.

Palavras-chave: Computação Quântica, Indústria Farmacêutica, Investigação & Desenvolvimento, Teoria dos Jogos

Título: "Navegar o salto quântico: abordagens estratégicas para empresas farmacêuticas em um ambiente competitivo de I&D"

Autor: Thorben Schulte

Table of Contents

Table of Figures

1. Introduction

"The enjoyment of the highest attainable standard of health is one of the fundamental rights of every human being without distinction of race, religion, political belief, economic or social condition. Governments have a responsibility for the health of their peoples which can be fulfilled only by the provision of adequate health and social measures." (World Health Organization, 1989)

Access to medicine is a human right, which is interdependent with many others, such as the right to life (Hogerzeil, 2006). Health is also a central part of the Sustainable Development Goals, goal 3.8 highlights the need to ensure universal health coverage by providing financial protection, access to essential, high-quality health care services, and affordable, safe, and effective medicines and vaccines for everyone (United Nations, 2024). To reach this goal, it is essential to focus on the availability, accessibility, acceptability, and affordability of quality-assured health products (WHO, 2019). For that, it is needed to look at all the relevant stakeholders, from the policy makers to the manufacturers.

But while the topic of health remains pivotal, pharmaceutical companies seem to miss the mark when it comes to the development of new drugs (Pammolli et al., 2011, p. 428). The goal of a manufacturer is "to make the right product, for the right customer, in the right amount, at the right time" (Wang et al., 2005). Nevertheless, drug shortages are a common occurrence, leading to supply gaps in various markets (Abu Zwaida et al., 2022; ASHP, 2024; Department of Health and Aged Care, 2024; Walker et al., 2017; Yang et al., 2016). By reviewing some studies, Shukar et al. (2021) shows that the usual causes of drug shortages are related to financial and manufacturing issues, shortage of raw materials and just in time inventory. Besides, this can also be related to challenges faced by pharmaceutical companies, which are complex and cover a broad spectrum of factors, including political, economic, social, technical, and legal aspects (Moosivand et al., 2019).

There are multiple sources for inefficiency in the pharmaceutical supply chains: significant number of stakeholders, limited understanding of Operations Management and Supply Chain Management, institutional and regulatory pressures, long development cycles, difficulties in predicting the exact demand for medicines, difficulties in predicting the patient mix, and the particular characteristics of medicines (Papalexi et al., 2020). There has been a growing concern about productivity draught in pharmaceutical R&D in general (Pammolli et al., 2011, p. 428) and some researchers perceive the whole business model as unsustainable (Ivanov & Cojocaru, 2023, p. 29). Schuhmacher et al. (2021)included 14 leading pharmaceutical companies in his analysis and shows that, even though spending in R&D has been growing in absolute and relative terms, R&D output such as scientific publications and new molecular entities (NMEs) does not increase the same way. There is also a high variability in R&D efficiency among the companies (Roland et al., 2024). The median cost per new product approval is $2.8 billion, with the most efficient company achieving $1.7 billion per approval, while the least efficient reached a notably high $6.9 billion per approval. Developing a new drug typically takes 10 to 15 years from discovery to market launch, with capitalized costs exceeding $2 billion (Langione et al., 2019), The success rate from the start of clinical development to launch is less than 10%. As a result, biopharma companies rely on a handful of blockbuster drugs to recoup the more than $180 billion the industry invests in R&D annually.

According to economic theory, the primary objective for investors is to augment the firm's market value and elevate the price of its shares through strategic investments. They aim to create value within an optimal timeframe while maintaining an acceptable level of risk (Brealey et al., 2020, p. 2). But this value maximization entails more than the short-term creation of profit: Companies decide to invest in intangible assets like research and development that do not have an immediate effect but are supposed to pay off in the future (Brealey et al., 2020, p. 2). This is especially true for the pharmaceutical industry, which is very R&D heavy: In 2021, pharmaceutical companies spent 129 billion dollars on R&D, marking an increase in business-based pharmaceutical R&D expenditure by 39 percent since 2010 (OECD, 2023, p. 206). This has led the pharmaceutical industry to having become one of the most R&D reliant industries, spending 30 percent of its gross value on R&D. In 2018, this percentage was only 13.3 percent (OECD, 2023, p. 206).

Lately, the advent of new innovative technologies promises to take the drug R&D industry out of its slump and make the whole process more efficient. One of these potential disruptors is quantum computing. According to Budde and Volz (2019), access to this type of computational resource has the potential to significantly enhance the efficiency of R&D departments and transform the development of new products, with far-reaching effects across the biochemical industry. This is due to its ability to greatly improve the understanding of systems governed by quantum mechanics, such as molecular structures and chemical reactions. Companies that can leverage quantum computing may be able to produce superior products at lower costs and in less time.

Despite the growing body of research on quantum computing in drug discovery, there still remains a knowledge gap in that area for managerial research. Past studies have been able to address the medical implications of quantum computing as a source for drug discovery as well as the potential productivity gains in drug development and how the industry should prepare for the new technology and its disruptive impact. While these studies have been effective at gathering opinions within the industry on the benefits of quantum computing and showing roadmaps for the implementation of quantum computers into the R&D process, researchers have failed to address quantum computing implementation from a competitive standpoint. The pharmaceutical industry is marked by fierce price competition and huge market pressures. In the decision-making process for a company to invest or not invest in quantum computing technology it is therefore pivotal to include the interaction between this decision and the decision of the competitors. This thesis aims to fill this knowledge gap by offering a fresh game theoretic approach examining the quantum computing investment decision as a game between two players, to better understand what factors influence that decision and what strategies a company should adopt to gain a competitive advantage. This is culminated into this research question:

"How should pharmaceutical companies, based on game theory, effectively develop dynamic capabilities in quantum computing for drug discovery in different scenarios?"

This thesis is structured as follows: in the next chapter, the author gives an overview of the pharmaceutical R&D process as a basis for this thesis, highlighting its challenges and limitations. He will also give an overview of quantum computing and its use cases as well as relevant management theories. The focus lies on game theory and dynamics capabilities, which are explored in conjunction with quantum computing. Then, the methodology chapter provides an outlook on the quantitative and qualitative methods used for answering the research question and presents the hypothesis of this body of work. After that, the results of the analyses are presented and set into the context of the scientific theories. The implications of the findings are explored, and inspiration for future research is given.

2. Literature Review

This chapter addresses relevant theories and explains the fundamental concepts of pharmaceutical R&D, quantum computing and strategic management.

2.1. Pharmaceutical R&D Process

The OECD defines Research and Development (R&D) as "*creative work undertaken on a systematic basis in order to increase the stock of human knowledge and to devise new* *applications based upon it. The term R&D covers three activities: basic research, applied research and experimental development.*" (OECD, 2017)

Basic research describes the exploration of different phenomena and the acquisition of new knowledge without having a practical use of that knowledge in mind. Instead, basic research focuses more on fundamental concepts. Applied research on the other hand focuses on the creation of knowledge that is aimed towards solving a practical problem or fulfilling a certain objective. Lastly, experimental development builds on existing knowledge and uses it to establish new or improving existing products or processes (OECD, 2017).

In the context of pharmaceutics R&D can be defined as the following:

"*Pharmaceutical R&D refers to the pharmaceutical research and development of new medicines*". (Light, 2012)

The drug development process is driven and motivated by a clinical need. If there is a disease or a medical condition where no adequate medicine is available, that can initiate a drug development process (Hughes et al., 2011, p. 1239), which then follows a specific process. The U.S. Food & Drug Administration (FDA) divides this process into various steps. In the first step, a new active agent is discovered (U.S. Food & Drug Administration, 2018). To discover a new drug, researchers must identify a target. For that, they investigate a specific function in the disease like a gene or a protein, that could be targeted by a drug to improve the condition (Deore et al., 2019, p. 63). That is followed by the target validation, where it is tested, if the target plays a significant role in the disease and if modulating it is effective (Blake, 2007). Then, in the hit discovery process, different compounds are tested on the target. The compounds that interact with the target in a useful way are described as hits. These hits get refined to have a stronger effect and be more selective, meaning that they only affect the specific target. The result of this process are promising drug candidates, called leads (Hughes et al., 2011, p. 1246). Lastly, these leads get further optimized by improving deficiencies in the lead structure. This process is called lead optimization (Hughes et al., 2011, p. 1248).

The leads get deeper explored and researched in the development stage where the mechanisms, effects and dosages are further analyzed (U.S. Food & Drug Administration, 2018).

To ensure that the drug does not pose a danger to humans, the second step consists of preclinical research, where the drug is tested in-vitro and in-vivo. Only if it proves to not be toxic in its used dosage, the drug development may move to the clinical research stage, where it is tested on humans (U.S. Food & Drug Administration, 2018).

The clinical research stage itself is divided into four phases. In phase 1, the drug is tested on 20 to 80 healthy participants or in some cases people with the specific condition for several months. The goal is to understand how the drug interacts with the body and how much the optimal dosage is. From these results the researchers can induce how they can administer the drug in a way that reduces side effects and increases the positive effects. About 70 percent of drugs then move on to phase 2. In phase 2, the drug is tested on several hundred people with the condition to further increase its safety. After several months to up to 2 years, the researchers gathered enough data to decide if the drug moves into the next phase and refine their research. Only 33 percent of drugs go into the pivotal study phase 3, where they are tested on 300 to 3000 individuals with the specific condition, in between 1 to 4 years it is researched, if the treatment proves beneficial and the long term and rarer side effects are determined. Only after this study, the developers can start a New Drug Application (NDA) at the FDA, which then decides if the drug will be allowed to be sold in the US. That makes the phase 3 so important but also challenging, since only between 25 and 30 percent of drugs end up being approved (FDA, Thu, 2019).

After the drug is approved, there is an additional phase 4 in which the drug is tested on several thousand volunteers with the condition as part of the Post-Market Safety Monitoring (FDA, Thu, 2019).

