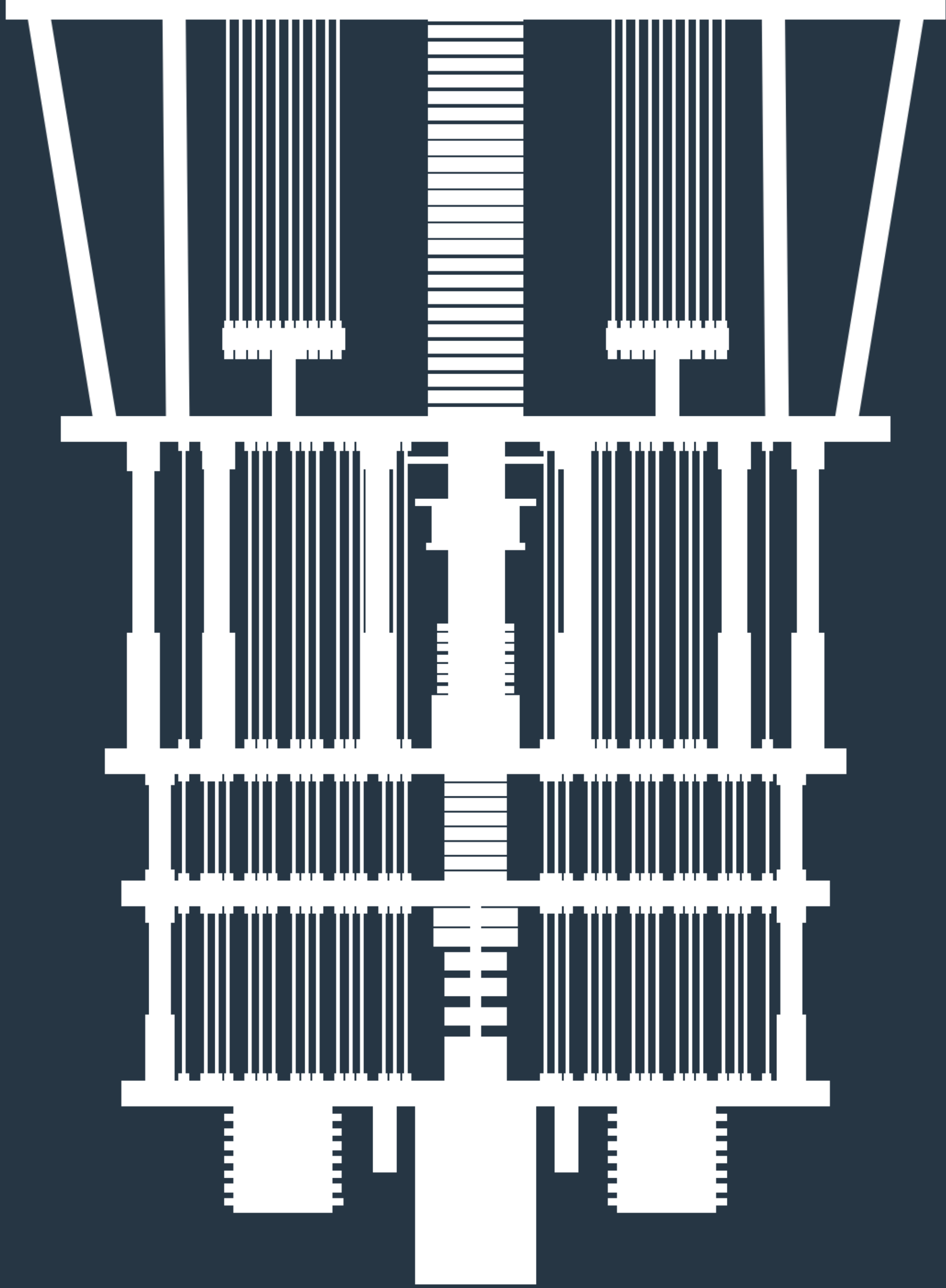

The Business Ecosystem of the Quantum Computing Market: Cooperation and Competition

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MSc Management of Technology

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MASTER THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

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Gratia. Haec enim est una virtus non solum maxima sed etiam mater virtutum omnium reliquarum.

Gratitude. For this one virtue is not only the greatest, but is also the parent of all the other virtues.

MARCUS TULLIUS CICERO

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This thesis marks the end of my time as a student. As I sit here writing these acknowledgements, reflecting on the past seven years, I cannot help but be overcome by a sense of nostalgia, content and pride. In these seven years in Delft I met some of my closest friends and learned not only how to be an engineer, but mostly to be a better person. Although I thought it would be much easier the second time, not falling for the same things I fell for in my previous thesis, I was provided with new challenges and still learned a lot throughout this project.

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Summary

The current second quantum revolution heralds the biggest technological advancements of the twenty-first century. At the forefront of this is the development of quantum computers, which promise to bring transformations to almost all sectors, from banking to drug research. With rising investments in developing full-scale, fault-tolerant quantum computers, the quantum computing provider market is starting to saturate with incumbents. In order to succeed, firms operating in this market need to start acting competitively. However, despite vast research on the potential applications, technological development and responsible innovation, little is known about strategic factors that drive the market.

To address this issue, this work identifies, describes and contextualises the use of alliances in firms' business strategy in the quantum computing business ecosystem. Through literature review, publications of various types of collaborations on firms's websites, and interviews with four experts in the industry, the work describes the quantum computing business ecosystem, links the cooperations to literature on strategies, and provides contextual implementations of various alliances.

First, a value proposition is constructed, containing five components: Hardware providers, cloud service providers, quantum software providers, managed services providers and end-users, each with its own set of challenges and strategies attached to it. Furthermore, two technology strategies pursued by firms can be identified: an open innovation approach and a full-stack approach. The use of various types of collaborations are described, including licensing, standards agreements, business networks, joint marketing, selling and offering agreements, consortia, strategic partnerships, mergers and acquisitions, and joint ventures.

For SMEs, alliances through bidding consortia, formed for tenders and subsidies, are the main use of cooperation. Strategies herein are the acquisition of capital, reduction of R&D costs, early product show-off, and staying in the loop for technological decision making on standards. Other partnerships are aimed at figuring out relationships with other firms in the industry, and fostering standardisation through the release of open-source software. The former is characteristic of the nascent ecosystem's formation, as the value proposition is still unclear and the industry's architecture is not set. The use of open-source software has also played a key role in the development of the classical computer, and firms are seen to adhere to a similar approach. Furthermore, we contextualise the strategic differences between the full-stack and open innovation approaches that are seen within the ecosystem. Where firms in the former are challenged by technical inflexibility, low sales volume and vast investment costs, firms in the latter need to balance an appropriability-adoption dilemma, create sufficient alignment with their value proposition and use extensive cooperation to ensure compatibility and modularity. However, through this, they get to enjoy increased economies of scale and agility.

All in all, the strategies can be summarised in two main categories: procurement of resources and embedding into the ecosystem. The work in this thesis encompasses a multitude of related fields including competitive strategy, ecosystems and alliances, and discusses the quantum computing industry from the standpoint of the technology providers and developers, which should aid managers in evaluating their strategic position in the ecosystem and in drafting cooperation strategies. From an academic perspective, this work provides the first managerial study of the quantum computing market from the standpoint of the technology providers. In addition to strategies, it identifies a lack of alignment of end-users as a key inhibitor to the constitution of the value proposition. Moreover, the findings of this thesis support the hypothesis that pre-adaptation-phase strategies are aimed at constituting Ortt and Kamp's technological innovation system (TIS) framework's building blocks, an important step to understanding ecosystem formation dynamics.

Lastly, we identify several key areas for future studies. This includes validating and strengthening the conclusions of this work through additional expert interviews, which should also help in exposing nuances in strategy between firm sizes, position in the value chain and geolocation, as well as similarities and differences with the development of the classical computer. Furthermore, future studies are suggested to investigate the differences in efficiency and effectiveness of governmental funding in the quantum industry, characterise end-users based on their expected moment of engagement with the quantum computing market, the role of alliances in quantum computing platform formation, and the link between innovation-phase strategies and the TIS framework's building blocks.

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Chapter 1

Introduction

Life nowadays is unimaginable without phones, computers and other electronic devices. Indisputably the biggest innovation of the last century, the digital era has completely transformed our everyday lives. Surprisingly, at the early stages of its development, the tendency was to severely underestimate the impact computers would have: it was estimated only hundreds would be needed to serve us globally. This was a result of technological incompetence in transistor technology, causing computers to be awkwardly big and unreasonably expensive. The discovery of quantum mechanics provided the knowledge necessary to create transistors based on semiconductors, and the resulting change to the digital era is what is known as the first quantum revolution [1]. Developments in physics in the early 1920s led to new understanding of materials and their transport properties, which were later used to fabricate the transistors that are still enabling our computers, phones and other electronic devices today. It spawned an enormous industry, became an asset of paramount strategic importance for all entities in the world and transformed our everyday lives. We are now at the forefront of a second quantum revolution: one in which we are able to harness and control single quantum systems. Like how the first quantum revolution was responsible for most of the technological advances in the twentieth century, it is speculated that physical technological advances in the twenty-first century will be mostly driven by the second quantum revolution [1].

At the forefront of this revolution is the advent of quantum computing. Introduced by physicist Richard Feynman in 1981, quantum computers use single quantum systems as a quantum equivalent of bits [2]. The idea was initiated for their capabilities of simulating physical systems. Systems that are governed by quantum mechanics, such as molecular structures and high-energy physics problems, are difficult to solve using classical computers and could be solved by a quantum computer considerably faster and more efficiently than their classical equivalent. However, the hype surrounding quantum computing did not fully take off until 1994, when Peter Shor introduced a quantum algorithm that could find the prime factors of integer numbers much faster than is possible classically [3]. As our inability to solve this problem for very large numbers is what lies at the basis of most encryption used today, a sufficiently powerful quantum computer could break the security of the internet, banks and many more digital applications. The strategic value of such a technology generated an enormous amount of interest in quantum computers, leading to large investments and widespread development.

1.1 Quantum Computing in a Nutshell

In quantum computers, the two-level bit is replaced by a quantum-mechanical two-level system: the quantum bit or qubit. This system adheres to the laws of quantum mechanics, providing it with two important qualities that separate it from its classical analogue: superposition and entanglement. The former entails that the two levels can be occupied simultaneously. This means that unlike of the classical which is either 0 or 1, the qubit can be both at the same time. Therefore, one can express the qubit state as

$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle\,, \tag{1.1}$$

where $|\psi\rangle$ is wavefunction describing the qubit's state, and $|0, 1\rangle$ are the two quantum mechanical levels in the Dirac notation. α and β are complex parameters that determine the qubit's state. Quantum mechanics dictates that upon measurement, i.e. reading out the state of our qubit, the its wavefunction collapses to one of the basis states, with the probabilities given by $P(|0\rangle) = \alpha^2$ and $P(|1\rangle) = \beta^2$. This also mandates that the wavefunction is normalised; after all, the total probability must be equal to one:

$$P(|0\rangle \cup |1\rangle) = \alpha^2 + \beta^2 = 1. \tag{1.2}$$

A common way of illustrating a qubit's superposition state is with the Bloch sphere, given in figure 1.1a, where the wavefunction is represented by a vector that can point in any direction in the sphere.

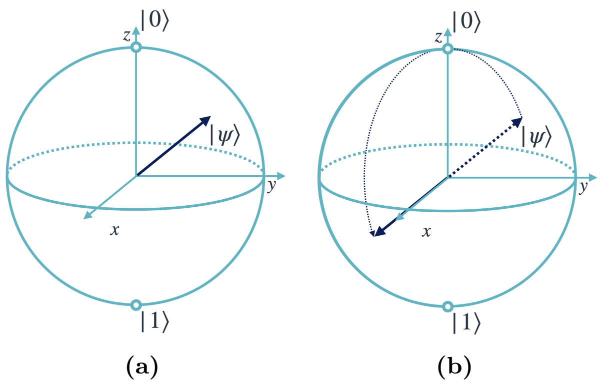

Figure 1.1: **(a)** Bloch sphere representation of the qubit's state $|\psi\rangle$. The vector can point anywhere along the sphere, determined by the complex values α and β. **(b)** The qubit's state can be altered by the application of a quantum gate, leading to a change in the vector's position on the Bloch sphere.

Similar to a classical computer, the qubit's state can be controlled using gates, which perform various operations. One of these operations is illustrated in figure 1.1b. As the qubit state can lie anywhere on the Bloch sphere, an infinite amount of operations can be constructed. Furthermore, gates that operate on multiple qubits, such as controlled-NOT gates, are also possible. The minimal set of gates which constitute all possible qubit operations and with which a universal quantum computer can be created was described by DiVincenzo [4]. Much of the quantum computing research is based around creating a stable and scalable platform to host qubits on which we can operate with this complete set of gates. Like in the classical case, a quantum algorithm is constructed by applying a consecutive set of various gates on a collection of qubits. An example on five qubits is shown in figure 1.2, which is an implementation of the Deutsch-Jozsa algorithm [5]. This algorithm was designed to be exponentially faster on a quantum computer than any possible implementation on a classical computer.

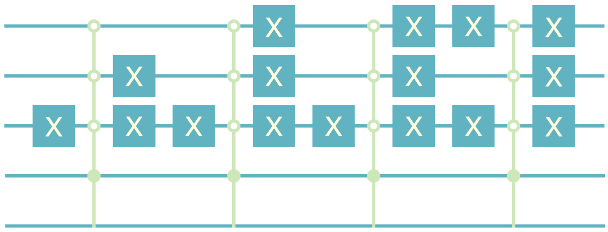

Figure 1.2: Five-qubit implementation of the Deutsch-Jozsa algorithm. The boxes represent single-qubit gates. Controlled-NOT gates are applied in between sequences of single-qubit gates, shown with the green vertical lines.

Although the Deutsch-Josza algorithm has no currently known application, quantum algorithms that solve some very significant problems have been developed. Perhaps the most famous, Shor's factoring algorithm can be used to find the prime factors of an integer number almost exponentially faster than the best classical computer can [3]. The reason this spawned significant interest in quantum computers is because much of our current encryption is based on our inability of factoring large integers. A sufficiently large quantum computer would therefore be able to break the encryption of banks, the internet and sensitive documents. Quantum computers are also inherently good at simulating natural systems, which are governed by quantum-mechanical laws. This was the reason they were introduced by physicist Richard Feynman in the first place [2]. Being able to simulate physical systems can enhance not just physics research, but also has applications in drug discovery, batteries, chemical processes and many more [6]. Furthermore, algorithms with applications in logistics, finance, and machine learning have also been discovered [7]. The computational advantages of quantum computing have been summarised by BCG and fall into four categories of mathematical problems [8], as shown in table 1.1.

Table 1.1: The four categories of mathematical problems where quantum computers can provide speedup [8].

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

With such widespread applications, many sectors are looking to benefit from quantum computing. However, before we can harness the power of large-scale quantum computers, there are some significant challenges to overcome. Generally, the quantum systems that make up the qubits are very easily influenced by their environment. Disturbances erase the information stored in the qubits, which we call decoherence. Decoupling the qubits from the environment is therefore necessary to make them more stable. However, in order to be able to harness qubits, rapidly applying all sorts of gates and measuring them, the qubits need to be strongly connected to each other and to the gate mechanisms. This poses a big challenge, where these connections must not inhibit the qubit's stability, but at the same time must be strong enough to allow for rapid calculations.

Although quantum error-correction algorithms have been developed to increase this stability, qubits and gates need to pass a threshold of stability before these algorithms start delivering an advantage [9]. Moreover, the increased stability from error correction comes at the expense of an increase in qubits and applied gates. Hence, in order to run large-scale simulations and algorithms, many qubits are required. Eventually, millions of qubits will be needed to perform successful quantum error-correction and practical computations [10]. This leads to the second big challenge in the development of full-scale, fault-tolerant quantum computers: scalability.

1.2 The Race to Quantum Advantage

The potential of quantum computers spawned a rapidly growing market [11, 12, 13], where actors are working on all stages necessary for its realisation, from quantum software and algorithms to the various hardware necessary to create and control qubits. A big milestone was reached in 2019, when researchers at Google demonstrated quantum supremacy with their successful implementation of an algorithm on a quantum computer that would take a classical computer much longer to complete [14]. Although disputed [15], this started the noisy intermediate-scale quantum (NISQ) era, in which (imperfect) control of upwards of 50 qubits is reachable [16]. This number is significant because it is beyond the simulable capacity of classical supercomputers. The next milestone in the development of QC would be quantum advantage, where we see useful applications of quantum calculations [6].

Although the NISQ era might not yet see useful business applications for QC, the potential market for and by the disruptive innovation is gaining traction. The developments in QC have attracted many large firms, including IBM, Google and Microsoft, but also have constructed a landscape full of small- and medium-scale enterprises (SMEs) that are working towards its realisation [13]. These players are not all trying to build their own complete quantum computer: Analogous to the semiconductor industry, we see a distinction between manufacturers that have a full-stack approach and those focused on a subsystem of the full-stack quantum computer [17]. The quantum business ecosystem has been described by Jenkins et al. [18], and they analyse firms' strategies as they invest in quantum computing. So far, qubits based on superconducting circuits and trapped ions are are the two leading technologies [17], but qubits based on semiconducting quantum dots [19, 20] and fault-tolerant photonics [21, 22] have also been deemed promising. Furthermore, ongoing research on alternate qubit platforms may provide more promising technologies down the line [23]. Figure 1.3 shows the quantum computing business ecosystem according to Jenkins et al., with the inclusion of more hardware platforms.

Much of the current research efforts are aimed at creating more stable and more scalable qubits, often made with highly specific, low-yield processes. However, very recently the use of advanced semiconductor manufacturing for qubits has been demonstrated, allowing for more reliable fabrication and large-scale production of quantum processors [24]. Moreover, a recent publication by Google showed the first instance of error-correction code that increases performance with the number of qubits [9]. These advances show an adoption of quantum technology by large, established firms, leading in industrialisation and commercialisation of the novel technology. However, to reach the universal fault-tolerant quantum computing regime, in which thousands of protected qubits are used for computation [16], we likely need millions of physical qubits [10]. With the current prospect of having qubits in the hundreds in 2023, such as presented in IBM's roadmap [25], we are still far away from its realisation.

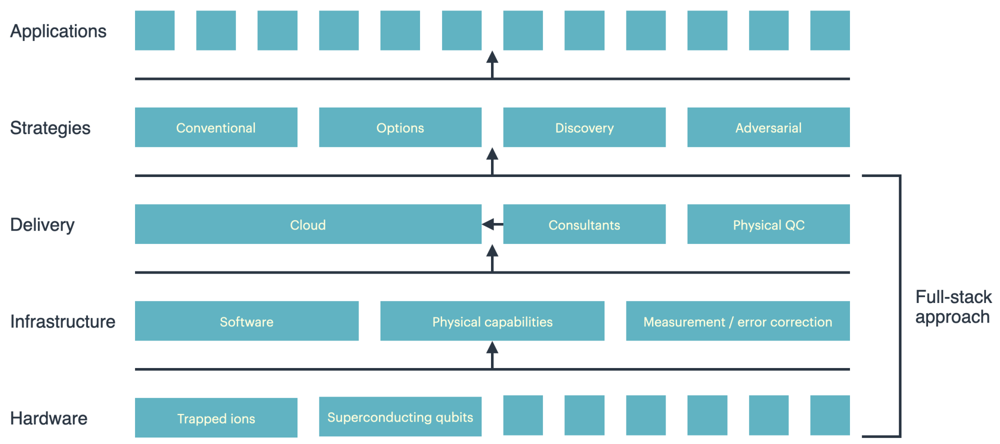

Figure 1.3: Quantum computing business ecosystem, adopted from [18]. The figure has been altered slightly to account for the rise of hardware platforms for qubits since the time of the publication.

1.3 Research Gap

The race to quantum advantage is causing vast investments from both governing agencies and firms who might benefit from the technology [12], as demonstrated in figure 1.4. As is the case with disruptive innovation, the currently large firms may not be able to hold their position in the market after a disruptive technology has been adopted [26]. For established firms, trend monitoring and early detection of possibly disruptive incumbents is crucial for maintaining their position [27]. This engagement can also be seen from leading classical computing firms, such as IBM, who are eager to lead the development of this novel innovation. For new firms, the volatility and uncertainty in the market opens up possibilities for growth and establishment in the forthcoming QC market. MacQuarrie et al. [13] compared the current state of the QC market to the supercomputing market of the 1980s, where the need for a replacement of the established architecture caused a surge in new firms developing alternate technology [28]. Once a dominant design emerged, the number of firms dropped rapidly. The QC market may experience a similar process once a dominant qubit design has been chosen. This dominant design may appear through strategic platform leadership, as was established by Intel in the microprocessor market by focusing on the end-users [29]. Furthermore, with the current hardware market starting to saturate with players, now is the time to start acting strategically [30], as those that win the quantum computing race may end up capturing significant share in a market that has been estimated to be worth between $450 billion and $1 trillion in the next 15 to 30 years [11, 31].

Scientific literature on the business of quantum computing describes market growth [13], provides frameworks and strategies for dealing with quantum computing [18, 32], discusses responsible innovation practices [33, 34], and reviews the current market and literature states [17, 35]. However, despite vast literature on the adoption of quantum computing technologies once the technology is enabled, little research looks at the business ecosystem that is developing quantum computers from a managerial perspective. The few works above that do take a managerial standpoint only describe the ecosystem, rather than providing prescriptive frameworks or strategies for decision making. The work by MacQuarrie et al. [13] identifies the pursuit of two strategies: a full-stack approach in which all innovation is developed in-house, and a structural open innovation approach, through which companies focus on a part of the complete stack. The latter option leaves room for SMEs who are developing QC components, where a platform leader drives an ecosystem of complements around a certain technology platform. This type of development mostly happens through strategic alliances, which have been the focus of a multitude of studies [36, 37], and quantum technologies are no exception. A key finding is that strategic alliances can provide SMEs the resources and knowledge to stand their ground against larger actors [38]. Furthermore, with the rise of the platform economy [39], inter-organisational collaboration is becoming increasingly important for strategy formulation [40].

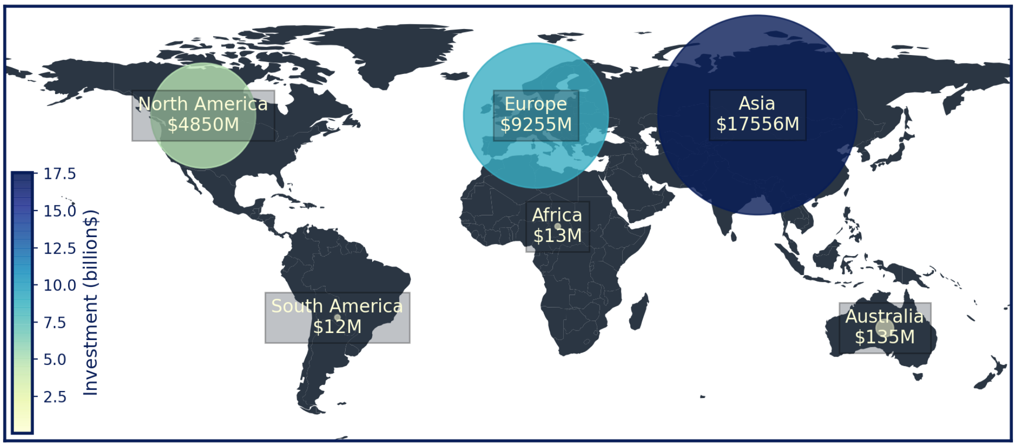

Figure 1.4: Continental investment in quantum computing. Includes both governmental and private funding [41].

To our knowledge, only a single document with suggestions for technology providers has been released, by the Boston Consulting Group (BCG) [11]. In this document, BCG stresses the importance of compliance with the surrounding complementaries, and of adopting an engagement and ecosystem strategy, which is in line with what is mentioned above. Hence, a need arises for research on platforms and ecosystems in the QC industry, and the ecosystem strategies that can be adopted by firms to fit this best. This applies both to those who are seeking to become platform leaders, as well as those developing complementaries to drive the networking effects and advance the platform. Moreover, research has recognised the importance of the emerging phase of ecosystems as the phase in which the industry value structure is formed and firms have the largest influence on setting it to their benefit [42]. However, with a significant portion of quantum startups consisting of university spin-offs, their executives often have little business experience and education. This work therefore also aims to provide a basis to inform these scientists about the basics of business strategy applied to their field.

In order to describe and assess strategy in the quantum computing market, we turn to strategic management literature. In its history, we see the body of literature co-evolve with an ever-increasing complexity of the business context. In the middle of the previous century, significant paradigms in strategic thinking include the resource-based view introduced by Edith Penrose, and the competitive forces model from Porter, which finds its roots in the structure-conduct-performance paradigm [43, 44]. The former focuses on a firm's difficult-to-replicate strategic assets as a constitute of competitive advantage, where the latter is concerned with building a defensible position against an industry's competitive forces. However, both these theories are suggested to be inapt at accurately dealing with the high-paced, global environment of the modern economy [45]. The traditional resource-based views of firms, focusing on a firm's assets, tend to underestimate the importance of timely asset attainment, reconfiguration and evaluation. This is especially the case in nascent industries, where the value proposition that will eventually rule the industry is not yet known or present. In Schumpeterian words, the 'rules of the game' are not yet set, hence conventional strategy, like Porter's industry analysis and differentiation strategies, will not yet suffice. As a result, ubiquitous examples of initially leading firms that lose to start-up entrants can be found. The problems for management in these contexts have been the subject of many studies in management. Christensen's famous 'Innovator's dilemma' focuses on this through the lens of disruptive innovations: those that alter the conventional value chain and thus require a new way of reconfiguring the business [26]. The dynamic capabilities approach tries to tackle the issue by stressing the importance of mobility and learning [46, 42]. Markides and Geroski address a potentially successful strategy in their book 'Fast second', where second-mover advantages combine early-to-market advantages with the imitation of tried-and-tested ideas initiated by first-moving firms [47]. Moreover, building on the dynamic capabilities approach, a recent paradigm is seen to describe the business environment as an ecosystem in which competition and cooperation coexist and firm-level value can be captured through platforms, construction of beneficial industry structures and complementarity [42, 48, 49, 29]. Although the subject has seen a vast amount of interest in recent years, the drivers and mechanisms of platform and ecosystem formation are still poorly understood [50]. Therefore, studying the ecosystem in an infant industry might provide novel insights into the early-stage mechanisms of platform formation, the actors and their roles in ecosystem emergence and how the ecosystem evolves over time. Furthermore, although the role of alliances in ecosystems has seen some study [51, 52], the development interdependence of quantum computing components could provide new insights into the competitive and cooperative elements of high-tech ecosystems.

1.4 Research Objective and Questions

This thesis aims to fill the research gap by studying actors in the quantum hardware market, and determining the drivers of the ecosystem innovation that is taking place. The research objective is therefore:

Research objective: *To identify, describe and contextualise the use of alliances in firms's business strategy in the quantum computing hardware ecosystem.*

Based on the main objective, the following sub-goals can be derived:

- *Map out the quantum computing hardware ecosystem, including players, stakeholders and cooperations.*
- *Link the cooperations to literature on alliance strategy and ecosystems, and provide parallels with historical developments in neighbouring industries, such as the microprocessor industry.*
- *Describe and identify the competitive advantages that are obtained for SMEs in this industry through strategic alliances.*

Conversely, we pose the following main research question:

Research Question: *What alliance strategies are present in the quantum computing hardware ecosystem, and how could they help firms to achieve competitive advantage?*

In order to answer the main question, we can constitute the following sub-questions:

1. *What does the quantum computer business ecosystem look like?*
   (a) *What actors, activities and architectures can be identified?*
   (b) *What (kinds of) alliances are seen?*
2. *Looking at literature on cooperative and competitive strategy, which roles and strategies described in literature can we see in the QC market?*
3. *What benefits can be expected from the identified strategies, and what risks are tied to them?*

As a result, this thesis will provide a contextual overview of alliances in the QC ecosystem, which should aid managers in drafting strategic alliance implementation plans.

1.5 Outline

In Chapter 2, we provide a review of the literature. It covers managerial literature on quantum computing and provides a theoretical and contextual background of literature on strategic management, starting from Porter's forces and the resource-based view pioneered by Edith Penrose, leading up to the ecosystem paradigm. Lastly, it includes a background of literature on alliances, which are to serve as a mechanism for ecosystems to form. Hereafter, we provide the methods of the research in Chapter 3. The value proposition for quantum computing is treated, and data collection and processing is explained. Next, the results are given in Chapter 4. First, business strategies are elucidated and contextualised, after which the use of various types of alliances is treated. We conclude this chapter with a discussion of the work. Chapter 5 then provides the conclusions of the research, as well as an outlook with recommendations for further studies.