According to the data above by the FDA, only between 5.8 and 6.9 percent of drugs that enter phase 1 make it out of phase 3. Another study shows that about 90 percent of clinical development fails (Sun et al., 2022, p. 3059).

2.1.1. Challenges and Limitations

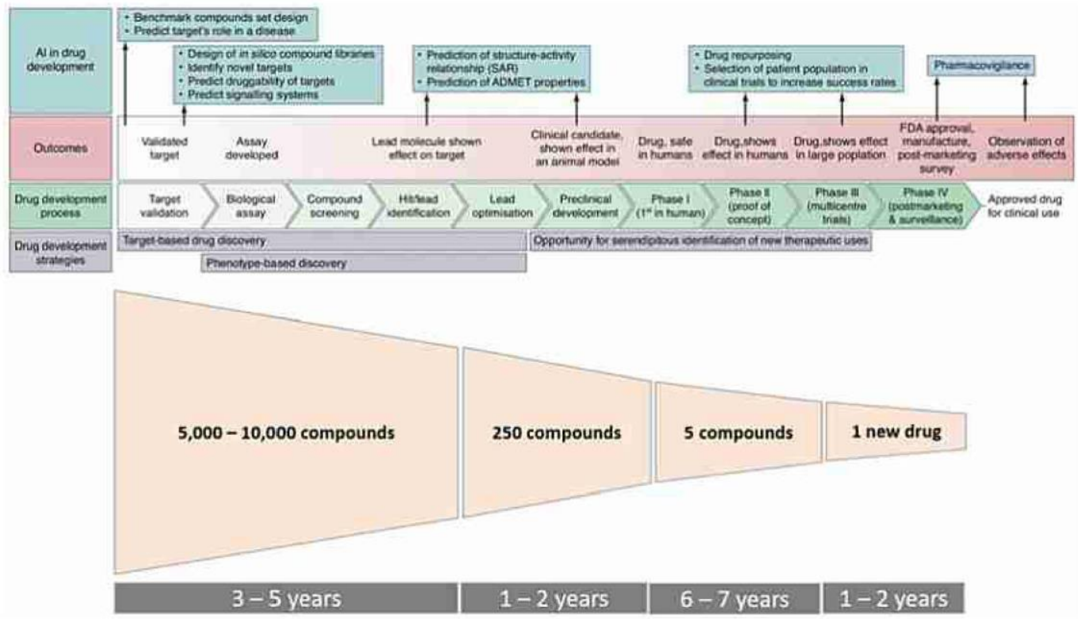

Figure 1: Cova, Vitorino et al 2022 - Artificial Intelligence and Quantum Computing. Pharmaceutical R&D Costs (Cova et al., 2022, p. 322)

As can be seen above, only a fraction of drugs makes it through the research stages to the market, while most of the research gets rejected. Furthermore, only three in ten new products make back their R&D costs on average (Kaitin, 2010, p. 356). The output of the knowledge production function is not matching the input, which has led to a long-term decline in productivity in drug R&D (Pammolli et al., 2011, p. 428). The whole pharmaceutical R&D process has become risky, expensive, inefficient and slow, not having faced any fundamental changes since the 1960s (Kaitin, 2010, p. 356).

There are multiple problems which render the drug discovery and development process so difficult. In the drug development process, drug approval mostly fails because of missing clinical efficacy, an unacceptable level of toxicity, poor drug-like properties, the drug not meeting the needs of the market or poor planning (Sun et al., 2022, p. 3059). A reason for drugs failing so often because of their toxicity could be found in the focus of many researchers on efficacy: They are so preoccupied that the drug has an effect on the target, that they disregard the selectivity of the drug, leading to unmanageable toxicity (Sun et al., 2022, p. 3059). This goes hand in hand with the observation that safety issues are becoming a bottleneck for drug development (Watkins, 2011, p. 788). Furthermore, target validation remains very challenging with today's methods (Sun et al., 2022, p. 3059).

From the organizational point, it has become a major challenge to recruit and keep patients that are needed for the clinical trials (Kaitin, 2010, p. 358). Also, since the 1990s companies have been increasingly focused on the development of blockbuster drugs. These are drugs which address huge markets, often for chronic diseases, that offer a huge revenue. Because of that, these markets are marked by dense competition, leading to many trials ending because of economic or market related reasons (Kaitin, 2010, p. 358). To increase revenues and become more competitive companies should therefor work on reducing the development times, faster drop unpromising drug candidates, improve patient recruitment as well as the protocol design process, reduce development cost while maintaining quality, boost productivity and focus on products of areas with a high therapeutic need (Kaitin, 2010, p. 359). One way, companies are addressing this is through contract research organizations (CRO). These functional server providers allow pharmaceutical companies to outsource part of their research and by this increase their efficiency (Kaitin, 2010, p. 359). In this scenario, large pharmaceutical companies act as the managers of the project in the early stages, while the smaller CRO develops the drug. Once it has undergone the necessary steps, the bigger company takes over in stage III of the clinical trials, which requires more resources and takes care of other important factors as well like governance, manufacturing, scale-up, marketing and sales (Kaitin, 2010, p. 361).

To mitigate some of the high costs and risks of drug R&D, governments often fund drug discovery in the early stages of the process (OECD, 2023, p. 206). This also effects what drugs are developed, since both private and public payers tend to discourage investments into innovative follow-up drugs through fierce price competition. On the market, a new improved drug is usually priced similarly to an older version, leading to low profitability for the development of new versions. Because of that, they favor drugs that target markets with low competition, allowing for higher returns (Pammolli et al., 2011, p. 436). This lower level of competition is accompanied by a higher risk and difficulty in the development process, that in turn leads to higher attrition rates (Pammolli et al., 2011, p. 436). Since all companies face this issue and are turning to more high risk, high potential investments, the overall risk-premium is pushed to higher risks, leading to pharmaceutical companies being able to take on riskier investments with a lower risk-premium (Pammolli et al., 2011, p. 437). This development has some negative consequences, as this “the winner takes it all” attitude and pricing schemes punish incremental innovation and parallel R&D, which are pivotal for save and innovative products in the long run (Pammolli et al., 2011, p. 437).

While high attrition rates and inefficiency remain a problem in drug development, some studies do show a decrease in attrition rates in the last years (Pammolli et al., 2020). Pharmaceutical companies have been able to discontinue non-viable projects faster than before, allowing for a more efficient resource allocation (Pammolli et al., 2020). A possible source for this productivity gain could be an increasing focus on target validation. Since companies are putting in more effort in analyzing their medical targets, the drug candidates could show themselves to be more effective in the clinical trials as well (Pammolli et al., 2020).

This productivity gain also goes hand in hand with an on average time increase for phase III clinical trials as well as preclinical research (Pammolli et al., 2020). A reason for this might be found in the better understanding of mechanisms of action, which on one side allows for new and better treatments but also makes development more challenging (Pammolli et al., 2020).

A problem that most of these studies share, is that the output in drug R&D is usually measured in the amount of drugs brought to the markets. However, this does not tell anything about the quality of the drugs that are put out, which should also be considered (Pammolli et al., 2011, p. 428).

A solution for the productivity crisis might be found in the implementation of new technologies: Cutting edge technologies like Machine Learning, Artificial Intelligence and theories like quantum chemistry are already used to improve drug discovery. A technology that holds a huge potential for disrupting the pharmaceutical industry in the future is quantum computing (Cova et al., 2022, p. 343).

2.2. Fundamentals of Quantum Computing

In a definition used by the European parliament, quantum computing is described as "an area of computing focused on developing computer technology based on the principles of quantum theory, which explains the behavior of energy and material on the atomic and subatomic levels" (European Parliament, 2019).

A quantum computer makes use of three principles of quantum mechanics that differentiate it from classical computers: superposition, interference and entanglement (National Academies Press (US), 2019, p. 10).

<u>Superposition</u>

In a classical computer, bits are used to store information. A bit is a two-state system, that can either take a value of 1 or 0. Combining an increasing number of bits, a computer can store an increasing amount of information by breaking the information down into binary values. The amount of information (= the number of different states) a system can store can therefore be described as $2^n \geq m$, n being the number of bits and m the number of different states.

Physically this is usually expressed by an electric circuit, that is either at ground (taking value 0) or running a current (taking value 1) (McMahon, 2008).

On a quantum computer on the other hand, information is not stored in bits but in qubits. These qubits can also take the values 1 or 0, which are noted in quantum notation as $|1\rangle$ and $|0\rangle$. Different to a bit, a qubit can also exist in a third state, that is called superposition and denoted as $|\psi\rangle$. Superposition can be described as a linear combination of the other two states: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$; α and β being complex numbers. Whenever a qubit is measured, it will either take $|1\rangle$ or $|0\rangle$. This happens with a probability that is determined by the squared calculus of the complex coefficients. I.e. the probability of the qubit taking $|1\rangle$ when measured equals $|\beta|^2$, while the probability of it taking $|0\rangle$ equals $|\alpha|^2$ (McMahon, 2008).

2.2.1. Interference

In the realm of physics, interference refers to the phenomenon observed when two waves propagate simultaneously within the same space. This interaction between waves can lead to three distinct outcomes: constructive interference, where the waves combine to amplify each other's amplitudes; destructive interference, resulting in a reduction of amplitude; or the formation of a standing wave. The outcome depends on the amplitude and phase differences between the waves (Lüders, 2023, p. 105).

Interference does not only affect classical waves, but also quantum systems. This makes it an essential principle for quantum computing:

In classical probabilistic computing, probabilities are exclusively positive, restricting the potential for cancellation effects. However, in quantum computing, qubits exist in states described by complex numbers, allowing for the representation of probabilities as both positive and negative. This unique attribute facilitates the cancellation of probabilities and allows for the use of interference in constructing effective quantum algorithms. An algorithm can use constructive interference to enhance desired outcomes while neutralizing undesired ones with destructive interference. Through cancellation of randomness a quantum algorithm leads to a controlled result (National Academies Press (US), 2019, p. 11).