Chapter 2

Literature Review

This chapter will provide the required background to treat the subjects of this thesis. We will begin by summarising the managerial literature on quantum computing in section 2.1, where we include both works that are concerned with strategy, as well as more general managerial works like business landscape descriptions, analogies with other industries and responsible innovation. This gives us a broad and complete overview of the sparse literature, demonstrating the need for managerial research on the subject in a broader sense. Hereafter, we will focus on strategy and review the managerial literature relevant for the quantum computing context. We start with a brief background on innovation, competition and strategy, laying out the historical foundations of strategic management in section 2.2. This includes Miles and Snow's typology, Ansoff's timing, Porter's forces and the resource-based perspective of the firm. Hereafter, the evolution of strategic management, first towards a dynamic capabilities approach and, from this, to ecosystems and platforms, is reviewed in section 2.3. Lastly, in section 2.4, we elucidate the strategic role of alliances, which are especially relevant as tools to foster the cooperative side of ecosystems. At the end of this chapter, a knowledge gap is identified based on our assessment of the current literature.

2.1 Quantum Computing in Management Literature

This section covers the body of literature that focuses on the managerial side of quantum computing. Due to the sparsity of the literature, we cover a large range of topics, providing a broad overview of the areas that have been studied. Table 2.1 summarises the identified topics. In the subsequent sections, these subjects will be elucidated.

Many works discuss the possible applications of QC, and their impact on the respective markets. Consultancy firms and firms developing quantum computers are releasing documents to prepare and educate the potential end-users of the technology [11, 6, 53, 54]. The businesses addressed in these documents are players acting in the finance, chemical, healthcare, medicine, energy, transport, and cybersecurity sectors, but with such widespread applications, the technology will likely reach other sectors as well. In scientific literature, the applications are laid out as a result of the quantum algorithms that have been developed. Federov et al. discuss in great detail how various algorithms apply in the three high-impact areas of simulation, optimisation and machine learning [23]. Hassija et al. also discuss the algorithms and how they apply to specific problems in logistics, financial risk analysis, random number generation and satellite communication [7]. Möller and Vuik discuss the improvements QC could make in scientific computing in their article 'On the impact of quantum computing technology on future developments in high-performance scientific computing' [55].

Table 2.1: Summary of the managerial literature on quantum computing. The takeaways are used in the motivation of this thesis.

Subject	Works	Key Takeaways
Potential applications	[11, 6, 53, 54, 23, 7, 55, 57, 58, 32, 56]	The businesses addressed in these documents are players acting in the finance, chemical, healthcare, medicine, energy, transport, and cyber-security sectors, but with such widespread applications, the technology will likely reach other sectors as well
Systematic literature review	[59, 60, 61]	Neglected role of organisational structure and effective intra-industry, industry-university and intra-university collaborations, and a reduced understanding of market demand
Current QC business landscape	[17, 13, 30, 11]	Rise of quantum startups, possibility for competitive warfare and mass-consolidation
Hype cycle	[12, 61]	QC is suggested to be in its peak of inflated expectations, which may result in a 'quantum winter'
Responsible research and innovation	[62, 63, 34, 64, 33]	Near-future issues of (too) strong guarantees, leading to a loss of trust in QC development if these expectations are not met
End-user strategy	[32, 56, 18]	The conventional, options, discovery and adversarial approaches, and roadmaps for implementing QC as end-user
Technology provider perspective	[11, 65]	Five key strategy points for technology providers: 1. Maintain a clear, milestone-defined 'tech maturity' roadmap informed by competitor benchmarks 2. Determine what core and auxiliary business model(s) will allow you to capture the most value over time (e.g., where to play in the stack) 3. Select priority industries and use cases to develop solutions for (and prioritise potential companies to partner with in each industry) 4. Solve for the complementary layers of the stack (e.g., hardware companies must develop a delivery mechanism, and software companies must develop a provisioning strategy) 5. Develop an engagement and ecosystem strategy

2.1.1 Potential Applications

Although many of the aforementioned applications will happen further down the line after the technology has sufficiently developed, near-term QC applications have also been discussed by Mohseni et al. [57] and Bova et al. [58]. Felix Gemeinhardt provided a very extensive managerial overview of potential QC applications, their impact and strategic opportunities in his thesis [32]. By applying a foresight framework, he first analyses the current state of the market, then lays out the possible implications of QC together with their expected timescales, and, lastly, provides the action plan for businesses to strategically deal with quantum computing shown in figure 2.1. A similar action plan for companies looking to manage the possible paradigm that QC may bring was published by IBM [56].

Figure 2.1: The action plan for businesses to start with, assess and implement quantum computing, proposed in [32].

Moreover, the work by Jenkins et al. identifies four strategies that are being pursued by firms in the QC application development market [18]: the conventional, options, discovery and adversarial approaches. The *conventional strategy* entails using quantum computers to solve problems much faster than classical computers can do. An example is the optimisation of driving routes, which currently is very computationally intensive. Companies that invest in various quantum technologies and applications, such that they do not miss out when an important development occurs, adhere to the *options strategy*. The *discovery strategy* describes firms that do research on quantum computing in the hopes of the discovery of a disruptive technology, such as in the chemical industry where quantum algorithms might be used to simulate chemical reactions. Lastly, firms in areas such as cybersecurity or finance fall under the *adversarial strategy*, in which firms anticipate facing other firms that make use of quantum technologies. Using these four strategies, firms are preparing themselves for the day quantum computing becomes commercially viable.

2.1.2 Systematic Literature Reviews

Despite ubiquitous papers on quantum computing technological developments and works focused on the applications of QC once the technology is ready, little managerial research has been done on the technological enablers. The main portion of managerial works focus on the current state of the market, and the various qubit platforms and development approaches that are chosen by the main players. Systematic literature studies make a distinction between the QC hardware and software sides of the development [61]. Challenges in the software architecture of quantum computers have been described in [59], in which a fuzzy analytic hierarchy process (fAHP) was applied to determine the key challenges and priorities for the development. Wang et al.'s systematic literature study discusses the most prominent research fields, leading institutions and authors, and the geographical location of research [60]. Leading the research, by scholarly output, are the United States, China and Germany.

2.1.3 Present QC Business Landscape

The present business landscape of quantum computing is described in great detail by Hassija et al. [17]. Besides a general introduction to quantum computing and its potential applications, they cover the current hardware landscape, and the qubit technologies that various players such as Microsoft and IBM are using. MacQuarrie et al. describe the development of the emerging quantum computing market through the lens of dominant design, based on the number of firms and patents surrounding quantum computing technology [13]. They identify two approaches that are being pursued for managing the QC value chain: A full-stack approach and a structural open innovation approach, in which partnerships are used to integrate hardware and software start-ups into a packaged value chain.

The rise of quantum computing has also been discussed in various opinion articles. Elizabeth Gibney compares the surge of incumbents and investment into the quantum computing market to a 'quantum gold rush', with firms making grand promises on a timeline that is too short [12]. This peak of inflated expectations is characteristic of the hype cycle that surrounds radical innovations. The position of various QC technologies on the hype cycle has been described by Gill et al. [61]. These inflated expectations have experts worrying for a quantum winter if they end up not being met [66].

The current state of QC development could potentially be compared to the early-state of the classical computer. In [67], Moguel et al. draw the comparison between QC and the classical computer of the fifties and sixties. Firstly, high costs of quantum hardware and specificity of setups is reminiscent of the single-copy computers such as the ENIAC. Secondly, quantum software is being programmed for specific problems on specific setups, which was also the case for the classical computers. Furthermore, vacuum-tube technologies used for early classical computers were unreliable and unstable, much like the problems of decoherence that quantum computers are facing. Hence, a disruptive innovation, such as was the case with semiconducting transistors, could also occur for quantum computing, if a radically innovative qubit platform is found. Lastly, the rise of incumbents in the QC market seems comparable to the supercomputing market of the 1980s, where the need for a replacement of the established architecture caused a surge in new firms developing alternate technology [13, 28]. Once a dominant design emerged, the number of firms dropped rapidly. This process of mass consolidation goes through a phase of harsh competition. Hence, there is an increasing need for quantum firms to position themselves strategically in the upcoming competitive arena [11].

2.1.4 Responsible Research and Innovation

Articles and documents focused on fostering the local quantum computing ecosystem illustrate the strategic value that is perceived in quantum computing [68, 69]. Governments invest heavily in QC technologies for their predicted ability to break traditional encryption [23, 70, 30]. This strategic and military potential of quantum computing [71], and its predicted socio-economic impact also give rise to a need for responsible research and innovation (RRI) [62, 63] and strategic management [35]. A multitude of papers on RRI in quantum computing has been released by the Networked Quantum Information Technologies (NQIT) hub, based in the United Kingdom [34, 64, 33], which distinguish between issues QC is or could be facing that are present, in the near-future and further down the line. Namely the near-future issues of (too) strong guarantees that are being made and verification of reported results are especially applicable to the technology delivery market studied in this thesis.

2.1.5 Technology Provider's Perspective

Lastly, there is a single mention of strategies for the technology providers. In a 2021 study by the Boston Consulting Group, five recommendations for strategies are done [11]:

- Maintain a clear, milestone-defined 'tech maturity' roadmap informed by competitor benchmarks
- Determine what core and auxiliary business model(s) will allow you to capture the most value over time (e.g., where to play in the stack)
- Select priority industries and use cases to develop solutions for (and prioritise potential companies to partner with in each industry)
- Solve for the complementary layers of the stack (e.g., hardware companies must develop a delivery mechanism, and software companies must develop a provisioning strategy)
- Develop an engagement and ecosystem strategy

Central in these recommendations is the notion of the environment and awareness of the firm's role in the stack, which can be seen as a platform to innovate on. Hence, platform and alliance strategy should be an essential component of firms' strategy formulation. Although supply-chain management in the superconducting qubit platform has been discussed by Alberts et al. [65], to our knowledge there exists no other literature on alliance strategies in the technology provider market. Besides Jenkins's paper on the quantum business ecosystem, which looks at it from an end-user perspective, another description of the ecosystem is given by Mario Coccia [72]. Although the contents of the paper are similar to those treated in this thesis, the quality of the work is not up to standard, hence we will exclude this paper from the literature review.

In this work, we are interested in characterising the quantum computing business ecosystem, specifically for hardware manufacturers that operate in this industry. The reviewed literature already analysed strategies of the structural open innovation approach versus a full-stack approach, comparable to the pure-play foundry and IDM approaches seen with semiconductor manufacturing. Furthermore, because the market is awaiting a dominant design for qubit hardware, actors are choosing their 'betting horse', such as Google's superconducting qubits, or investing in multiple hardware platforms, like Microsoft's Azure Quantum platform. A question that remains is to which extend quantum computing will follow a path similar to that of the classical computer, in which a dominant design emerged with the invention of semiconducting transistors, where the addition of foundry services overtook the approach of integrated design manufacturing [73], and that spawned an industry housing the largest companies in the world today. For firms, investors and governments, the question is how to position themselves to maximise their probability of maintaining and growing their market position as the quantum computing paradigm unfolds. More specifically, for SMEs the question is how to position themselves in the ecosystem to maximise their captured value, as well as their competitive advantage, and face off against large, established firms. This gives rise to a need for the tools to analyse their position, the ecosystem and the strategic options available to them.

2.2 Innovation, Competition and Strategy

In this section, we will explore the literature regarding innovation, competition and strategy. We can make a distinction between technology strategy and competitive strategy. Technology strategy can be defined as the decisions of an organisation toward the activities that involve technology selection, acquisition and exploitation [74]. Strategy is defined along measurable variables, called dimensions, and can be applied in various contexts, such as product development, production, and management. Miles et al. proposed that organisations go through an adaptive cycle and move through this cycle with four categories of strategies, defender, prospector, analyser and reactor, each with their respective set of traits [75]. Along the dimension of product timing, four strategy types have been identified by Ansoff and Steward: first to market, follow the leader, application engineering and me too [76]. Different strategies may work better depending on the market context. Luo and Park looked at different firms adopting various of Miles and Snow's strategies in the Chinese market. They show that the defender and prospector strategy types lead to poor performance due to mismatched markets [77]. Market analysis and understanding strategic configuration is therefore important for firm performance.

Conversely, competitive strategy - or business strategy - is the strategy concerned with outperforming competitors. Its main purpose is to create sustained competitive advantage by achieving goals that are in line with the organisation's vision, mission and objectives [78]. Obviously, technology strategy and competitive strategy are not separate. The technology strategy of a firm can be part of its competitive strategy, and hence the concepts are complementary. In this work, we are concerned mostly with strategy as the means of firms to achieve competitive advantage.

2.2.1 Competitive Strategy

Strategic decision making with regards to competition has been studied extensively. Perhaps the most widely diffused theory, developed by Michael Porter, describes competitive strategy along the dimensions of cost, product differentiation and product timing [79]. Where prior research on corporate strategy either focused on the business itself, excluding the environment, or only a single aspect of the industry, Porter's competitive strategy 'identifies the industry as the basic unit of analysis, and the product as the basic unit of business' [79]. The industry around a focal firm is characterised by five blocks of actors: Competitors, buyers, suppliers, substitutes and potential entrants. The forces between these actors are what drive industry competition, and based on this Porter formulated four generic strategies: cost leadership, product differentiation, cost focus and differentiation focus [80]. To illustrate the use of Porter's model for firms in the QC industry, an exemplary analysis is given is Appendix A from the viewpoint of a superconducting QC hardware developer. Porter's analysis is to serve as a base on which competitive strategies can be built. A schematic depiction of Porter's framework is given in figure 2.2. Since its introduction, many adaptations of Porter's competitive strategies have been suggested in literature. An overview of various alterations to Porter's generic strategies that have been proposed can be found in [74].