2.2.2. Entanglement

Quantum entanglement describes how two quantum system can exist in a state, where the properties of system A depend on the properties of system B. This correlation is independent of both quantum systems being near each other and would continue even if they were spatially divided (McMahon, 2008, p. 147).

In quantum computing, entanglement makes it possible to change large numbers of qubits at once, instead of just changing them separably, which is essential for parallel computing (Microsoft, 2024).

Parallel computation describes the quantum computer's ability to perform multiple operations at the same time. While a classical computer would encode multiple strings separately, a quantum computer does this in one step. This ability allows quantum computers to solve problems that could not be efficiently solved by a classical computer (Djordjevic, 2021).

2.2.3. Purpose of Quantum Computing

The purpose of quantum computing is to solve problems that cannot be solved efficiently using classical physical principles. Quantum algorithms are particularly useful in the fields of cryptography, unstructured search, optimization, solving large equation systems and simulating quantum systems (National Academies Press (US), 2019, p. 9).

But while quantum algorithms can offer huge speedups, they are not automatically the best option for all mathematical problems: The more structured a problem is, the higher are the speedups. In less structured use-cases, however, quantum computing might not outperform classical computation. Since a high performing quantum computer has not been developed yet, there is a huge knowledge gap in the use cases for quantum algorithms and how they could be used in different areas (National Academies Press (US), 2019, p. 11).

2.2.4. Benefits of Quantum Algorithms

The efficiency of a quantum algorithm can be proven by comparing its time efficiency with its classical counterpart. In algorithm complexity theory, an algorithm is deemed efficient, if its computational steps are a polynomial function of the input length. On the other hand, an algorithm is deemed intractable, if its computational steps are an exponential function of the input length. With the time it takes to compute these steps exponentially growing, the computation soon becomes non-viable as the input length increases. An example of a mathematical problem that is suggested to be intractable using classical computing is the factorization of prime numbers. A quantum algorithm known as Shore's algorithm can solve it in a polynomial number of steps. This shows how quantum computing can solve mathematical problems that have formerly been deemed intractable (Olatunji et al., 2021).

Apart from speedup, the benefit of quantum computers is that they can simulate quantum systems in an efficiency and preciseness not possible with classical computers. Since the whole system is built on quantum mechanics, simulating a quantum system takes a quantum computer no longer than a classical computation on a classical computer. This performance facilitates the use of quantum computers for simulating chemical reactions and speeding up scientific research (Zalka, 1998).

2.2.5. Challenges of Quantum Computing

The DiVincenzo criteria encompass five prerequisites a quantum computer must possess (DiVincenzo & Loss, 1998, p. 424):

1. **Hilbert Space Control:** In quantum computing, a Hilbert Space is a space that represents all the possible values the qubits can take. Within this Hilbert Space, the quantum computer needs to be able to precisely define and control the available quantum states.
2. **State Preparation:** Before the computation can start, all qubits must be set to a known starting state. This is often done by cooling down the system, causing the qubits to reach ground state.
3. **Low Decoherence:** Minimization of interactions with the environment to prevent interference in the computational Hilbert space, ensuring that quantum computation remains reliable. This involves ensuring that decoherence time significantly exceeds the switching time and employing fault-tolerant techniques to mitigate errors.
4. **Controlled Unitary Transformations:** Ability to subject the quantum system to precisely defined sequences of unitary transformations, essential for quantum computation. Precision in these transformations is crucial to prevent errors and maintain coherence.
5. **State-Specific Quantum Measurements:** Capability to perform quantum measurements on specific subsystems of the computational state, ideally using projection measurements of individual qubits. These measurements should yield results that can be interpreted as classical bits, enabling the readout of the quantum computation. Recent advancements have shown that ensemble measurements may be sufficient under certain conditions, but they still need to be subsystem-specific.

Despite significant progress, quantum computing faces significant challenges that hinder its development and practical application.

Decoherence and Environmental Interference: Balancing isolation from the environment with external control poses a significant challenge. Interactions with the environment lead to decoherence, undermining the stability of quantum systems. On the other hand, qubits need to be controlled and observed, which requires some form of contact to the environment (Preskill, 2018).

Error Susceptibility: Quantum computers are highly susceptible to errors due to their delicate quantum states. Unlike classical computers, where errors can be mitigated through the abundance of electrons and the digital nature of the computers, errors in quantum systems propagate and accumulate, posing a significant obstacle to reliable computation (Gottesman, 2009).

NISQ Era Limitations: Quantum computers are currently entering the NISQ era, characterized by noisy intermediate-scale quantum devices. While reaching milestones in qubit quantity, the quality of qubit operations remains a challenge, limiting the complexity of achievable computations. Every qubit operation introduces a level of noise that leads to an inacceptable level of error with growing operation complexity (Preskill, 2018).

However, even with a growing number of qubits, for many applications the current number of qubits is not enough. While NISQ computers would have between 50 and 100 qubits (Preskill, 2018), complex applications like factorization of large prime numbers need millions of qubits (Fowler et al., 2012).

Error Correction Overhead:

While quantum error correction could improve the quality of quantum operations, they with a significant overhead resulting in a need for a huge number of physical qubits, that is currently not possible to implement. The way these methods would work is by entangling a vast number of qubits in a way that makes them less susceptible to decoherence by the environment. Scientists are also developing other possibilities that might reduce errors but could come with others (Preskill, 2018).

2.2.6. Use Cases

Quantum Computing is seen as an industry disruptor with various use cases. Business sectors that could profit from using quantum computing include cybersecurity, chemical engineering, banking and finance, and advanced manufacturing (Bova et al., 2021, p. 10). Quantum computers are interesting for a use case if (1) it can be solved using the technology, (2) cannot be (feasibly) solved using classical computers, and are (3) relevant enough to employ such a resource intense technology (Zinner et al., 2022, p. 381).

The impact of quantum computing on the economy is estimated to be very high. According to McKinsey, in 2035 the impact of quantum computing will have a value between 620 and 1,270 billion US dollars. The biggest value will be created in the financial services industry, followed by chemicals, life sciences and automotive. In life sciences the lower estimate for value add is 74 billion while the upper estimate equals 183 billion US dollars (Mc Kinsey & Company, 2023).

There are five problems, where quantum computers are believed to have the highest disruptive impact: Quantum simulation, Optimization, Quantum Machine Learning (Fedorov et al., 2022, p. 31) and Artificial Intelligence, Sampling in search, Factorization (Mc Kinsey & Company, 2023). In the area of life science, there will be the most disruptive effects coming from quantum simulation and optimization, followed by quantum machine learning and artificial intelligence (Mc Kinsey & Company, 2023).

2.2.7. Current State

In 2023, IBM introduced the first quantum computing chip with over 1000 qubits. The IBM condor is a superconducting processor with 1,121 qubits. But while this marks a significant jump in qubit quantity, qubit quality is becoming an important research topic as well. Because of that, IBM stated that year, that they are going to focus on decreasing the error of quantum computers (Castelvecchi, 2023, p. 238). As stated above, quantum error remains a huge problem, hindering very advanced use cases, meaning there is still no certainty when advanced machines will be available that can make full use of quantum advantage.

Quantum advantage means that a quantum computer can calculate problems that are not feasible to solve with regular super computers. If a quantum computer company is able to show quantum advantage it would hold a monopoly position until a competitor is able to do the same (Bova et al., 2023). But even without quantum advantage, quantum computers could hold competitive advantages in some areas, where calculations might be cheaper using them, occurring lower flexible costs (Bova et al., 2023).

It is likely that quantum computer companies will not sell their whole computers but offer quantum computing as a service (QCaaS) in the beginning. As can be observed with super computers, there will probably be a high demand for that service that exceeds the supply, leading to high competition for obtaining computational time (Bova et al., 2023).

2.2.8. Quantum Computing und Drug R&D

Quantum Computing can be used in two ways in drug discovery: Quantum algorithms can simulate the electronic structure of the drug, and they can used for quantum machine learning, which is helpful for drug R&D. To tap into the full potential of these technologies it would be necessary to use a fault tolerant quantum computer, a machine that does not exist yet (Cova et al., 2022, p. 336).

Regular super computers are already being used for drug discovery, however, they come with a catch. While they can also simulate molecule structures to a varying degree of accuracy, an increase in accuracy comes with an exponential increase in computational cost (Cova et al., 2022, p. 337). As described above, algorithm that require an exponential increase of computational power quickly turn infeasible, that is why quantum computers could potentially tap into a realm of molecule simulations which go far beyond the simulations of regular super computers.

While this technology in theory offers huge benefits, it also comes with some issues. First, chemical problems need to be translated into quantum computational problems. Furthermore, there is a need for quantum knowledge, software and hardware. These also need to fit the requirements of the lab and need to be usable by non-quantum computing experts (Cova et al., 2022, pp. 337–338).

If companies are able to prepare well and create a quantum computing workforce, the technology has the potential to develop more effective and safer drugs, select better molecule candidates for clinical trials, reduce costs and developing times, make it easier to repurpose preapproved drugs for new applications, and make it possible to develop novel antibody structures and motifs for before undruggable targets (Cova et al., 2022, p. 343). It has been argued that the technology could fundamentally reinvent pharma as a whole (Ivanov & Cojocaru, 2023, p. 29).

As spiraling costs, lengthening development timelines and low success rates are threatening pharmaceutical R&D, the use of quantum computing could bring a turnaround through improving modeling, prediction and design capabilities along the whole drug R&D pipeline (Ivanov & Cojocaru, 2023, p. 29). Quantum knowledge is already positively affecting drug research, with quantum chemistry experts being able to make more accurate predictions (Ivanov & Cojocaru, 2023, p. 29).

The initial applications, according to Langione et al. (2019) will likely focus on the early phases of R&D, such as drug discovery and design. However, the impact will also influence later stages of R&D, as improved early designs are expected to lead to higher clinical success rates.

Quantum computing and quantum machine learning simulation could compress the R&D cycles from 10 -15 years to 3-5 years, lowering time by 50 to 70 percent. Cost could decrease by 70-

90 percent and success rates increase to 30-50 percent (Ivanov & Cojocaru, 2023, p. 29). This would not only create additional value for the pharmaceutical industry, but new diseases could become treatable, and more patients could profit from cheaper treatments on a global scale. The pharmaceutical industry would also become more sustainable (Ivanov & Cojocaru, 2023, p. 29).

In an interview from 2021, pharmaceutical companies were expecting to see first benefits from quantum computing by 2025/2026 and significant improvements in pharmaceutical R&D between 2030 and 2036 (Zinner et al., 2022, p. 380). To profit from this technology, companies should prepare by educating their employees, building partnerships and developing use cases. Depending on the wished intensity, companies can build informal partnerships with hardware providers and individuals from the organization can acquire quantum skills, but companies can also already enter contracts with quantum algorithm developers and apply quantum computing experts, if they want a deeper commitment (Zinner et al., 2022, p. 381). Another differentiation would be between companies that develop use cases together with an external quantum computing partner or that let the external partner explore them together with a biochemist of theirs (Zinner et al., 2022, p. 382). Apart from these strategic decisions, companies must keep an innovation mindset and adapt a respective corporate culture if they want to get the most use out of quantum technology (Zinner et al., 2022, p. 382).

In the realm of technology development, pharmaceutical companies should incentivize the development and research of hard and software, that fits their specific needs via investments. They should engage different stakeholders from the quantum computing ecosystem and build leadership in quantum computing initiatives, to build partnerships that will later help them make use of the technology once it is in the market. And lastly, they need to develop processes that align with their goal and leverage quantum computing to fulfil the company's objectives (Ivanov & Cojocaru, 2023, p. 30)

Even though all these recommendations aim to give companies a head start on how to deal with quantum computing becoming a reality, after all there is no single right approach to quantum computing. Instead, companies must adapt in their own way (Zinner et al., 2022, p. 382).

2.3. Management Theories

When it comes to innovation, companies can deal with it in different ways. In the following, various management theories are presented that can explain how companies deal with innovation strategically.

2.3.1. Resource-Based View of the firm

The Resource-Based View (RBV) of the firm proposes that companies achieve competitive advantage through the acquisition and management of valuable, rare, inimitable, and non-substitutable resources (Barney, 1991, p. 115). If a company is able to achieve all four, it holds a competitive advantage.

In the field of quantum computing in drug discovery it could be argued that the technology is valuable, since it could decrease development costs and times significantly, rare and inimitable, since until now it has not been done and a non-substitutable resource, as the capabilities of quantum computing go far beyond the capabilities of classical super computers. Therefore, a successful implementation could give a pharmaceutical company a competitive advantage. The important thing here is that management is in accordance with the other resources of the firm and the firm's goals.

While the model is highly regarded in business research, there is also some criticism of it. On its own, the model might be incomplete, since it only looks at the resources and capabilities of the companies but ignores the stakeholders. Stakeholder theory suggests, however, that engaging stakeholders is pivotal for a company's success and thus should be included into the RBV model (Freeman et al., 2021, p. 1767). Depending on the specific use case, it might also make sense to include other management theories into the model as well (Lockett et al., 2009, pp. 24–25). There also needs to be more direct empirical research to be done, to show how the theory works in practice (Gerhart & Feng, 2021, p. 1812). RBV states that the competitive differences stem from heterogeneity in the firm that increases over time. However, it remains unclear where these differences stem from in the first place. To better understand competitive advantages, scientists need to understand how differences in firms form (Lockett et al., 2009, p. 24).

The RBV draws a rather static image of the markets, insinuating that obtaining VRIN resources goes hand in hand with a competitive advantage. This view however goes against the reality, where markets are rapidly changing and companies need to dynamically react to that, to obtain and renew competitive advantages. A model that explains this is the Dynamic Capabilities Theory (Ambrosini & Bowman, 2009).

2.3.2. Dynamic Capabilities Theory

The Dynamic Capabilities Theory extends the RBV by focusing on a firm's ability to adapt, integrate, and reconfigure resources in response to changing environments (Teece et al., 1997). The goal of the approach is to use the internal capabilities to react to outside changes rapidly and obtain a short-term competitive advantage (Teece et al., 1997). An important factor for the development of dynamic capabilities is intellectual capital inside the firm (Farzaneh et al., 2022, p. 54).

In the context of quantum computing, dynamic capabilities are crucial as companies must not only acquire these technologies but also develop the ability to deploy them effectively within R&D workflows. This includes investing in talent, restructuring R&D processes, and fostering a culture of innovation (Zinner et al., 2022, p. 382). Through dynamic capabilities companies can reach new customers and open new markets (Martínez-Vergara & Valls-Pasola, 2021).

An important point in dynamic capabilities is that following the customer's need will not always lead to a competitive advantage. Instead, innovation might seem like a worse choice in the beginning but in the future become a competitive advantage (Bower & Christensen, 1995).

In the case of quantum computing, it could mean that the technologies make the drug R&D process even more expensive and complicated in the beginning but facilitates it in the long run.

An additional concept that can be important in this context is open innovation. It describes how companies change from a silo mentality to sharing theirs and profiting from the knowledge of others. This approach can be combined with the dynamic capabilities approach (Teece, 2020).

2.3.3. Game Theory

Between the company, its competition, clients or suppliers: Interaction is at the core of any business. Game Theory is a powerful tool for modeling strategic interactions between firms, particularly in competitive environments where decisions by one firm influence others (Erhun & Keskinocak, 2003).

A game describes in this context a strategic interaction between players where the outcome of each player depends on the decision of all the involved players. To analyze a situation using game theory it is important to know the involved players, the rules of the game, the results of the game for each possible set of actions and the pay-off based on the result (Erhun & Keskinocak, 2003). Game Theory is based on two assumptions: The players act rationally, meaning that they act in a way that serves their highest interest. And players take into consideration what the other players might do (Erhun & Keskinocak, 2003). Depending on the type of game the players might have all the information about it or not (Erhun & Keskinocak, 2003).

In a game, players will pick the dominant strategy, that promises the highest benefit based on the other's action. If all players reach a state where they cannot improve by changing their decision, that is called a Nash equilibrium (Brickley et al., 2000). Innovation happens in an area where multiple stakeholders follow different interests and motivations, game theory allows to analyze these intra-, inter- and meta-organizational games (Baniak & Dubina, 2012, p. 180). This way, it can e.g. be analyzed if companies should invest into innovation and following which strategy (independent, imitation, cooperation) (Baniak & Dubina, 2012, p. 183).

Following game theory, innovation is best done in a way that competitors cannot just jump on the wagon, but instead the company is able to build a high level of expertise that creates some space for its competitors and is difficult to replicate. At the Nash equilibrium smaller firms refrain from investing and either specialize in an area or adapt to the knowledge created by others, while large businesses invest in innovation. This is because especially ground research gets easier duplicated and is a very expensive endeavor for a small firm (Baniak & Dubina, 2012, p. 183).

In the context of quantum computers adoption, Game Theory can help predict how pharmaceutical companies will respond to the integration of new technologies by their competitors. By analyzing payoffs associated with each choice, firms can identify optimal strategies. Game Theory thus provides a quantitative lens through which the impact of quantum on strategic decision-making can be examined.

2.3.4. Disruptive Innovation Theory

Disruptive Innovation Theory, developed by Clayton Christensen, explains how new technologies can fundamentally alter industry landscapes by displacing established methods. This theory is often misunderstood, as not every new technology is automatically disruptive (Si & Chen, 2020, p. 16). Quantum computing has the potential to be a disruptive force in pharmaceutical R&D, by challenging traditional computational methods and reshaping competitive dynamics. Companies that adopt quantum computing early can position themselves as leaders in innovation, while those that lag may face competitive disadvantages.

3. Methodology

After explaining the literature that this paper is based on, the following chapter introduces the hypotheses for this research and then explains the methodology used to evaluate them.

3.1. Hypotheses

Based on the literature and the identified knowledge gap, the research question **"How should pharmaceutical companies, based on game theory, effectively develop dynamic capabilities in quantum computing for drug discovery in different scenarios?"** was developed. To answer this research question, several hypotheses were built which were examined based on the conducted research.

H1: *Leading companies have established advanced strategies for quantum computing integration.*

Quantum computing has been found to be a disruptive technology in pharmaceutical R&D, as described in the literature review. As pharmaceutical companies are on average R&D heavy and are part of a fiercely contested market, it is expected, that they will aim to gain first mover advantage by establishing a comprehensive strategy for the future use of quantum computing in their research.

H2: *Investing in quantum computing is the dominant strategy for increasing profits in pharmaceutical companies.*

In the literature review it has been found that quantum computing can dramatically cut the R&D costs and development times. While quantum computing comes with high costs, it is expected that the costs will be offset by later savings in the industry, regardless of competition.

3.2. Foundations of Scientific Research

According to Max Planck, the objective of science is to gain knowledge for society by using the scientific method. This paper aligns with this mission by aiming to give a more holistic perspective on the adaptation of quantum computing in drug discovery and help researchers and practitioners to better understand the disruptive force of the technology.

There are certain criteria that scientific research must fulfill. Based on Pürer (2003), these are intersubjective comprehensibility, objectivity, reliability, and validity. Intersubjective comprehensibility means the work is systematically documented and the research logic is also comprehensible to outsiders. Objectivity, conversely, means that the research results are independent of the researcher themself. Personal attitudes and expectations should have no influence on the study results or interview responses. Reliability means that a research instrument always delivers the same results under the same conditions. If a researcher decides to repeat an experiment or a study in the future, they should be able to measure the same value, given that all external conditions are the same. Finally, there is the criterion of validity. This criterion describes the fact that an instrument measures what it is supposed to measure. In other words, it must be suitable for collecting the required values (Pürer, 2003, p. 556).