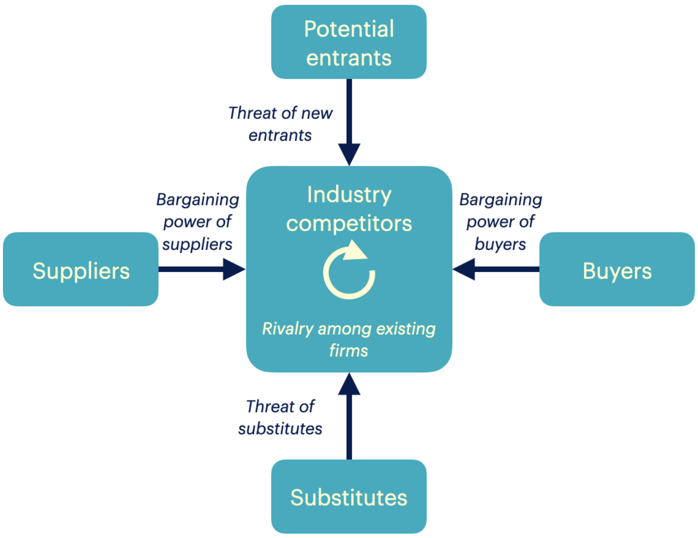

Figure 2.2: Porter's model of industry forces that drive competition [44].

However, there are some limitations to Porter's theory, which are of relevance in today's markets. Firstly, because the goal of Porter's model is to choose the best position for oneself in an industry, and shield others from obtaining the same position, the industry itself is viewed as exogenous: it is assumed fixed. However, more recent literature stresses the importance of the way in which the industry structure can be changed, both by external factors and the firm itself [42]. Furthermore, the role of supporting institutions, complementors, cospecialisation and network externalities is insufficiently treated in the model [45]. Hence, other views have been developed.

2.2.2 Dynamic Capabilities

One of the most influential alternate theories, pioneered by David Teece, moves the focus from looking at industry competition and a firm's position against the industry's forces, to a dynamic capabilities theory that emphasises the competitive advantage of a firm's specific, hard-to-imitate capabilities and assets [46]. It is a delineation from Porter's framework, moving from an industry to an ecosystem view, and a continuation of the resource-based theories that are started by Edith Penrose [43]. The theory revolves around organisational processes, positions and paths, and finds a firm's source of competitive advantage to reside in its competences that are hard to imitate. Organisational processes are defined as the way the firm-specific assets are integrated such that they enable distinctive activities to be performed, with examples such as quality, miniaturisation and systems integration. Positions are a firm's specific assets, including specialised plant and equipment, but also difficult-to-trade knowledge assets, or reputational and relational assets. Lastly, the theory recognises a path dependence in the firm's options, and stresses that history of the firm determines where a firm can go. All three concepts are found to be related to the firm's strategic posture, as they define the current position, and the moves and future paths available to the firm. Teece identifies three key components of dynamic capabilities: sensing, seizing, and transforming. Sensing refers to a firm's ability to identify changes in the market and its own internal capabilities. Seizing refers to a firm's ability to take advantage of opportunities presented by these changes. Transforming refers to a firm's ability to reconfigure its resources and capabilities to adapt to these changes. For our work, the main take-aways of the Teecian paradigm include the significance of organisational boundaries: the degree of integration (vertical, lateral, horizontal) of a firm determines its dynamic capabilities to a great extend. For QC, which is a rapidly changing environment, high-flexibility in the company's organisational structure may trump economies of scale obtained through extensive vertical integration. Furthermore, the dynamic capabilities framework emphasises the strengths that lie in an open innovation approach, which enables rapid innovations by upstream suppliers to drive downstream competitive success [45]. This could provide an interesting argument in favour of open innovation approach over the full-stack approach in the QC market, although it should be noted that the dichotomous open-closed thinking has been under scrutiny and that a more nuanced view can be adopted [81]. Moreover, the work lays the foundation for the role of industry architecture, ecosystems and platform leadership, which constitute a significant portion of this thesis. These subjects will be treated in the next section.

2.2.3 Business Context and the Technology Innovation System

It is argued that successful strategy is determined by its fit in the organisation [75] and coherence is among the most mentioned key success factors of business strategy. Therefore, besides market analysis, also knowledge of the firm's fit with the strategies is necessary to ensure effective strategy deployment. Business context has been shown to be of great importance to innovation management [82]. Hence, the total environment should be analysed in a strategy analysis. Specifically for radical technology in the emerging phase, niche strategies have been explored by Ortt and Kamp [83], in which they are assessed based on their diffusion-readiness with their technology innovation system (TIS) framework. This framework consists of seven elements that can hamper the large-scale diffusion of a radically new innovation, including product performance and quality, product price, production system, complementary products and services, network formation and coordination, customers, and innovation-specific institutions. The work seems relevant to the case of quantum computing and may allow bottlenecks to diffusion to be identified. However, note that this framework is made for the adaptation phase of an industry, which is the phase between first market introduction and large-scale diffusion. Arguably, quantum computing is currently in the phase prior to this. The researchers of the paper indicate that this phase requires more than standard innovation project practices to turn an invention into an innovation. This might refer to the probing phase, as described by Aarikka-Stenroos et al. [84].

With this general conceptual background on competitive and technology strategy, we can now turn to a more specific aspect of recent strategy literature: that based around ecosystems and platforms. Here, we will see a continuation of the Teecian paradigm, and we will see how the developments in a neighbouring industry - the innovation in classical computing - revolved around ecosystems, platforms and industry architecture. The actors present in this strategic playing field are largely the same in QC's development, hence a lot can be learned about their historical strategic paths. To conclude this section, a summary of the literature on strategy is given in table 2.2.

Table 2.2: Summary of the literature on technology and competitive strategy.

Subject	Works	Key Takeaways
Technology strategy	[74, 75, 76, 85, 86, 87]	Technology strategy concerns itself with the selection, acquisition and exploitation of technology. Various typologies have be identified, based on the dimensions that are studied.
Porter's forces model and adaptations	[44, 79, 80, 74]	The five components, competitors, buyers, suppliers, substitutes and potential entrants, and the industry forces between them, the rivalry among existing firms, the bargaining power of buyers and suppliers, and the threat of new entrants and substitutes. These lead to the strategies of cost leadership, product differentiation, cost focus and differentiation focus.
Dynamic capabilities theory	[46, 45, 42]	Porter's forces model, resource-based theory and game-theory based approaches to strategy are inapt at dealing with the current high-paced, high-tech business environment. A firm can enjoy a sustained competitive advantage by possessing dynamic capabilities, which are the firm's abilities to integrate, build and reconfigure internal and external competences to address rapidly changing markets. The dynamic capabilities can be disaggregated into the ability to sense and shape opportunities and threats, to seize opportunities, and to maintain competitiveness through enhancing, combining, protecting and reconfiguring (in)tangible assets.
Technology Innovation Systems (TIS)	[83]	The seven elements for large-scale diffusion: product performance and quality, product price, production system, complementary products and services, network formation and coordination, customers and innovation-specific institutions. Working these out may explicate the bottlenecks for the case of quantum computing.

2.3 Ecosystem Innovation and Cooperative strategy

In the modern economy, there has been a recognition of the value that can be added through inter-firm collaboration, leading to the rise of platforms [39]. These platforms are characterised by a web of value-increasing complements that surround it, usually not owned or initiated by the firm that built the platform. We call this web of multilateral firms an ecosystem, borrowing from biology to signify its symbiotic nature [49]. Due to their capacity-enhancing effects, inter-firm collaborations are gaining increasing significance in the field of SMEs's innovation [88], which are typically resource-limited. Ecosystem strategy can be seen as a continuation of Teece's dynamical capabilities framework, explained in the previous section. It builds on the resource-based theory that focuses on the recognition, acquisition and exploitation of difficult-to-imitate assets that constitute a firm's competitive advantage.

2.3.1 Defining Ecosystems

The differences between research on strategy in ecosystems, alliances and networks are described well by Rahul Kapoor in terms of the units of analysis and key considerations [89]. Research on alliances tends to focus on the firm or alliance, with the research contributing to alliance governance, drivers and firms's capabilities to manage alliances. Networks revolve around the ties that are formed through the web of strategic alliances, providing firms with advantages in terms of information, resources and status. Both of these methods focus on the voluntary, dyadic relationships between firms. In ecosystem research, however, the starting point is the focal value offer, rather than a firm or alliance. Therein, ecosystem research studies the interplay of actors that contribute to this value proposition, through their activities, the strategies that both complementors and the focal firm pursue, and the impact of this interplay on the constitution of the proposition's value.

An extensive overview of research on ecosystems is provided by Jacobides et al. [48]. In their literature overview, they distinguish between three different groups of papers on ecosystems:

- A **business ecosystem**, in which a firm is centred and its environment is studied,
- an **innovation ecosystem**, which focuses on a particular innovation or value proposition, and
- a **platform ecosystem**, which studies the organisation of actors around a platform.

By characterising different types of complementaries, they show how ecosystems are different from other industry structures, such as conventional supply chains, and constitute a theory of why and when ecosystems emerge. One of the key factors for emergence of ecosystems is modularity, which allows interdependent components of a system to be fabricated by different producers, with limited required governance. The two distinct types of complementaries that they identify are a unique type, in which product A requires product B in order to function (or, in a less strict sense, the value of product A is maximised with product B), and a supermodular type, in which more of A makes B more valuable. The former type can also be generic, meaning that although B is required for A to function, the good or service is generic enough that firms can assume its availability and appropriation. Hence, no coordination is required from the firm that requires the generic complementary. Based on this characterisation, they argue that either uniqueness or supermodularity, combined with nongeneracy, is required for the formation of ecosystems, as in that case a need arises for alignment of complementaries in order to create value. However, they specify that although this is a necessary condition, the presence of these properties alone is not sufficient to explain the formation of ecosystems.

2.3.2 Platform Leadership

Research by Gawer and Cusumano provides a framework for studying large-scale innovation through the lens of platform leaders. This platform leadership is defined as *"the ability of a company to drive innovation around a particular platform technology at the broad industry level"* [29]. Central to this concept is the importance of the technology provided by the platform leader to the ecosystem. A clear example of platform leadership is provided by Intel, who was able to grow from a hardware-manufacturer at the low end of the computer stack, supplying microchips for the PC industry, to the driver of the PC architecture. This example illustrates the change of platform ownership that happens when changing bottlenecks in the value proposition allow hitherto unimportant complementors to capture novel value and shift the platform ownership to their account. Prior to Intel's leadership, IBM held the personal computer market with the IBM PC. However, as they were dependent on vendors Intel and Windows for the microprocessor and operating system, IBM lost control of its platform when other firms began to produce clone computers that ran the same application software [90]. Gawer and Cusumano propose a distinction between internal and external platforms, based on the openness of the platform to third-parties. An internal platform allows a company to efficiently develop and produce a stream of derivative products, which provides it a certain degree of flexibility in product feature design, without sacrificing economies of scale. External platforms differ from the former in that access to platform connectors is provided to third parties, which can develop their own complementary products, technologies or services on top of the platform. The level of openness to the platform can vary on a multitude of dimensions, such as the level of access to information on interfaces that link to the platform, the type of permitted platform use, or access licensing cost. This openness is further explored by Joel West, who contextualises the platform formations in the workstation and PC markets, in which the aforementioned platform ownership shift took place [90].

Due to platform flexibility and unstructured nature of third-party innovation activities, end-use of the end-product or service is usually not fully determined. This provides a means for the platform to reach its full potential through a range of probing activities as are characteristic for commercialisation of disruptive innovations [84]. This degree of open, unstructured innovation, however, also makes the platform leader dependent on its complementaries - as the network of products constitutes the value of the platform - and vulnerable to changes in the power of complementary developers. IBM, for example, lost its leadership position to its alliance partners Intel and Microsoft, as the microprocessor and operating system turned out to be two key components in the PC platform [91]. As a result, leaders face a difficult task of orchestrating and fostering the stream of innovation activities that build on their platform, which entails managing stimulating relationships with certain complementing firms, whilst competing with others, or even the same. Platform leaders and competitors must therefore balance collaboration and competition, spanning a complex strategic maze in which coherent decisions need to be taken. Tying back to Porter's model, providing opportunities to developers of complementaries that build on the platform increases the bargaining power of buyers and suppliers (which include the complementary developers). It also increases the threat of new entrants, mainly consisting of complementary developers that have the power to vertically integrate. However, the barriers to entry from substitutes and competitors are reduced for competing platforms, as positive network effects increase the power of the platform overall. A careful trade-off is therefore to be made between empowering complementors, and increasing the attractiveness of the platform.

During the emerging phase of an industry, actors have an influence on the constitution of the industry architecture, which is *"an abstract description of the economic agents within an economic system ... and the relationships among those agents in terms of a minimal set of rules governing their arrangement, interconnections, and interdependence"* [42]. In their work, Jacobides et al. elaborate on the interplay between industry architecture, ecosystem attractiveness and vertical integration within the ecosystem. They pose that excessive focus on value appropriation can impede value creation, through reducing complementors's incentives to innovate. Furthermore, they suggest that managing or influencing the industry architecture to capture key bottlenecks in the value proposition can lead a firm to capture a disproportionate amount of value created by an innovation. At the end of their work, they propose a framework for choosing scope to maximise profits, which judges a firm's decision on whether or not to vertically integrate into complementary component space. This can be illustrated by Intel's careful considerations of integration decisions in the microprocessor industry [92]. Different key roles of actors during this formation phase have been identified by Dedehayir et al. [50].

2.3.3 SMEs in Business Ecosystems

Tukiainen et al. studied the strategies of technology startups in business ecosystems [93]. They identify three classifications with regards to ecosystem behaviour:

- firms that link to a **single ecosystem leader**,
- firms that cater to **many ecosystem leaders**,
- firms that have the ambition to become a **leader of their own ecosystem**.

Each of these cases is then linked to a set of strategic behaviours, including innovation type, the network and risk level. The researchers conclude by stating that a fit in the patterns of behaviour between leadership, innovation and network activities is required. In the risk level assessment, they stick to the three types of risk that are characteristic to innovation ecosystems, as identified by Adner [40]:

- **Initiative risks**: Initiative risks include the typical risks that are seen in project management, such as project's feasibility and competition.
- **Interdependence risks**: Interdependence risks arise due to the cooperation and reliance on other firm's complementaries, looking at the total probability that an ecosystem of partners will succeed on their efforts in a given time frame. If there is a complete dependence of a firm's project on its complementaries, then the total probability for success is the product of all success probabilities of the partners. For example, if there are four firms developing the technology, and each has a 90% probability of success, the total probability of success for the project will be only 66%. Hence, despite high probability of individual success, the interdependence significantly lowers the overall success rate.
- **Integration risks**: Integration risks look at the necessary integrations in the supply chain to the customer. Delays in the adoption process at different stages in the product's chain will stack up, hence significant delays can result for getting the product to market if a complex value chain is required for the product to reach its end-user

2.3.4 Strategy in Ecosystems

The strategic implications of the ecosystem have also been studied by Ron Adner. In his paper *"Ecosystem as a Structure: An Actionable Construct for Strategy"* [49], he distinguishes between two views on ecosystems:

- **Ecosystem-as-affiliation**, which denotes the ecosystem as "communities of actors that are defined by their networks and platform affiliations", and
- **ecosystem-as-structure**, in which the configurations of activity are linked to a value proposition.