To ensure these criteria are fulfilled, the paper's research followed an empirical approach. Empirical research is defined as the following:

"To proceed empirically means to gather experience about reality, to systematize it and to apply this systematics to the subject area […]. The procedure is documented in such a way that it is intersubjectively comprehensible and can therefore in principle be repeated by others." (Brosius et al., 2012, p. 3)

Gaining experience in a systematic way plays a central role in empirical research. A researcher needs to proceed systematically and intersubjectively comprehensibly in their re-search. This distinguishes empiricism from hermeneutics, which makes observations solely based on experiences (Brosius et al., 2012, p. 3).

The empirical approach of the paper allows outsiders to test and apply the results in different environments, making them more applicable to a multitude of use cases and opening the field for further research.

In empirical research, quantitative and qualitative methods can be differentiated. Qualitative methods attempt to depict a phenomenon as broadly as possible. Smaller samples are often used, and more space is given to the individual case. Quantitative methods, on the other hand, reduce a phenomenon to its fundamental aspects and make it quantifiable. Large sample sizes are then used to statistically confirm or refute the phenomenon (Brosius et al., 2012, p. 4).

Both methods come with their own benefits and disadvantages: Qualitative research reveals underlying issues that might go beyond the original inquiry. Furthermore, it provides a deeper understanding of the values and beliefs of the person or object the research is dealing with. Conversely, quantitative research does not offer objectively verifiable results and is more resource-intensive, as qualitative methods, such as interviews, take a lot of time to conduct and evaluate (Choy, 2014, p. 101). Quantitative methods make it possible to evaluate huge amounts of data and offer results with higher reliability (Dudwick et al., 2006). However, they cannot capture the experiences and context of the individual people in the same detail as qualitative explorations do (Dudwick et al., 2006).

In line with the research goal, this thesis followed a mixed-method approach, combining quantitative analysis with a game theory model and qualitative insights from case studies. The quantitative analysis leverages existing data on cost and time savings associated with quantum computing, using game theory to model strategic decision-making within the industry.

3.3. Qualitative Analysis Case Study

Even though quantum computing is not currently used at its full potential because of the lack of technology, companies are starting to incorporate it as part of their R&D efforts. As explained in the literature review, pharmaceutical companies that invest early in quantum computing can gain a competitive edge. To understand how pharmaceutical companies are preparing themselves for quantum computing, the author decided to deduct a case study.

A case study is ideal for offering an in-depth analysis of a problem that is still lacking research (Ridder-Hans, 2020, p. 84). Since there is a huge research gap on how exactly companies are leveraging quantum computing skills in their R&D, a case study can help close this gap and expand the knowledge on that topic. For the selection of the cases, it is important to say, that case studies are not samples, instead they are chosen in a way that creates the largest amount of new knowledge (Tellis, 1997)

Therefore, this thesis analyzed the ten biggest global pharmaceutical companies, by market capitalization by looking at their most recent annual report analyzed for the mentioning of quantum computing as well as other sources about cooperations that could be found online. When mentioned, it was further classified as an “active investment or partnership” related to the company’s R&D or as another type of mention, such as on the general importance of the topic or the hardships it has been facing. From this, a SWOT analysis was performed. A SWOT analysis is a strategic planning tool used to evaluate the Strengths, Weaknesses, Opportunities, and Threats related to a business or project. It helps identify internal and external factors that can influence an organization's ability to achieve its objectives. In the context of quantum computing in pharmaceutical companies, the SWOT SWOT analysis looks at both internal factors (strengths and weaknesses) and external factors (opportunities and threats), making it possible to gain a more holistic picture from it (GÜREL, 2017).

First, a review of annual reports was performed to identify mentions of quantum computing. A search for articles and interviews conducted by the company was also carried out. It was checked if the company was actively investing in quantum computing R&D or just acknowledging its importance in the sections on R&D, innovation, and strategic partnerships. It was noted if the company is forming alliances with quantum computing firms, conducting in-house research, or simply recognizing it as a trend. Secondly, the information was classified in Strenghts, Weaknesses, Opportunities and Threats - Strengths: Does the company have a clear strategy for quantum computing? Are they allocating resources, or are they leaders in their field due to technical expertise? Weaknesses: Is there a lack of investment, strategy, or expertise? Are they lagging behind competitors? Opportunities: What future benefits can be realized if they pursue quantum computing? Are there chances for partnerships or groundbreaking discoveries? Threats: What risks do they face if they ignore quantum computing? Are there uncertainties in the technology's development that could pose challenges? Finally, strategic recommendations were given after conducting the SWOT analysis on potential strategic actions. For example, if the company is weak in quantum computing investment, it could explore partnerships with tech companies or increase its R&D funding in this area to capitalize on future opportunities.

3.4. Quantitative Analysis Using Game Theory

As mentioned in the literature review, game theory helps to better understand the interactions between different players on the market. Specifically, it explores how the potential savings in R&D costs and time influence these decisions and how quantum computing integration could impact the competitive landscape. In the quantitative part of the thesis, game theory was used to better understand how companies might act in an investment decision in an area of quantum computing and what dominant strategies might emerge from it.

The quantitative analysis relies on secondary data from published reports, journal articles, and industry insights that quantify the time and cost savings achieved through quantum computing in pharmaceutical R&D. The primary data point utilized is an estimate showing the extent of these savings, which serves as the basis for constructing the payoff matrices in the game theory model. To build the game theoretic model, the author considered the following factors:

- Players: Pharmaceutical companies considering quantum computing integration in their R&D.
- Strategies:
  - Adopt quantum computing: Companies invest in quantum computing technology, aiming to leverage its benefits.
  - Do not adopt quantum computing: Companies continue with traditional R&D methods without quantum computing.
- Payoffs: Payoffs were calculated based on the collected data, reflecting the potential gains (cost savings, efficiency improvements) versus the associated costs (investment in quantum computing, uncertainty of returns)

Three scenarios were developed to capture varying degrees of benefits from QC adoption:

- Scenario 1: High Adoption Benefits: Assumes significant cost and time savings from QC, resulting in a strong competitive advantage.

- Scenario 2: Moderate Adoption Benefits: Reflects moderate savings with some uncertainties, representing a balanced scenario.
- Scenario 3: Low Adoption Benefits: Assumes minimal savings, highlighting the risks of high initial costs and uncertain returns.

For each scenario, a payoff matrix was constructed and a Nash Equilibrium identified, which helps determining the optimal strategy for each player and understanding how quantum computing can shift competitive dynamics in pharmaceutical R&D.

3.5. Limitations

Since the analysis relies on secondary data, this may not fully mirror the investment details in all companies. Also, companies will not share certain sensitive information about their business strategies and research, making it difficult to obtain all the needed information. Lastly, the topic of quantum computing in drug discovery is a fairly recent one, that is subjective to rapid change. Newer developments could change the results of this study. Also, the assumptions made in the game theory model, such as uniform cost savings and investment levels, may not reflect real-world variability.

4. Results

4.1. Case Study Results

After analyzing the ten different business cases under the SWOT framework, the following results were found:

Strengths:

• Strategic Focus: Several major pharmaceutical companies, including Pfizer, Roche, and Novartis, have established dedicated task forces or groups focused on quantum computing, reflecting a clear strategic focus on leveraging this emerging technology.

• Partnerships and Collaborations: Strong partnerships with quantum computing firms, such as Eli Lilly's collaboration with XtalPi and Roche's partnership with Cambridge Quantum Computing, showcase a proactive approach to integrating quantum technologies into drug discovery processes.

• Investment in Research: Companies like Novo Nordisk, with its 1.5 billion DKK investment in quantum computing, demonstrate leadership in long-term research and development, positioning them as potential leaders in the quantum computing space for life sciences.

Weaknesses:

- Lack of Consistent Mention in Annual Reports: Despite their interest in quantum computing, only Merck has mentioned it in its 2023 annual report, suggesting that quantum computing may not yet be a central part of the strategic narrative for most of these companies.

- Limited In-House Expertise: While some companies have created quantum task forces, many rely on external partnerships for expertise, indicating a lack of in-house quantum computing capabilities.

- Slow Adoption: Many companies have only begun to explore quantum computing, which may leave them behind if they do not accelerate their R&D efforts or expand their quantum computing initiatives.

Opportunities:

- Transformative Potential: Quantum computing holds the promise to revolutionize drug discovery, speeding up processes and finding solutions that classical computing cannot, offering immense long-term benefits.

- Expansion of Partnerships: There is potential for more pharmaceutical companies to engage in partnerships with quantum computing startups, which could lead to innovative breakthroughs in healthcare.

- Market Leadership: Companies investing early in quantum technologies, like Novo Nordisk and Pfizer, have the opportunity to establish themselves as pioneers in the quantum computing space within life sciences, offering a competitive advantage.

Threats:

- Technological Uncertainty: Quantum computing technology is still in its early stages, and its development is fraught with uncertainties, such as overcoming qubit noise and integrating it with current AI and machine learning models.

- Geopolitical Risks: Economic sanctions and restrictions on the import/export of advanced materials, such as chips crucial for quantum computing development, could hamper progress, as noted by Merck.

- Competitive Lag: Companies that do not invest heavily or strategically in quantum computing may fall behind competitors, missing out on the potential breakthroughs that could disrupt the pharmaceutical industry.

This analysis suggests that companies should prioritize forming strategic partnerships, building in-house expertise, and accelerating investments in quantum computing to leverage future opportunities and mitigate risks.

4.2. Game Theory Analysis

The analysis aimed to evaluate the strategic decision-making of pharmaceutical companies regarding the adoption of quantum computing technologies in their R&D processes under fierce competition. A payoff matrix was constructed based on cost savings, time reduction, and potential investment costs associated with quantum computing integration. Three scenarios were modeled: High Savings, Moderate Savings, and Low Savings, each reflecting different levels of quantum computing’s impact on R&D efficiency and costs.

The calculated payoffs for adopting quantum computing ranged from significant losses due to high initial investment costs to substantial gains, depending on the level of cost savings achieved. For the High Savings scenario, companies could potentially save up to $900 million per project, offsetting the investment cost partially or wholly, depending on the scenario's probability and investment level. However, with current estimated costs of quantum computing adoption ranging from $5 billion to $20 billion, the payoffs were negative in most scenarios, suggesting that current QC costs might still be prohibitive for widespread adoption.

Sensitivity analysis revealed that the strategic attractiveness of quantum computing adoption is highly sensitive to the level of investment costs. When investment costs were assumed at the lower end of the range ($5 billion), the payoff for the High Savings scenario improved significantly, approaching break-even. However, as investment costs increased to $10 billion and beyond, payoffs became increasingly negative, indicating that high upfront costs are a significant barrier to adoption.

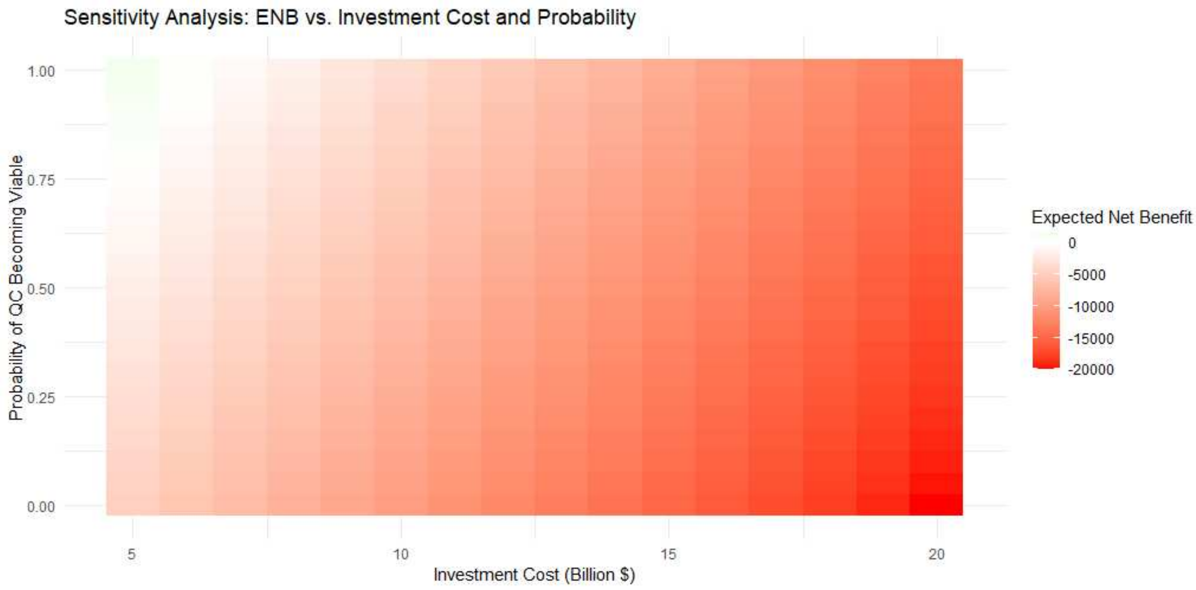

Figure 2: Sensitivity analysis

This analysis underscores the importance of potential future reductions in the cost of QC technology, either through technological advancements or quantum computing-as-a-service models, which could shift the equilibrium towards adoption. The visual analysis (Figure 1) clearly illustrates this shift, with payoffs becoming positive only when investment costs are controlled or drastically reduced.

The payback period analysis demonstrated how quickly companies could recoup their investment in quantum computing technologies under different savings scenarios. For the High Savings scenario, the payback period was estimated to be between 5 and 10 years, depending on the exact savings and initial costs. In contrast, for the Moderate and Low Savings scenarios, the payback periods extended significantly, often beyond a typical pharmaceutical R&D cycle of 10-15 years.

The analysis shows that payback periods decrease notably as cost savings increase and investment costs decrease. However, with current cost estimates, achieving a favorable payback period remains challenging unless technological or service cost reductions occur in the near future.

The impact of scenario probabilities on expected payoffs was also examined. The High Savings scenario, with a probability of 30%, contributed the most to expected payoffs when compared to the Moderate and Low Savings scenarios. However, even with a favorable outcome probability, the expected payoffs did not fully offset the investment costs under current conditions, indicating that while the potential benefits of quantum computing are substantial, the uncertainty surrounding these outcomes remains a critical factor.

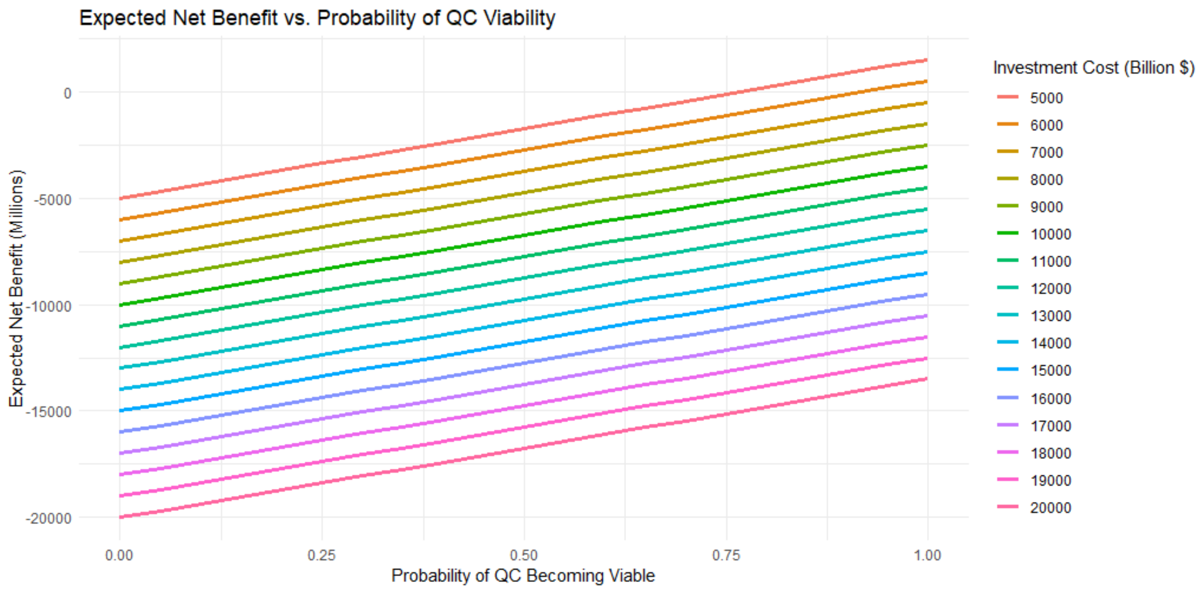

Figure 2: Expected Net Benefit vs. Probability of QC Viability

Figure 3 demonstrates that even small changes in scenario probabilities significantly affect the expected payoff, highlighting the strategic uncertainty pharmaceutical companies face when considering quantum computing adoption. If the probability of high savings increases due to technological advancements or more successful implementations in the industry, expected payoffs could shift positively, encouraging more companies to invest.

The equilibrium analysis indicated that at current cost and probability levels, pharmaceutical companies are more likely to continue with traditional R&D methods unless quantum computing costs decrease significantly, or savings and success rates improve markedly. The study suggests a potential future shift towards quantum computing adoption as costs become more manageable, driven by advances in technology and market dynamics.

In the scenario analyzed, the early mover advantage was not quantified but used as a concept that will be further evaluated in the discussion. A higher first mover advantage would make a higher initial investment more attractive, under the assumption that the other company does not invest. This leads to a prisoner’s dilemma scenario, where the dominant strategy would be to invest, and the Nash equilibrium lies in both companies investing while not being able to profit from the higher payback.

Overall, the findings highlight the delicate balance between potential savings and high initial costs associated with quantum computing. While the technological promise of quantum computing is clear—offering significant reductions in R&D time and costs—realizing these benefits on a large scale will require substantial reductions in the costs of adoption or alternative cost structures, such as QC-as-a-service models, to make adoption a strategically sound decision.

5. Discussion

The top 10 pharmaceutical companies in the world sum up together with a market cap of 2,902.9 trillion dollars. North American companies compose 60% of the ranking: Eli Lilly (1º), Johnson & Johnson (3º), Merck (4º), AbbVie (5º), Pfizer (9º) and Amgen (10º). Novo Nordisk from Denmark in second, Roche and Novartis from Switzerland in sixth and eight, respectively, and AstraZeneca from the UK in seventh complete the ranking (Gavali, 2024).

Of these 10 companies, only Merck mentioned quantum computing in their 2023 annual report. In this case, it was only mentioned that wars and economic sanctions could come in the way of the development of quantum computing, as import/export restrictions could limit the access to important materials, such as advanced chips (Merck, 2024). While quantum computing did not find a space in the annual reports, the topic appeared in articles and interviews regarding all companies researched.

The benefits that quantum computing could potentially bring to the pharmaceutical industry were heavily mentioned. Herman Van Vlijmen, a leader within Johnson & Johnson, states that the transition from classical to quantum computing will disrupt the processes of the pharmaceutical industry, including drug discovery (Dargan, 2024). An article from Roche (Roche, 2024) explains that this disruption will be possible because of the superposition and entanglement qualities of qubits, which will provide much quicker solutions to the industry's problems. The Senior Manager of Data Science of Amgen adds that not only the number of qubits is important, but its quality. Overcoming qubit noise and dealing with gaps between mathematics, machine learning and generative AI within Health Science will be fundamental for the expansion of quantum computing (Quantum Tech, 2023).