Through this structuralist's view, a firm's ecosystem strategy is defined as *"the way in which a focal firm approaches the alignment of partners and secures its role in a competitive ecosystem"*. As Adner puts it: *"If the heart of traditional strategy is the search for competitive advantage, the heart of ecosystem strategy is the search for alignment. The value, rarity and inimitability of resources finds its analog in multilateral partnerships, and sustainability of advantage has as much to do with maintaining relationships as it does with keeping rivals at bay."* Constituting the notion of ecosystem strategy as such holds the following implications. Firstly, each firm within the ecosystem defines its own ecosystem strategy, based on their notion of a value proposition. In order for the value proposition to take form, a firm needs to bring partners into the positions and roles that the proposition requires. To do this, the firm must first recognise gaps in the ecosystem, then closing these gaps through its own efforts or a complement's. For the latter, the firm must incentivise the gap's solution by creating the right conditions for attractiveness. Two types of risk can be identified from this alignment. Herein lies the willingness of a partner to undertake the necessary activities, as well as their abilities to do so. Furthermore, challenges arise from partners's view of the division of activities and roles. A question that must be answered for the ecosystem is who becomes a platform leader, and who takes a follower's role.

The concept of industry platforms also ties into the research of this thesis, as QC is to serve as a platform on which third parties can build complementaries (software, applications) that serve the end-users. This is valid both for the full-stack and open innovation approaches that are seen in the industry. However, the closedness of full-stack development makes it a more internal platform, whereas structural open innovation is a clearly external approach. The supermodularity is visible: The more advanced the technology of the complementaries (the other component developers, next to the application developers), the more attractive the platform becomes. We can distinguish between the hardware-stack developers and the end-user complementaries, who are developing the applications and cloud platforms: The former need to be more technologically advanced, whereas in the latter case also diversity makes the industry as a whole more appealing, with more end-users enticed about the opportunities that QC may bring to their businesses. Furthermore, whereas the application and cloud-platform developers are solely supermodular - their contribution is not a necessity to QC working, but rather to target more use-cases and, thus, more end-users - the hardware-stack developers are both supermodular and unique. The quantum computing ecosystem therefore provides an opportunity to study platform leadership and ecosystem innovation, with multiple firms currently trying to build their leadership position.

The literature on ecosystems enables us to take a holistic standpoint in viewing the quantum computing business environment. Firms are trying to capture their part of the market, and many are platform leader wannabes. A question that remains is to what extent parties have the same view of the value proposition. This is a necessary prerequisite for alignment, as underlined by Adner. Table 2.3 contains a summary of the literature on ecosystems and strategy discussed in this section.

Table 2.3: Summary of the literature on ecosystems and strategy.

Subject	Works	Key Takeaways
Defining ecosystems	[42, 48, 49, 89]	Three types: a business ecosystem, an innovation ecosystem and a platform ecosystem, each focused around their respective antecedent. Kapoor explicates the distinction between ecosystems, value networks and alliances. Adner provides a novel definition of ecosystem as *"the alignment structure of the multilateral set of partners that need to interact in order for a focal value proposition to materialise."*
Platform leadership	[39, 29, 91, 90]	The four levers of platform leadership, internal and external platforms, and platform 'openness'.
Entry decisions of platform owners	[42, 92]	The role of industry architecture in value appropriation. Contextualisation of entry decisions of Intel into complementary markets.
Function of startups in business ecosystems	[93]	Three types of startups within and between business ecosystems: Those pertaining to a single ecosystem, those pursuing a multi-ecosystem strategy, and those that strive to create their own ecosystem.
Strategy in ecosystems	[40, 49, 36]	The four levers of platform leadership: Firm scope, technology design and IP strategy, external relationships with complementors, and internal organisation. The three types of risk associated with ecosystems: interdependence risks, initiative risks and integration risks. Assessing these risks should provide answers to the strategy questions of where to compete, when to compete, and how to compete.

2.4 Strategic Alliances

Alliances constitute "an agreement between firms to do business together in ways which go beyond normal company-to-company dealings, but fall short of a merger or full partnership" [94]. This encompasses both formal and informal mutual agreements by two or more independent firms, to their mutual benefit. Thus, the types of alliances include joint marketing/promotion, joint selling/distribution, production, design collaboration, technology licensing, R&D contracts and other outsourcing purposes [37]. Formal alliances can be set up with various cooperative agreements. Vanhaverbeke and Noorderhaven studied alliance blocks in the microprocessor industry, where the network of agreements included joint R&D, customer-supplier relations, technology exchange agreements, licensing and second-sourcing agreements, standards agreements and bidding consortia, and direct investments [52]. With inter-firm co-operations being an integral part of ecosystem innovation, literature on alliances and their role in strategy in the business context could not be ignored.

Elmuti and Kathawala provide a broad overview of strategic alliances, their types, objectives, risks and critical success factors. They posit the following reasons for entering into strategic alliances [37]:

- **Growth strategies and entering new markets**: Establishing partnerships with companies that have experience in a market that is new to the focal firm can significantly ease entry in the novel market. This can include licensing agreements to build the brand's image in a new market, joint selling or distribution, and other outsourcing purposes.
- **Obtaining new technology and/or best quality or cheapest cost**: One reason for joining in alliances is to gain access to novel technology, or capabilities that the focal firm does not have. This is especially relevant in the case of high-tech SMEs, which don't always have the resources to make it on their own. Secondly, outsourcing business functions to a firm that can deliver a similar commodity at better value, i.e. lower price and/or better performance, can benefit the focal firm.

This includes marketing, sales, accounting, but can also relate to technology or labour.

- **Reducing financial risk and sharing cost of R&D**: Developing new products and technologies can sometimes be to expensive or bear too much risk for a single company to be willing to accept. In this case, joint development efforts can lower the financial risks and the costs associated with the development.
- **Achieving or ensuring a competitive advantage**: Especially for small companies, alliances can be a way (or even a necessity) to gain a competitive advantage. By excelling in their niche of expertise, while reeling in other competencies needed for their product through alliances, small companies can manage to compete against much larger ones. This is also the vision of a platform leader wannabe, who aims to outperform (much larger) competitors by fostering an ecosystem of complements, ultimately delivering a superior value proposition to the consumer.

The work by Franco and Haase adds to this by including the two alternative, socially-oriented drivers for engagement in alliances, namely, the signalling effects of existing interfirm relationships and previous participation in collaboration or similar efforts [38]. Reciprocal firms form their own alliances in order to compete against an existing alliance of complementary firms, which is the basis for the similarity of alliance blocks described by Vanhaverbeke and Noorderhaven [52]. In their work, they describe how alliances can be used to increase the position of one's design in the market, such as was the case for the microprocessor architecture in the 90s. Here, the rise of a new architecture basis, called RISC, led firms to develop their own proprietary architectures based on this technology. In this industry, the complementarity of microprocessors and operating system software was of crucial importance, as there are switching costs associated with changing from one microprocessor architecture to another. On top of that, there are network externalities associated with microprocessors, where the derived utility of the product increases with the number of agents consuming it. Increasing the installed base was therefore a critical driver in alliance forming. Another means to establish market dominance for its technology would be through the acquisition of firms with competing technologies, which would set the firm's own design as the standard. However, buying market dominance is hindered by antitrust law in Europe and the US, hence the need for alliances as an alternative. Expectations play a very important role in systems competition, where buyers's perception changes their buying behaviour, and can cause a positive feedback loop in the adoption of a new system. In the paper, the authors mention the use of alliances with well-established and reputed firms, in order to manipulate buyers's perception of the firms strengths and reputation.

Objectives of alliances can be seen from a resource-, organisation-, cost- and market-related perspectives [38]. According to resource-based theory, alliances are a way of obtaining additional resources. This view covers aspects such as increased production and improvement of manufacturing times, but also obtaining the best financing. Through the lens of this perspective, alliances provide benefits from mutual exploitation of innovative capabilities and technology transfer. Transaction cost economy (TCE) emphasises alliances as a means to reduce risk and costs, and to achieve economies of scale. Market-related aspects include the access to new markets, consolidation of market position and creation of competitive strengths/advantages.

Table 2.4: Summary of the literature on alliance and business strategy.

Subject	Works	Key Takeaways
Drivers for alliance formation	[37, 38, 95]	Alliances are formed for growth strategies, to enter new markets, to obtain new technology and/or quality or cheapest cost, to reduce financial risk and share costs in R&D, to achieve competitive advantage, to counter existing alliances, or due to previous participation in alliances. They can also be used to shape the industry structure, to reduce the potential threat of competition, to raise entry barriers or to overcome them, to enhance resource use efficiency or to acquire new skills.
Types of alliances	[94, 37, 52]	Alliances constitute "an agreement between firms to do business together in ways which go beyond normal company-to-company dealings, but fall short of a merger or full partnership". Types of agreements therefore include joint R&D agreements, joint marketing, selling and distribution agreements, design collaboration agreements, technology transfer agreements, licensing or second sourcing agreements, standards agreements, direct investments (non-majority stakes), bidding consortia, (industry) consortia, and informal agreements.
International expansion through alliances	[96]	Exploration or exploitation orientation of alliances, depending on whether the firm uses the alliance to leverage its current assets and competencies, or to develop new competencies and assets. In this paper, the focus was on alliances for international expansion.
Competitive advantages that can be gained through alliances	[95]	Alliances can aid a firm in the competitive sense by enhancing its competitive advantage through either its distinctive skills (capabilities) or unique resources (assets). This is in line with resource-based theory and the dynamic capabilities theories. The paper lists many of the kinds of capabilities and assets that can be enhanced through alliances, such as patents and reputation on the asset side, and R&D skills and marketing skills on the capabilities side.
Alliances in SMEs	[88, 97]	SMEs are found to be following one of two strategies w.r.t. alliances, based on their presence in their niche pool. When the firm is small relative to their direct rivals, they use alliances to gain scale and scope. When they are a leader in their niche, they avoid alliances.
Alliance use in the microprocessor industry	[52, 51]	Contextual use of alliances in the microprocessor industry. Companies like Intel, IBM and Microsoft, who were key players in the developments in this industry, are also developing quantum technologies today. Some notable alliance strategies include partnerships with reputable firms to increase brand image and using the positive network externalities of microprocessors - in the ecosystem sense where we have supermodularity - to gain an initial edge over competition, which feeds the positive feedback loops of standards battles.

The strategic use of alliances for SMEs has been described by Benjamin Gomes-Casseres [97]. He distinguishes between two types of small firms: Those that are relatively large in their niche, and those that are small compared to their direct rivals. The former group usually follows what he calls a 'deep niche' strategy: One in which they pursue market dominance and technological leadership in their market niche, through which they are able to differentiate enough to achieve a competitive advantage. This group of small firms also usually refrains from engaging extensively in alliances, as they do not have a great need for outsourcing and economies of scale have a relatively small contribution in the advantage. The latter group consists of small firms that directly face firms much larger than them in their market. In order to overcome competitive disadvantages, they have to seek collaborators that complement their capabilities. In a constellation, which is the set of firms linked together through alliances, firms can draw on two sources of competitive advantage. Group-based advantages come about through capabilities that are in the group and how the group is managed, which result in positive network effects. Firm-based advantages encompass the distinctive capabilities of each firm. However, the alliances also give rise to two sources of risk, namely a loss of control, due to partners's influence on the firm, and limited appropriability, due to shared returns in an alliance.

For SMEs, alliances can also be used as a way of procuring capital. This can be used as an alternative, or a complement to conventional venture capital funding. In the high-tech sector, the use of alliances has been shown to increase the probability of exit through either an IPO or acquisition. In their paper, Ozmel et al. [98] study the link between strategic alliances, VC rounds and exits in the biotech sector. In their work, they study the use of strategic alliances as a project-level alternative to VC for acquiring resources. They show that increased alliance activity makes future alliances more likely, while reducing the probability of future VC activity. This is ascribed to potential conflicts of interest that arise due to the different levels of equity acquisition, with VC being at the firm-level while alliance capital is project-level based.

This concludes our literature review on alliances. To summarise, table 2.4 provides the key takeaways of the works treated above. Having treated the literature on the quantum computing market, business strategy, ecosystems and alliances, we should be adequately prepared to describe and assess the quantum computing business ecosystem. The next section will identify a knowledge gap.

2.5 Knowledge Gap

The literature discussed above covers many of the facets surrounding quantum computing technologies: from possible implementations, to current market state, to assuring responsible innovation. Firms in many areas looking to anticipate or capitalise on the quantum revolution can use the trend analyses and roadmaps that have been suggested by existing works. However, for players that are developing and enabling the technology, little information exists regarding intelligent decision making and market factors. In the QC hardware market, there are two main categories of firms: large (tech) firms that are using their own capital power to invest in development of quantum technology, and small- and medium-size enterprises (SMEs) that are backed by investors. The first category consists of companies such as IBM, Microsoft and Google, the second entails the ubiquitous start-ups and scale-ups that have spawned in the market as a result of large (VC-like) investments. Because of this boom of quantum computing firms, the SME quantum computing industry will most likely be were most of the competitive warfare will take place in the short term. The firms will therefore have to prepare by positioning themselves strategically against rival SMEs. Furthermore, these firms do not have the capacity to take on the tech giants, and must therefore stay clear of giant's space, until it's too late for these large firms to react to a threat. Lastly, with the development happening along the lines of ecosystem innovation, alliance formation and partnerships will become increasingly important tools of strategy. These criteria constitute a strategic maze that SMEs will have to navigate, to secure a sizeable position in the future quantum computing industry. Although some managerial studies provide descriptive analyses of the strategies that are being pursued in the market, there are no extensive studies regarding the attitudes that should be adopted to perform optimally in the QC development market.