Beyond talking about the potential of quantum computing, pharmaceutical companies have been engaging in key partnerships to make this a reality. For instance, Eli Lilly's deal with XtalPi reached U$250 million (Park, 2023). With this partnership, Eli Lilly is interested in bringing AI and quantum physics algorithms to the company and boosting their drug discovery process. Moreover, Roche established a partnership with Cambridge Quantum Computing, which also provides algorithms for developing drug discovery and development processes (Swayne, 2021). Partnerships are also a goal for Pfizer, which works closely with IBM to bring in quantum computing expertise (Pfizer Healthcare Hub, 2024). The importance of partnerships with startups was also found as a common theme while analyzing the relation of the companies to quantum computing was the importance of partnerships with startups. Merck established partnerships with HQS Quantum Simulations, from Karlsruhe, Germany, and with Rahko, from London, UK, dealing with software for quantum chemistry and quantum-based machine learning, respectively (Beckmann, 2020). Additionally, AstraZeneca partnered with startup SandboxAQ, which brings AI and quantum technology that could reduce time, risk and cost of processes and deliver faster treatments to patients (Taylor, 2023).

The forementioned companies have also created research initiatives within their own ecosystems. The creation of task forces to tackle quantum computing has been seen in Roche, Novartis and Pfizer. At Roche, the task force is focused on monitoring the field of quantum computing, while also setting up collaborations and trying out early applications. At Novartis, a Predictive Analytics & Design group works with cutting-edge computing technology to maximize the use of the company's huge data resources to inform research in order to develop new therapies (Mijuk, 2018). Also, Pfizer has created a group, this one called Quantum Computer Exploration Group, a specialized team with the aim of positioning the company as a leader in quantum technology in the coming years (REFERENCE).

As for Novo Nordisk, the Novo Nordisk Foundation Quantum Computing Programme was created to develop quantum computing hardware and algorithms to foster practical applications in life sciences. The 12-year programme received an investment of 1.5 billion Danish Krones to support quantum research and to develop a fully functional quantum computer (Novo Nordisk Foundation, 2022).

5.1. Research Question

H1: Leading companies have established advanced strategies for quantum computing integration.

Based on the case study, the first hypothesis does not hold up to the results. While all companies are investing some resources into quantum computing (e.g. through partnerships and task forces), the only company showing a deeply institutionalized commitment to quantum computing is Novo Nordisk. The other companies are lacking long-term commitments and comprehensive strategies for quantum computing adaptation. It needs to be noted though, that this result is only based on publicly available information, it could be possible that companies do not communicate their strategic plans on quantum computing as a way to remain competitive in their research.

H2: Investing into quantum computing is the dominant strategy for increasing profits in pharmaceutical companies.

The results confirmed that quantum computing has the potential to drastically reduce both the time and cost of pharmaceutical R&D. However, while the potential benefits are clear, the analysis also underscored the significant barriers to adoption, primarily due to high initial investment costs and uncertainties around the viability of quantum computing technology. Current estimates suggest that the cost of acquiring a quantum computer, including hardware and operational expenses, could run into tens of billions of dollars. This poses a substantial financial risk for companies considering early adoption, especially when weighed against uncertain returns.

The game theory analysis provided valuable insights into the strategic decision-making landscape for pharmaceutical companies. The analysis demonstrated that the decision to invest in quantum computing is highly sensitive to key variables such as investment costs, cost savings, and the probability of quantum computing becoming commercially viable. Under current conditions, with investment costs estimated between $5 billion and $20 billion, the payback was often negative, indicating that adopting quantum computing may not be financially viable for most companies without significant cost reductions or shared investment models such as quantum-computing-as-a-service (QCaaS).

Furthermore, it was considered, that first movers could profit from additional advantages if their competition does not adapt to quantum computing, since they could sell their drugs sooner and for a cheaper price, leading to dominance in a very price sensitive market. The higher this initial incentive is, the higher are the changes investing will become the dominant strategy, leading to a Nash equilibrium where most players will invest into quantum computing, with no player gaining a dominant advantage. In this case the hypothesis will hold true, if the competitive advantage turns out to be low and the sunk costs do not decrease the hypothesis would instead be rejected, as investment will be unprofitable in the beginning.

How dependent the profitability of the investment is on various factors was proven in the sensitivity analysis: Even modest changes in the probability of quantum computing success have a profound impact on the expected returns. As the probability of quantum computing viability increases, the payback shifts closer to positive territory, suggesting that advances in quantum computing technology, reduced uncertainty, or successful industry case studies could play a critical role in altering the strategic calculus for companies.

The payback period analysis highlighted that, even under favorable conditions, companies might need to wait 5-10 years or more to recoup their investments in quantum computing. For many firms, especially those under pressure to deliver short-term financial results, this extended payback period represents a significant risk. The analysis suggests that until investment costs decrease, or cost-sharing models are developed, quantum computing adoption will remain limited to companies with substantial financial reserves or those willing to take on higher risk for long-term gains.

“How should pharmaceutical companies, based on game theory, effectively develop dynamic capabilities in quantum computing for drug discovery in different scenarios?”

Based on the findings and in accordance with disruptive technology theory, companies should choose an approach that fits their specific requirements. Quantum computing is a disruptive technology that will reinvent drug R&D. For bigger companies that are highly affected by large R&D spending, funding groundwork quantum computing could be beneficial to accelerate the technological development and build dynamic capabilities through the number of resources and the economies of scale leading companies are able to put into their research.

For smaller companies, however, it is not profitable to fund this initial research, as the sunk cost might be higher than the costs they are saving through efficiency gains. Instead, they should consider an innovation imitation strategy or participate in open innovation, through collaboration on projects with other organizations and public institutions, thus obtaining access to quantum computing knowledge for a cheaper price, since they are unlikely to be able to compete with the big players on research capabilities anyway. To build dynamic capabilities they should rather focus on specific areas and niche applications that they build and maintain a competitive advantage in.

In general, it is important to maintain an eye on the market developments, as sunk costs, new business models like QCaaS and increasing availability of quantum computing might change the initial cost and will likely make future investments more profitable.

5.2. Implications for the Pharmaceutical Industry

The findings of this study have several important implications for the pharmaceutical industry:

- Strategic Adoption Decisions: Pharmaceutical companies must carefully weigh the potential benefits of quantum computing against the significant financial risks. The results suggest that companies should adopt a cautious approach, investing in quantum computing only when the probability of success is sufficiently high or when costs are shared through consortia or service models.

- Role of quantum computing -as-a-Service: The concept of QCaaS, where companies access quantum computing capabilities through cloud-based services or partnerships, could provide a more financially viable pathway for adoption. This model could reduce upfront costs and distribute risk, making quantum computing technology more accessible to a broader range of companies.
- Need for Continued Technological Development: The industry must continue to monitor developments in quantum computing technology, as advancements could dramatically alter the cost-benefit equation. Public and private investment in quantum computing R&D, as well as pilot projects, will be essential to reducing technological uncertainty and demonstrating real-world value.
- Long-Term Value Creation: Beyond cost savings and efficiency gains, quantum computing has the potential to increase the success rate of drug discovery projects significantly. This could lead to the development of new treatments for previously untreatable conditions and improve global access to affordable medicines, aligning with broader industry goals of innovation and public health impact.

5.3. Limitations of the Study

While the study provides valuable insights, it is important to acknowledge its limitations. The analysis relied on available estimates and projections of quantum computing costs and savings, which are inherently uncertain given the early stage of quantum computing technology. Additionally, the game theory model simplified complex strategic decisions into a binary framework, which may not capture all nuances of real-world decision-making.

Further research should aim to incorporate more detailed data as quantum computing technology evolves, including case studies of early adopters and empirical validation of the modeled assumptions. Additionally, exploring qualitative insights from industry experts could complement the quantitative findings and provide a richer understanding of the strategic and operational challenges associated with quantum computing adoption.

6. Conclusion

This study provides a comprehensive evaluation of the impact of quantum computing on pharmaceutical R&D, highlighting both the transformative potential and the significant financial challenges associated with adoption in an environment with fierce competition. While the promise of quantum computing is clear, particularly in terms of cost reduction and efficiency gains, the high initial costs and technological uncertainties mean that widespread adoption is likely to be gradual and dependent on future developments. By providing a structured framework for evaluating quantum computing investment decisions using game theory, this research contributes to the ongoing conversation about how next-generation technologies will shape the future of pharmaceutical innovation.

References

Ambrosini, V., & Bowman, C. (2009). What are dynamic capabilities and are they a useful construct in strategic management? *International Journal of Management Reviews*, *11*(1), 29–49. https://doi.org/10.1111/j.1468-2370.2008.00251.x

Baniak, A., & Dubina, I. (2012). Innovation analysis and game theory: A review. *Innovation*, *14*(2), 178–191. https://doi.org/10.5172/impp.2012.14.2.178

Barney, J. (1991). Firm Resources and Sustained Competitive Advantage. *Journal of Management*, *17*(1), 99–120. https://doi.org/10.1177/014920639101700108

Blake, R. A. (2007). Target validation in drug discovery. *Methods in Molecular Biology (Clifton, N.J.)*, *356*, 367–377. https://doi.org/10.1385/1-59745-217-3:367

Bova, F., Goldfarb, A., & Melko, R. G. (2021). Commercial applications of quantum computing. *EPJ Quantum Technology*, *8*(1), 2. https://doi.org/10.1140/epjqt/s40507-021-00091-1

Bova, F., Goldfarb, A., & Melko, R. G. (2023). Quantum Economic Advantage. *Management Science*, *69*(2), 1116–1126. https://doi.org/10.1287/mnsc.2022.4578

Bower, J. I., & Christensen, C. M. (1995). *Disruptive technologies: Catching the wave.*

Brickley, J., Smith, C., & Zimmerman, J. (2000). An Introduction to Game Theory and Business Strategy. *Journal of Applied Corporate Finance*, *13*(2), 84–98. https://doi.org/10.1111/j.1745-6622.2000.tb00056.x

Castelvecchi, D. (2023). Ibm releases first-ever 1,000-qubit quantum chip. *Nature*, *624*(7991), 238. https://doi.org/10.1038/d41586-023-03854-1

Cova, T., Vitorino, C., Ferreira, M., Nunes, S., Rondon-Villarreal, P., & Pais, A. (2022). Artificial Intelligence and Quantum Computing as the Next Pharma Disruptors. *Methods in Molecular Biology (Clifton, N.J.)*, *2390*, 321–347. https://doi.org/10.1007/978-1-0716-1787-8_14

Deore, A. B., Dhumane, J. R., Wagh, R., & Sonawane, R. (2019). The Stages of Drug Discovery and Development Process. *Asian Journal of Pharmaceutical Research and Development*, *7*(6), 62–67. https://doi.org/10.22270/ajprd.v7i6.616

DiVincenzo, D. P., & Loss, D. (1998). Quantum information is physical. *Superlattices and Microstructures*, *23*(3-4), 419–432. https://doi.org/10.1006/spmi.1997.0520

Djordjevic, I. B. (2021). Basics of quantum information, quantum communication, quantum sensing, and quantum networking. In A. T. Azar & N. A. Kamal (Eds.), *Design, Analysis, and Applications of Renewable Energy Systems.* Elsevier.