As the developments in quantum computing are a global endeavour, where the many actors are simultaneously and cooperatively developing the various components, applications and platforms that constitute a complete QC value proposition, neglecting interdependencies, roles, activities and positions of actors would most likely lead to insufficient insight into the effects of strategies. To account for this, an ecosystem perspective can enhance the insights into the roles of complementors/platform leader wannabes, bottlenecks, and the strategies that they are pursuing. Mapping the groups that make up the QC value proposition, from hardware producers to the end-user, and identifying each group and interactions, should provide insight into their motivations, beliefs and perceived value. This, in turn, should allow us to analyse the strategies in the ecosystem, and assess their implications.

Furthermore, although the subjects have seen a vast amount of interest in recent years, the drivers and mechanisms of platform and ecosystem formation are still poorly understood [50]. Hence, studying the ecosystem in an infant industry might provide novel insights into the early-stage mechanisms of platform formation. In addition, the role of alliances in technology adoption has been studied, but the developmental interdependence of quantum computing components could provide new insights into the competitive and cooperative elements of high-tech ecosystems. We will contrast the developments in the quantum industry with those in neighbouring industries, to see if any parallels can be found. The research in this thesis will therefore indicate areas in which longitudinal studies could help provide answers to these questions.

Chapter 3

Methods

This chapter explains the methods and framework of this thesis. Starting from quantum computing's value proposition, we will describe the ecosystem, the types of actors, and their connections in section 3.1. In doing so, a brief overview of various firms within each category is given. Hereafter, the search method for public data on cooperations is described in section 3.2. Lastly, the expert interviews are covered in section 3.3, which includes the selection criteria, a set of guiding questions on alliances and their use, and the data processing.

3.1 The Value Proposition for Quantum Computing

Building on the works by Ron Adner [40, 49], who views the ecosystem as a configuration of activities built around a value proposition, we aim to construct this value proposition for quantum computing. For this, we take a broad industry view, in which the full chain is studied from technology providers to end-users. By decomposing the full value network in its various components, we can analyse the value-adding activities that are taking place, which should serve as a background for building strategy. In our view, we will take QC's value proposition, which is based on the benefits it could bring to end-users based on the applications described in the introduction. Herein, we thus assume the potential, rather than the current situation. Obviously, the choice of prospect here is non-trivial, and therefore we will consider a multitude of scenarios with different realisations of QC's promises. However, our methods serve as building blocks for strategy, which can be applied in a broad context. Due to the dynamic nature of ecosystems, any strategy formulation that is static is bound to fail, which is also emphasised by Adner [40]. Hence, the strategy-formulating approach should always be an iterative one.

Experts have underlined the complementary nature of quantum computing to its classical counterpart [11]. Most likely, the value proposition will look similar to that of conventional (high-performance) computing, as illustrated in figure 3.1. The system contains five groups of actors: Hardware providers, cloud service providers (CSPs), software developers, managed services providers (MSPs) and the end-users. Assessing the incentives for each of these groups to participate in the development and adoption of QC should help in identifying the added value at each position, and the alignment necessary to complete the value proposition.

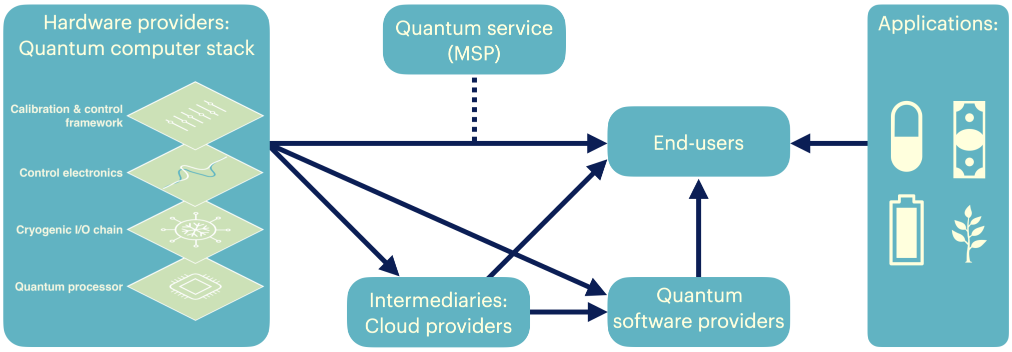

Figure 3.1: Quantum computing value proposition, based on the chain of its classical counterpart, high-performance computing.

3.1.1 Hardware Providers

The quantum computing hardware providers lie at the core of the developments in the QC industry, as technological performance is one of the key aspects holding back the diffusion of quantum computers. Various qubit platforms are still being pursued, each of which has its own ecosystem of components and firms. We will more explicitly treat the ecosystem around superconducting qubits here, and will show how the stack for such a computer is built up of various levels. The same holds for other qubit technologies, which each have their own stack.

Figure 3.2 shows an illustration of the quantum computing stack for a quantum computer based on superconducting qubits, which has been adopted from Alberts et al. [65]. At the bottom of the stack, we have the quantum processing unit (QPU) which is the quantum equivalent of a classical CPU. It contains the qubits and architecture connecting them. As superconducting qubits need to be kept at very low temperatures to shield them from thermal noise, the QPU is kept in a cryogenic fridge, which cools it down to temperatures close to absolute zero. This cryogenic fridge and the input-output chain of cables that goes in it, is the second layer of the stack. Hereafter, several electronics are connected to the QPU in order to measure and control the qubits. In order to control the qubits, and run algorithms, layers of calibration and control software need to be developed, much like the software layers between the processor and high-level coding language in a classical computer. All together, this stack should provide a user with the platform to develop, test and run quantum algorithms.

Firms are working on the various levels of the quantum stack, with some pursuing a multi-level strategy like full-stack development, some pursuing a horizontally integrated strategy which takes up a single layer in several different qubit technologies, and others focusing on a single level or even component. The lowest end of the stack consists of the very basis of quantum computers: qubits. Without a single dominant qubit technology, hardware providers are seen to develop a multitude of qubit technologies. Currently, the main technological platforms are trapped ions, superconducting circuits, photonics, neutral atoms, and spins in semiconductors. Table B.1 shows some of the companies that are developing qubit technologies, as well as their technological basis.

The consecutive layers of the stack depend on the qubit technology being used. As illustrated in figure 3.2, for superconducting qubits, a cryogenic chain is needed to keep the qubits at extremely low temperatures, whilst connecting them with the outside environment for control. This provides two additional types of companies: those developing the cryogenic fridges and those developing cables to connect the qubits to the outside control electrics. Furthermore, control electronics and software are needed to manipulate the qubits and read them out. Spin-based qubits have a similar stack, as they also need to be kept in cryogenics refrigerators. Photonic and trapped ion based qubits do not require cryogenics, hence their stack is different.

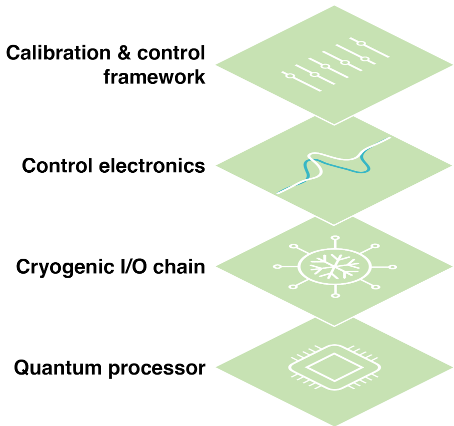

Figure 3.2: The quantum computer hardware stack for the superconducting qubit platform. Within levels of the stack there mostly exists internal competition, whereas between-level interactions are mostly cooperative due to their complementarity. Figure adopted from [65].

This component of the value proposition also contains software startups developing the calibration and control frameworks for quantum platforms. This includes startups like Orange Quantum Systems, who create diagnostic software to characterise quantum chips, and Q-CTRL, a quantum firmware developer. This firmware is the layer between higher-level and more abstract code, such as quantum algorithms, and the quantum hardware, and establishes the (hardware-specific) pulse schemes that need to be sent to the quantum processing unit [99].

In this component of the value proposition, alignment and compatibility of all the levels in the stack are key to achieving a stable, well-working quantum computer. For full-stack developers, this is simply achieved by sharing the proprietary interfaces and connections between the various components within the firm. However, other players need extensive cooperation to ensure the compatibility of their products with others. This requires strategic sharing of interfaces and connectors, alliances, and modularity. One advantage, however, is the flexibility of such an approach.

3.1.2 Cloud Providers

Many current cloud computing providers are carefully monitoring the developments in the quantum computing market, as to not miss out on the radical innovations that may come out. With large up-front costs for acquiring a quantum computer, a likely scenario is that firms looking to benefit from quantum computers would do so through cloud services. Current large cloud computing developers are therefore investing heavily in QC, in the hopes of reaping large returns and establishing market dominance by being early to market. Actors like IBM[1], Google[2], Microsoft[3], Alibaba[4] and Amazon[5] all have developed their own quantum cloud services platform, through various strategies. Whereas IBM, Google and Alibaba are pursuing a mostly internal platform strategy, developing the full hardware and software stack by themselves, Microsoft and Amazon have invested in and adopted the technologies from external developers, and are therefore trying to orchestrate the external ecosystem. It should be noted that although Google has developed their own technologies, they are also supporting a selection of third-party quantum hardware, and are therefore not purely internal. Other full-stack developers, among which IonQ[6], Xanadu[7], Rigetti[8], AQT[9], and Oxford Quantum Circuits[10], have also launched their own cloud access.

Very recently, quantum computing has started to be adopted in the high-performance computing (HPC) industry, with the first hybrid quantum-HPC configurations being announced[11]. Once this proof of concept has been fulfilled, this could signal that more HPC centres will start adopting quantum technologies and could lead to more widespread cloud adoption of quantum.

3.1.3 Software Providers

On the application side of the platform, there are many parties developing use-cases for quantum computers. In order to cater to the end-user, large full-stack developers like IBM have started partnerships with end-users and are rolling out documents that describe use-cases in several sectors, such as logistics, financial services and battery development [53, 6]. Other full-stack developers are engaging in similar efforts, which are all aimed to entice potential end-users about quantum technology.

Next to large full-stack developers, dedicated quantum software startups have started to emerge. Some of these focus on a specific area of quantum computing algorithms, like chemistry or portfolio optimisation, while others are developing platforms to generate and run quantum algorithms, like the company Strangeworks. Table B.2 shows various quantum software companies, and their areas of focus.

As software developers sit in between the hardware and end-users, they need to involve both of these categories. Upstream, ensuring compatibility with qubit architectures means implementing hardware-specific firmware. Many quantum software firms are hardware-agnostic, meaning that their software can run on any qubit platform, in order to minimise risk. In this sense, they pursue a multi-platform strategy, as described by Tukiainen et al. [93]. Downstream, quantum software producers need to develop use-cases and educate end-users, in order to stimulate adoption of their algorithms.

3.1.4 Quantum Managed Services Providers

In conventional cloud computing, there is a group of companies that manage IT for companies, including networks, security and HPC, called managed service providers (MSPs). Although currently their use is limited in quantum, large MSP firms, including ATOS and Accenture, have started to incorporate quantum computing in their business offerings. These companies are dependent on the end-users for their market, hence, they need to foster the adoption of quantum technologies. For these firms, introducing their current clientele to quantum technologies provides them both experience in the quantum realm, and ensures them a quantum-ready future.

3.1.5 End-Users

In the future, we can distinguish three groups of end-users, based on their connection to other components of the value proposition. A part of the end-users will personally own and operate a quantum computer, on which they run quantum algorithms in-house. We expect, however, that due to high fixed and operating costs, and limited usefulness of quantum at the moment, this group will remain rather small for the time being. A second group will use cloud service providers to gain access to quantum computing, on which they will run algorithms that have been developed in-house. Most likely, as soon as significant benefits are obtained using quantum computers, firms will start developing proprietary software in-house, and this group will start growing. As an example, this could be the case in finance as soon as quantum advantage is obtained here.

As discussed in the literature review, the strategies of (potential) end-users of QC have been studied by Jenkins et al. [18], where the conventional, options, discovery and adversarial strategies were identified. In this work, we are more interested in characterising the strategies of QC providers, hence we will not treat the end-users more in-depth. However, we do note that alignment of the end-users is paramount for any large-scale diffusion of quantum computing. To reach the right end-users, mapping the milestones at which one expects certain groups of end-users to jump in on quantum computing, for each of the applications, could help in predicting key turning points in QC's diffusion. This could help QC providers to target niche groups of end-users at the right time.

3.2 Public Cooperation in the Quantum Computing Context

The advantages of cost and risk reduction, technology and knowledge transfer, and access to additional resources make alliances appealing in the context of complex technology development. Especially for SMEs, alliances have been shown to be able to provide firms with competitive advantages [38]. Consequently, alliances are ubiquitous in the QC development ecosystem and are a key component of firms' strategy. As stated in literature, alliances are most often used for growth or penetrating new markets, to outsource for better quality and/or cheaper costs, to reduce financial risk and individual costs, to achieve a competitive advantage of some sort, or even to better a firm's reputation. The alliances in the quantum computing context are seen to fall into one or more of these categories. In the results, we will provide an overview of the use of alliances in the quantum computing ecosystem. For the overview, we could categorise the alliances based on the parties involved (intra- or inter-industry, intra- or international, etc.), the type of alliance (e.g. patent licensing or shared R&D), or the strategic goals of the alliance (e.g. new market development, acquiring knowledge or resources, etc.). Here, we will divide the alliances based on their type, as this most clearly illustrates the added benefits, and is easily obtained through news publications. In order to find alliances, we use three approaches: Firstly, queries on search engines that include the type of partnership and "quantum computing" provide some starting point for a search to the use of a certain alliance type. Secondly, searches of the type of partnership combined with firms's names (e.g. "strategic partnership IonQ") give more specific alliance uses. Lastly, the websites and social media pages of QC firms are explored for news posts about cooperation.

3.3 Expert Interviews

In order to challenge our value proposition and the alliance strategies in the market, and to gain insight into the use of strategy in alliances and the conscience herein, we will conduct semi-structured interviews with experts in the QC hardware field. In this section, the approach to the interviews will be laid out. In order to accurately challenge the assumptions and views, we first pose a series of guiding questions. Hereafter, we will set the criteria for interviewee selection. Lastly, we explain the method of candidate selection and explain the criteria for the firms and candidates that we approach within the selected firms.

3.3.1 Interview Questions

Information that we would like to gain and the questions that could accompany it are given in table 3.1. During the interviews, the interviewees are asked for their use of certain alliance types, and the various strategic goals that they have for such an alliance. As stated in the literature study, alliance types include joint R&D, joint marketing/promotion, joint selling/distribution, design collaboration, technology transfer agreements, licensing and second-sourcing agreements, standards agreements and bidding consortia, direct investments and informal agreements. To reduce bias, the list was provided only after an initial open question of which alliance types they used.

The goals of the interviews are two-fold. Firstly, we would like to illustrate firms' strategies in achieving a critical role in the value chain of QC, as well as their strategy in achieving an edge with this ecosystem over the full-stack approaches that are available. Secondly, the use of alliances provides insights into the strategies the companies use to achieve the ecosystem goals. Not only can it be used as contextual illustrations for the use of alliances in QC, but combined with case-study literature on platform ownership it should help in describing the attitudes that are present in the ecosystem. As the quantum industry is still in its emerging phase, the landscape is likely to still change drastically before its maturity. However, as industry architecture is still moldable, now is also the time to for firms to strategically alter the architecture for them to reap maximal rewards in the future [42].

Table 3.1: Topics and related questions for the interviews.

Subject	Questions
Background of the interviewee, and their relation to strategy in the business (insofar that is not known already)	• *Can you tell me about yourself and your involvement in* [Company name]*?*
The company's involvement in ecosystem or platform leadership	• *What SDK's do you use, and which industry networks/consortia did you join? (for example: IBM quantum network or Qiskit)* • *What does your company do to involve other component players? How do you get your products embedded in the network of complements?* • *What do you do to reach the users of quantum computers? How do you see the value proposition of QC?*
Number of alliances and the types (if possible)	• *What kinds of cooperations does* [Company name] *use? (Provide a list of options after they answer)* • *For various alliance types: When did you start using this kind of alliance? How many alliances does* [Company name] *roughly use of this type?*
Strategic goals in the alliances	• *With what goals do you generally seek and establish alliances?* • *Per alliance (type) that they use: Why do you engage in this alliance? What goals do you have for it?*
Context, background and success in gaining intended goals for certain alliance (per type or per strategy in them)	• *Can you provide an example of an alliance of* [Insert type] *type? How did the alliance start and who initiated the alliance? What factors did you take into consideration when forming the alliance? What (kinds of) parties were involved? What role did your company play in the alliance? What goals did you have for the alliance? Were you successful in achieving these goals?*
Strategic intent: Were they engaging in the alliance to achieve certain goals?	• *Do you assess the alliances on their relevance in your strategic roadmap? Would you say you are the alliances you form more exploratory or exploiting?* • *What performance indicators do you use for evaluating the realisation of the strategic goals you set for the alliance?* • *Do you actively create alliances, or do you join existing ones? Which parties in your environment would you say are the initiators in alliances?*
Closing questions	• *These were the interview questions, thank you for your time! Is there anything you think is still important to discuss around this topic of ecosystems and alliances?*

3.3.2 Expert Selection

Our selection criteria on the experts are the following:

- Must be involved in strategy formulation
- Must be involved in decisions regarding alliance formation and involvement in cooperations

For company selection, different criteria will lead to different company pools and, thus, constitute an important part of the interview methods. Although a single constraint of being a company involved in the development of quantum computing technologies would be ideal and complete, this is not feasible for this study. One option for selection, which is accessible, would be to choose the local ecosystem: quantum startups in the Netherlands. After the interview, a snowballing strategy is employed by asking if the participant knows any people that might provide valuable insights to the research.

Initially, eight local candidates for the interviews were invited. Of these eight, two were available in time for the project. Hereafter, the search for candidates was enlarged to also include non-local candidates in the network of the researcher. In the end, this provided one additional interview. In these three initial interviews, the candidates were asked to refer to other potential candidates, which would enlarge the sample size through the snowballing effect [100]. Five additional candidates were invited, of which one was available in time for an interview. Therefore, in total, four participants were interviewed.

3.3.3 Data Processing

The interviews are recorded using Microsoft Teams, which is able to automatically transcribe the conversations. After reviewing and adjusting the transcriptions, they are loaded in ATLAS.ti, a program for qualitative data analysis [101]. The interview data are processed using coding techniques developed by Corbin and Strauss [102]. This means that no framework is used *ex ante*, and the transcripts are first analysed using an open coding approach. Sections of interest are labelled with a 'code', which results in a large base of various codes after scanning through all interview transcripts. After this initial round, codings are grouped in categories. These categories can later be added to additional higher-level categories in a step called selective coding. Consequently, the categories are used to bundle experts's opinions on the various matters.

Notes

[1]https://quantum-computing.ibm.com; these footnotes will be used to reference to companies's websites and news posts on quantum products, partnerships and other statements for firms's publicity. All links have last been accessed on 29-06-2023.

[2]https://quantumai.google/cirq/google/concepts

[3]https://azure.microsoft.com/en-us/products/quantum

[4]https://www.alibabacloud.com/topic-center/tech/19tggrvkim7a-quantum-computing-alibaba-cloud

[5]https://aws.amazon.com/braket/

[6]https://ionq.com/quantum-cloud

[7]https://www.xanadu.ai

[8]https://www.rigetti.com

[9]https://www.aqt.eu/qc-systems/

[10]https://oxfordquantumcircuits.com

[11]https://eurohpc-ju.europa.eu/selection-six-sites-host-first-european-quantum-computers-2022-10-04_en

Chapter 4

Results

In this chapter, the results of the research are given. We start by explicating the use of cooperations in the industry in section 4.1, giving the likely incentives and benefits gained from each alliance type. Hereafter, insights from the expert interviews on alliances are given in section 4.2. Next, we move on to business strategies by quantum computing providers in section 4.3, giving contextual descriptions of strategies and analogies from neighbouring industries. Here, we link the identified strategies to literature on alliances and ecosystems. We end with a discussion in section 4.5, which brings recommendations for further studies.

4.1 Use of Cooperations

Based on our search of public statements, the uses of various types of alliances are summarised below. We stress, however, that these are just the agreements that have been published and that chances are that many more formal and informal agreements are used by firms. This is confirmed in our interviews, where multiple experts spoke of non-public partnerships, and one even confirmed that roughly 50 percent of their end-user partnerships is private. We order the alliances based on the closeness of the parties involved, where the scale begins with little to no cooperation from licensing, and goes up to extensive collaboration and contact in the case of a complete merger or acquisition. A sketch of the scale for the categories that have been used is given in figure 4.1. Note that this is an approximate scale and may not truly reflect the tightness of collaboration. As many of the partnerships were announced as 'strategic partnership', which is an umbrella term and could entail many things, this is seen as a range in the diagram. Although it was not always clear what the partnership exactly entails, it is still useful to include this search term, as most of the collaborations were characterised as such. No public announcements of design collaborations, technology transfer agreements or informal agreements were found, hence they are not included.

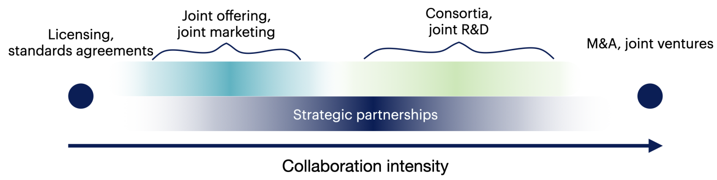

Figure 4.1: Categorisation of cooperations based on the likely intensity of the collaboration. The scale ranges from very little intensity in the case of licensing or standards agreements on one end, to very intense collaboration in the case of a complete merger, acquisition or joint venture on the other. We signify these two limits with the two dots on either end of the spectrum.

4.1.1 Licensing

The use of licenses are mostly a result of industry-academia partnerships that have been formed. These can be due to the startups origin: many are university spin-offs. IonQ, for example, mentions their use of exclusive patent licensing in their annual report: "Licensing of intellectual property is of critical importance to our business. For example, we license patents (some of which are foundational patents) and other intellectual property from the University of Maryland and Duke University on an exclusive basis. If the license agreement with these universities terminates, or if any of the other agreements under which we acquired or licensed, or will acquire or license, material intellectual property rights is terminated, we could lose the ability to develop and operate our business."[12].

Additionally, licensing out proprietary software, or interface connectors, can help in the establishment of a platform. This was seen in Intel, in its USB connectors which allowed many computer peripherals to be developed, like printers, keyboards, monitors, etc. [92]. Although similar licensing may also be present in quantum computing, we could not find public information about this yet. Note, however, that this does not include software companies that offer access to their products as a licensed service, which is offered by many quantum companies, as for example by Quantinuum[13], Microsoft[14] and Rigetti[15].

4.1.2 Standards Agreements

Although no notion of formal, industry-wide standards agreements was found, there is an increasing recognition of the need for standards in quantum technologies [65, 103]. For this, a multitude of institutes and firms are working on standards roadmaps. The main current focus here seems to be on performance metrics, which are used to assess the performance of the quantum computer. IBM here, uses the notion of 'quantum volume', which encapsulates a multitude of properties into a single number[16]. This standard has also been used by other companies to demonstrate their quantum computer's capabilities, like Quantinuum with its H1-1 system[17]. On the institude side, the IEEE standards association, for example, has a multitude of standards listed for quantum technologies[18]. Metrology institutes are also looking into standardisation of benchmarking and calibration of QC, with some even looking into certification possibilities[19].

4.1.3 Business Networks

Several business networks have been formed. These include corporate business networks, such as the IBM Quantum Network[20] and the Microsoft Azure Quantum Network[21], or institutional networks, like the Quantum Economy Network, which was started by the World Economic Forum[22]. The former are started to benefit the initiating firm through knowledge and information transfer, alignment, and establishment of new partnerships, whereas the latter are mostly incentivised to foster good ecosystem health and responsible innovation.

4.1.4 Joint Marketing, Selling and Offering Agreements

Joint offerings have been used by Microsoft and Classiq[23], or Multiverse computing and IQM[24]. In both cases, the offer includes quantum software from the one to be ran on a hardware platform of the other. Due to the complementary nature of these offerings, their conjunction is an offer that brings added value to the end-user. From an SME perspective, the joint offering can provide credibility and branding through affiliation with a large incumbent, such as Microsoft. For an incumbent, joint offerings can provide compatibility, increased network, and increased adoption, all of which aid in their platform position.

A second reason for joining in this type of cooperation is also seen, which is to gain access to novel markets. This is the case for the partnership between D-Wave and NEC, which allows D-Wave to the develop its presence in the Japanese market through large Japanese multinational NEC[25].

4.1.5 Consortia

The QC market has seen the establishment of various industry consortia. In the US, the Quantum Economic Development Consortium (QED-C) and Quantum Industry Coalition (QIC) have been established, in Europe the Quantum Industry Consortium (QuIC) and in Japan the Quantum STrategic industry Alliance for Revolution (Q-STAR). The goal of these consortia is to benefit the industry as a whole, by coordinating federal investments and policy, by collaborating to fill gaps in technology, standards and workforce, and by identifying high-impact use-cases. These alliances typically consist of many parties, and have a dedicated board managing the consortium. Additionally, there are many national bodies which are formed to carry out or support national quantum initiatives, like Quantum Delta in the Netherlands. These have similar goals, but are focused more locally and try to get the national ecosystem to prosper.

Similarly, industry-government partnerships are also present. Several alliances are formed to complete governmental-funded projects. Europe's Quantum Flagship programme, for example, financed 21 scientific projects that involve both research institutes and corporate parties, on a range of quantum subjects. Among the projects is AQTION, an initiative to build a trapped ion quantum computer in Europe, resulting in the startup AQT. The projects are started on a tender- or subsidy-basis, meaning that firms have to apply for the grant to be admitted. This causes groups of firms to link up and collaborate in carrying out the project on a bidding consortium basis, like was the case for AQTION, but also for other projects like QLSI, in which ATOS, Infineon, Quantum Motion and others participate, or DAQC, which is carried out by IQM, Infineon and others. It is worthwhile to note that in the microprocessor development, similar activity was seen [52].

Lastly, consortia are used for system integration. For example, to construct a complete off-the-shelf quantum computer by various modular component manufacturers, the ImpaQT consortium was created. This consortium includes five quantum computing startups and high-end technology supplier Demcon, which are planning on combining their various technologies to create a complete quantum computer[26].

4.1.6 Strategic Partnerships

One of the main uses of alliances are strategic partnerships between firms. Although this is an umbrella term that encompasses many of the other categories, it is one of the most widely used terms to indicate cooperation. As it is not always clear exactly what kind of collaboration is meant by it, we have included it as a separate category. In the following, we will illustrate how strategic partnerships are used for market access, to develop an end-user base and foster adoption of quantum technology, and to develop compatible, complementary technologies.

Firstly, quantum startups can be seen to collaborate with local actors in order to gain access to new markets. Mainly, this is seen in Japan, where three western quantum companies have recently started working together with Japanese partners to develop the local market. This includes US-based IonQ's partnership with SoftBank[27], UK's Quantinuum with Mitsui[28], and Israel's Quantum Machine's partnership with Toyota Tsusho[29].

Additionally, we can see alliances being formed between QC companies and potential end-users. In these cases, use-cases are explored and the requirements from the technology side can be established. For example, IBM has partnered with many potential end-users, releasing use-case documents in which the benefit of quantum technology to the problem at hand is illustrated such as for the maratime logistics sector [53]. Furthermore, they also have a multitude of client cases on their website, with partners like materials firm JSL, car manufacturer Daimler-Benz, and oil & gas company ExxonMobil[30]. Similar partnerships are seen by nearly all full-stack developers, including Microsoft, Google, IonQ, and more. Although not as common, software developers are also seen to partner with clients to co-solve quantum use-cases. For example, 1QBit has entered partnerships with parties including Dow, Biogen, RBS and Allianz[31].

Intra-industry partnerships are also seen, mostly to develop compatible, complementary technologies. Dyadic partnerships of this sort include quantum control electronics supplier Quantum Machines and quantum firmware company Q-CTRL[32], or Q-CTRL's partnership with quantum algorithm developer Classiq[33].