Erhun, F., & Keskinocak, P. (2003). *Game theory in business applications*. http://www.unife.it/economia/lm.economia/insegnamenti/economia-applicata-avanzata/mat-did/trade-scm/game-theory-in-business-applications2003-per-lezione.pdf

European Parliament. (2019). *List of some Definitions and Background Documents on Quantum Computing.* European Parliament. https://www.europarl.europa.eu/meetdocs/2014_2019/plmrep/COMMITTEES/AIDA/DV/2021/04-23/ListBackgroundDocumentsQuantumComputing_EN.pdf

Farzaneh, M., Wilden, R., Afshari, L., & Mehralian, G. (2022). Dynamic capabilities and innovation ambidexterity: The roles of intellectual capital and innovation orientation. *Journal of Business Research*, *148*, 47–59. https://doi.org/10.1016/j.jbusres.2022.04.030

FDA (Thu, 2019, April 18). Step 3: Clinical Research. *FDA*. https://www.fda.gov/patients/drug-development-process/step-3-clinical-research

Fedorov, A. K., Gisin, N., Beloussov, S. M., & Lvovsky, A. I. (2022, March 31). *Quantum computing at the quantum advantage threshold: a down-to-business review*. http://arxiv.org/pdf/2203.17181

Fowler, A. G., Mariantoni, M., Martinis, J. M., & Cleland, A. N. (2012). Surface codes: Towards practical large-scale quantum computation. *Physical Review a*, *86*(3). https://doi.org/10.1103/PhysRevA.86.032324

Freeman, R. E., Dmytriyev, S. D., & Phillips, R. A. (2021). Stakeholder Theory and the Resource-Based View of the Firm. *Journal of Management*, *47*(7), 1757–1770. https://doi.org/10.1177/0149206321993576

Gerhart, B., & Feng, J. (2021). The Resource-Based View of the Firm, Human Resources, and Human Capital: Progress and Prospects. *Journal of Management*, *47*(7), 1796–1819. https://doi.org/10.1177/0149206320978799

Gottesman, D. (2009, April 16). *An Introduction to Quantum Error Correction and Fault-Tolerant Quantum Computation*. http://arxiv.org/pdf/0904.2557

GÜREL, E. (2017). Swot Analysis: A Theoretical Review. *Journal of International Social Research*, *10*(51), 994–1006. https://doi.org/10.17719/jisr.2017.1832

Hogerzeil, H. V. (2006). Essential medicines and human rights: what can they learn from each other? *Bulletin of the World Health Organization*, *84*, 371–375.

Hughes, J. P., Rees, S., Kalindjian, S. B., & Philpott, K. L. (2011). Principles of early drug discovery. *British Journal of Pharmacology*, *162*(6), 1239–1249. https://doi.org/10.1111/j.1476-5381.2010.01127.x

Ivanov, A., & Cojocaru, M. (2023). Reinventing the Pharmaceutical R&D Pipeline: The Transformative Potential of Quantum ML Simulation. *Sage Science Review of Applied Machine Learning*, *6*(11), 22–31. https://journals.sagescience.org/index.php/ssraml/article/view/113

Kaitin, K. I. (2010). Deconstructing the drug development process: The new face of innovation. *Clinical Pharmacology and Therapeutics*, *87*(3), 356–361. https://doi.org/10.1038/clpt.2009.293

Light, D. W. (2012). *Pharmaceutical research and development of new medicines.* Health Action International. https://haiweb.org/encyclopaedia/pharmaceutical-research-and-development/

Lockett, A., Thompson, S., & Morgenstern, U. (2009). The development of the resource‐based view of the firm: A critical appraisal. *International Journal of Management Reviews*, *11*(1), 9–28. https://doi.org/10.1111/j.1468-2370.2008.00252.x

Lüders, K. (2023). *Grundlagen der Physik*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-66364-6

Martínez-Vergara, S. J., & Valls-Pasola, J. (2021). Clarifying the disruptive innovation puzzle: a critical review. *European Journal of Innovation Management*, *24*(3), 893–918. https://doi.org/10.1108/EJIM-07-2019-0198

Mc Kinsey & Company. (04/2023). *Quantum Technology Monitor*. https://www.mckinsey.com/~/media/mckinsey/business%20functions/mckinsey%20digital/our%20insights/quantum%20technology%20sees%20record%20investments%20progress%20on%20talent%20gap/quantum-technology-monitor-april-2023.pdf

McMahon, D. (2008). *Quantum Computing Explained* (1st ed.). *Wiley - IEEE Ser*. IEEE Computer Society Press.

Microsoft. (2024, March 27). *Azure Quantum | Entanglement*. https://quantum.microsoft.com/en-us/explore/concepts/entanglement

National Academies Press (US). (2019). *Frontiers of Engineering: Reports on Leading-Edge Engineering from the 2018 Symposium.* https://doi.org/10.17226/25333

OECD. (2017). *Research and development (R&D)*. Organisation for Economic Cooperation and Development. https://doi.org/10.1787/09614029-en

OECD. (2023). Pharmaceutical research and development. In OECD (Ed.), *Health at a Glance. Health at a Glance 2023.* Organisation for Economic Cooperation and Development. https://doi.org/10.1787/0bdf62a7-en

Olatunji, O. O., Adedeji, P. A., & Madushele, N. (2021). Quantum computing in renewable energy exploration: status, opportunities, and challenges. In A. T. Azar & N. A. Kamal (Eds.), *Design, Analysis, and Applications of Renewable Energy Systems* (pp. 549–572). Elsevier. https://doi.org/10.1016/B978-0-12-824555-2.00019-8

Pammolli, F., Magazzini, L., & Riccaboni, M. (2011). The productivity crisis in pharmaceutical R&D. *Nature Reviews. Drug Discovery*, *10*(6), 428–438. https://doi.org/10.1038/nrd3405

Pammolli, F., Righetto, L., Abrignani, S., Pani, L., Pelicci, P. G., & Rabosio, E. (2020). The endless frontier? The recent increase of R&D productivity in pharmaceuticals. *Journal of Translational Medicine*, *18*(1), 162. https://doi.org/10.1186/s12967-020-02313-z

Preskill, J. (2018). Quantum Computing in the NISQ era and beyond. *Quantum*, *2*, 79. https://doi.org/10.22331/q-2018-08-06-79

Ridder-Hans, G. (2020). *Case Study Research: Approaches, Methods, Contribution to Theory* (2. Rainer Hampp Verlag). Rainer Hampp Verlag. https://www.wiso-net.de/document/EBOK,AEBO__9783957102638234

Si, S., & Chen, H. (2020). A literature review of disruptive innovation: What it is, how it works and where it goes. *Journal of Engineering and Technology Management*, *56*, 101568. https://doi.org/10.1016/j.jengtecman.2020.101568

Sun, D., Gao, W., Hu, H., & Zhou, S. (2022). Why 90% of clinical drug development fails and how to improve it? *Acta Pharmaceutica Sinica. B*, *12*(7), 3049–3062. https://doi.org/10.1016/j.apsb.2022.02.002

Teece, D. J. (2020). Hand in Glove: Open Innovation and the Dynamic Capabilities Framework. *Strategic Management Review*, *1*(2), 233–253. https://doi.org/10.1561/111.00000010

Teece, D. J., Pisano, G., & Shuen, A. (1997). Dynamic capabilities and strategic management. *Strategic Management Journal*, *18*(7), 509–533. https://doi.org/10.1002/(SICI)1097-0266(199708)18:7<509::AID-SMJ882>3.0.CO;2-Z

Tellis, W. (1997). Application of a case study methodology. *The Qualitative Report*, *3*(3), 1–19.

U.S. Food & Drug Administration. (2018). *The Drug Development Process*. https://www.fda.gov/patients/learn-about-drug-and-device-approvals/drug-development-process

United Nations. (2024, September 12). *Goal 3 | Ensure healthy lives and promote well-being for all at all ages.* Department of Economic and Social Affairs. https://sdgs.un.org/goals/goal3#targets_and_indicators

Watkins, P. B. (2011). Drug safety sciences and the bottleneck in drug development. *Clinical Pharmacology and Therapeutics*, *89*(6), 788–790. https://doi.org/10.1038/clpt.2011.63

World Health Organization. (1989). *Constitution*. World Health Organization.

Zalka, C. (1998). Simulating Quantum Systems on a Quantum Computer. *Proceedings: Mathematical, Physical and Engineering Sciences*, *454*(1969), 313–322. http://www.jstor.org/stable/53167

Zinner, M., Dahlhausen, F., Boehme, P., Ehlers, J., Bieske, L., & Fehring, L. (2022). Toward the institutionalization of quantum computing in pharmaceutical research. *Drug Discovery Today*, *27*(2), 378–383. https://doi.org/10.1016/j.drudis.2021.10.006