4.1.7 Mergers, Acquisitions

Although these extrema do not fall within our definition of an alliance, it is still worthwhile to treat M&A activity briefly here. One of the first acquisitions was seen in November, 2021, when quantum software provider Cambridge Quantum was acquired by conglomerate Honeywell, and it was reformed to Quantinuum[34]. Other activity includes Quantum Machine's acquisition of QDevil[35], IonQ's merger with Entangled Networks[36], Bluefors's acquisition of Rockgate[37], QCI's acquisition of QPhoton[38] and Pasqal's acquisition of Qu&Co[39]. Furthermore, recently Rigetti, D-Wave and IonQ merged with special purpose acquisition companies (SPACs), in order to facilitate their IPO.

4.1.8 Joint Ventures

We have identified two joint ventures in the QC industry. Swiss quantum startup Terra Quantum and high-performance computing company Novarion created QMWare, a hybrid quantum-classical HPC software company[40]. A joint venture has also been used on a project-basis by Qilimanjaro and spanish telecom group GMV, to facilitate the first complete quantum computer in Southern Europe[41].

4.2 Experts's Opinion on Cooperation

Within the next couple years, experts expected to observe a lot of consolidations and a lot more M&A activity in the quantum ecosystem. Although it was not asked for explicitly, the impeding quantum winter, if you will, was brought up by two of the experts. Moreover, one expert said that everyone in the ecosystem was well aware that it would be wise to think strategically, much more than before, although not all companies were said to be acting on this already.

Tenders and subsidies were most frequently mentioned in the context of alliances. For the formation of a tender or subsidy, various parties bundle up into the formation of a bidding consortium, which then applies together to receive the capital. For SMEs, this is a very important source of capital, and this is the main reason mentioned for engaging in this kind of alliance. Similar behaviour has been observed by Ozmel et al. in biotech startups [98], where alliance capital was used as an alternative, or complement, to venture capital. Other reasons include staying in the loop of technological decision making on standards, and being able to get product development out more rapidly, in order to provide an early product show-off. Although they are similar in the goals attached to them, there are a couple of important differences between tenders and subsidies. Firstly, in tenders, there is an obligation to deliver and, hence, typically lower-risk projects are attached to it, whereas subsidies have an obligation to try, and failure is more acceptable. Furthermore, tenders are a source of revenue, meaning that the capital covers more than just the costs of the project and the firms can use the capital in their own way, whereas subsidised capital will, at most, only cover costs and needs to be spent solely to the processes related to the subsidy project. However, in acquiring capital using subsidies, one must make sure to not get too diversified in their portfolio, as a different project is needed for every subsidy. Applications should therefore be judged on their alignment with the firm's strategic roadmap and on their risk.

Regarding funding from the EU and national incentives, the political incentives were also underlined. The calls put out for subsidies and tenders are often almost a guaranteed win for those parties that are well-connected in the industry. Building an extensive network with academia, industry and institutions is therefore of paramount importance for success. Furthermore, these types of capital are subject to geopolitics. Countries and governments invest heavily to foster quantum ecosystems in their country, hoping to capitalise on a global quantum industry. Related to this, the bureaucratic nature of these capital streams also came up during one interview. It was argued that due to the inefficiency of the European investments, the capital might be less effective than that of, for example, the American market. The extend and implications of this provide interesting topics for future research.

One of the guiding questions was aimed at finding out whether the companies used their alliances more for exploration or exploitation purposes, which was previously studied by García-Canal et al. [96]. Here, exploitation refers to leveraging the alliance to exploit its assets and acquire revenue, where exploration is aimed at building out the company's asset and competence base. Varying answers were obtained here, illustrating that the picture is rather nuanced. One expert described their use of alliances, especially the bidding consortia, to be mostly exploitative, due to their company's small size. They used these alliances to shoehorn a license to their products into a package deal, which then provides them revenue. Another company expert argued that the use was more exploratory, in that they used the alliances as a catalyst to expand their asset base. A tender or subsidy can be used to accelerate the development of a new product or technology, hence such use of these alliances is more exploratory. The same expert, however, also described the use of tenders as a source of revenue, and therefore it should not be seen as purely exploratory. A subsidy, however, only covers, at most, the costs of a project and will therefore always lean more towards an exploratory side. Only if the company is involved in a subsidy project as a vendor rather than a participant can it truly be seen as exploitative. A third expert described their use of collaborative projects with end-users as a means to get revenue, as the end-user is a paying client in the project, but also to as a mechanism for expanding their intellectual property. Here, again, we see a nuanced picture of the use of alliances for exploratory or exploitative purposes.

In the open quantum approach, the use of cooperation was also mentioned to be for figuring out relationships with other component players. In this industry, there is no clear value chain yet, and the interfaces between various components have not been set in stone. Hence, firms are not just engaging in partnerships to achieve a certain strategic goal, but also to explore the relationship they can have with another component player. One interviewed expert mentioned a partnership with a complementary developer, which they set out to see if they could form a joint offering. In the end, instead of a collaboration, they ended up having a regular supplier-customer relationship. The expert mentioned, however, that this might change in the future. Cooperations should therefore also be seen as a dynamic probing process, which companies use to figure out their exact place in the value chain.

Two out of three interviewed companies said there was no clear initiator in alliances: their collaborations were sometimes established by themselves, sometimes by the other party involved. The third company answered that they were often the initiator. This company was a niche player, of which the position in the value proposition was often said to be misunderstood. Hence, their collaborators needed to be educated on their product first, before they were willing to engage in any collaboration. Although there are likely some more initiating parties in the QC ecosystem, which is often the case for a platform leader wannabe, these were not identified in this research. Formation of cooperations seemed to be mostly on an ad hoc basis, with feasibility, risk, and alignment with the firm's roadmap the mentioned selection criteria.

Two of the three companies developed their own open-source software software packages. These packages were both aimed at standardising the backbone of the proprietary software that they developed, such as code for quantum measurements or for compiler optimisation. Notably, all companies mentioned their use of, or compatibility with Qiskit, IBM's quantum SDK. This illustrates that this is a very widely adopted platform, signifying IBM's strong presence in quantum computing. This will allow IBM to rapidly obtain information on trends and developments in the field.

To conclude this section, table 4.1 briefly summarises five key cooperations and the identified strategies therein.

Table 4.1: Key cooperations and the strategies with which they are used.

Cooperation	Identified Strategies
Bidding consortia in tenders and subsidies	Tender and subsidies provide capital procurement, early product show-off and allow companies to stay in the loop for decisions on technical standards. The main risk in using tenders is not being able to deliver on promises, the risk in using subsidies is to get too diversified.
Managing open-source software package	Managing a company's own open-source package can be used to foster standardisation, or to push for adoption of the software. An obvious risk here is that open-sourcing takes away the appropriability of the software.
End-user partnerships	Constitution of the value proposition demands education of end-users, in order for adoption of quantum computing to take place. Through projects with end-users, intellectual property can be generated with firms' strategic position can be strengthened. Risks here would be similar to risks of any kind of collaborative R&D project.
Joint offerings	Joint offerings, marketing or selling can add value for the customer due to complementarity, or can provide access to new markets.
Standards agreements	Although not formal, pushing for standards on performance metrics and diagnostics are used.

4.3 QC Provider's Business Strategies

In the current QC market, cooperation is the dominating factor in strategy[42]. And, although no academic literature on business strategies from a technology provider's perspective exists, public statements from providers allow us to catch a glimpse of the strategic factors that they deem important. IonQ, for example, which is one of the first publicly listed quantum computing startups, talks about their corporate strategy in their 2021 annual report[43], where they mention the following five key points for their strategy:

- Leveraging their trapped ion technologies
- Offering Quantum Computing as a Service (QCaaS)
- Selling quantum computer hardware
- Enhancing proprietary position
- Further developing their partner ecosystem

We could characterise the first point as leveraging their technological competitive advantage, the second and third as product visions, and the last two as competitive strategies. Furthermore, they mention the following goals for entering in strategic partnerships:

- Obtain expertise in relevant markets
- Obtain sales and marketing services or support
- Obtain equipment and facilities
- Develop relationships with potential future customers
- Generate revenue

Here, again, similar points are observed. The first item addresses an aim to build on their competitive advantage through relevant knowledge acquisition. Penetrating the market with radical and disruptive innovations often requires niche approaches [83], hence knowledge and innovation leadership are prerequisite. The second and third point are general outsourcing strategies, in which superior knowledge and capabilities are obtained through specialised alliance partners. This is a frequent reason for entering alliances, as mentioned by Varadarajan and Cunningham [95]. Furthermore, although the last point seems rather trivial, it is actually rather important in the QC context. With no currently viable end-user applications, many QC companies are not yet generating product revenues. With cospecialisation being of such importance for the constitution of the value proposition, collaboration can generate sales that are otherwise not possible. IonQ hence tries to lift itself out of a funded-research-institute position, by developing relationships with potential future customers - through shared R&D projects or co-exploring use cases - and by generating revenue through actual product sales.

However, while currently cooperation is prosperous, standards battles will ensue at some point, indicating the need for adoption of any leveraged technologies. These battles are subject to winner-takes-most competition (unless commoditisation is significant), hence the need for technology diffusion. Here we can learn from platform strategies as studied by Cusumano and Gawer [29, 91], microprocessor architecture standards adoption as studied by Vanhaverbeke or Molina [52, 51], and operating system battles of various industry giants in the open-source paradigm [90]. One should recognise the distinction between short-term and long-term: In hardware, technological superiority is still the de facto differentiator, but it is subject to bandwagon effects. Hence, as soon as adoption is starting up, this should become a priority for firms developing hardware, as the ones that are able to get a head start in adoption and standards battles, will most likely define the direction of the industry and the development. This is the crux of the tipping effect in standard battles, in which the positive feedback loop in adoption and innovation leads to a tipping of the scale in favour of that technology which achieves a head start. In software, bandwagon effects will also be significant as positive network externalities are seen in the adoption of software platforms. Firms should focus on their source of competitive advantage here: If this is software-propriety based, there is the risk of becoming undifferentiated if the industry shifts to more open-source standards. Other sources of competitive advantage are also available, like IBM's support services on its open-source Linux operating systems. Additionally, pushing of open-source software with proprietary complements like Apple did in its battle against Linux and Microsoft in operating systems - e.g. shifting its operating system to open-source Darwin but keeping its graphical interface proprietary - can help maintain a differentiation while benefiting from adoption and technological developments of the underlying software technologies. However, a risk here would be that the adoption and development might be hindered by reducing the software's functionality [90].

4.3.1 Platform Leadership Wannabes

With its large market potential, and with the likely winner-takes-most outcome that is characteristic in standards and platform leadership battles, many firms are trying to achieve a central position in their perceived value proposition. In order to do this, they need to perform a platform strategy that enables them to obtain a unique position in the eventual industry architecture. Note that, like emphasised by Teece and Jacobides, firms themselves have a crucial and significant role in constituting and shaping this architecture [46, 42]. Moreover, the 'tipping' phenomenon in standards contests makes platform distribution and adoption critical in turning the industry architecture to a firm's hand. In this light, the appropriability versus adoption consideration of proprietary versus open approaches is an important question to answer. Historically, this has been studied in light of alliance blocks in the adoption of microprocessor architectures [52, 51], and in the reaction of large incumbents, including IBM and Microsoft, to open-source software movements [90]. From the former, we recognise the need for alliances in the adoption of a technology and the creation of a sufficiently large installed base. In the latter, hybrid strategies are elucidated which aim to answer this appropriability-adoption dilemma.

Similarly in the QC context, both these phenomena are observed: the ubiquitous use of end-user partnerships by high-stack players, the formation of various industry networks, like IBM's Quantum Network or Microsoft's Azure Network, and the release of several open-source software development kits (SDKs), like IBM's Qiskit, are all aimed at tipping the standards in favour of the associated firm. Furthermore, the sharing of open interfaces, like the aforementioned open-source SDKs or shared technological hardware interfaces, all points in the direction of platform establishment. Firms need to balance quick distribution and adoption through open-sourcing and cooperations, and differentiation and profit potential through propriety. Furthermore, platform ownership and power are major concerns, which stem from industry architecture and firms's position within this. For full-stack developers, their business model may make it such that they can appropriate their platforms in various ways. One of the interview companies uses end-user projects to build their platform. Although the end-user obtains the results of the project, and gets some exclusivity to the algorithms developed in the project, the interviewed company gets to keep all the quantum-related IP. Although this IP cannot be deployed immediately with the customer's competitors, it allows the interview company to build a platform of IP, which provides them a versatile software platform with many different applications.

We can already observe differences in the approaches of Microsoft and IBM in their aim to constitute their own quantum platform. Microsoft's Azure Quantum is a cloud service platform that offers the users the option between various hardware platforms: trapped ions, neutral atoms and superconducting qubits. The qubits are offered by various hardware vendors such as Rigetti, IonQ and Pasqal. Furthermore, Microsoft itself invested heavily into developing exotic Majorana qubits, which have been theorised to offer topological protection from decoherence and could potentially provide a significant improvement over current qubit platforms [104]. With this options approach Microsoft refrains from having to choose a 'betting horse' and risk missing out on market capture if the wrong technological basis is chosen. Furthermore, it is in line with the 'Wintel' approach that was taken by Microsoft and Intel in the PC development era, where Microsoft was the firmware and operating software provider, which it developed by working together with hardware developer Intel. In the quantum case, Intel has been replaced by a multitude of qubit hardware vendors, but Microsoft's position in the value proposition remains similar in that it develops the higher-level operating software, although the personal computer system now has made way for a cloud platform instead. IBM, on the other hand, is taking an approach similar to that of their mainframe computers. Through in-house, full-stack developments, IBM aims to create an internal platform, which would allow high margins. Additionally, adoption of their platform, information flow, and platform leadership is established through ubiquitous end-user partnerships, their open-source software Qiskit, and one of the largest networks in quantum, the IBM Quantum Network. Much like Microsoft, IBM's strategy resembles the approach that they took in developing the classical computer.

Economies of scale and agility are mentioned as main advantages of the open innovation approach, as opposed to the full stack approach. Experts underlined that with the technological uncertainty that's present in the market - no platform or component is standardised - maintaining flexibility is important. As the smaller size of component developers within this approach makes them more agile, this provides significant advantages. Secondly, due to the network of complements, and the modular nature of the components, firms that are involved in the open quantum development may be able to acquire more scale advantages. As one of the interviewees argued: ”If you supply only a part, then your volume is much higher. So I think actually if you are open architecture, your margins are much higher.” The reasoning for scale advantage is the following: component developer providing its modular component to many system integrators and other component players will sell many more units than a fully integrated provider that only provides a hand full of full-stack setups. Due to these larger quantities, the costs can be divided over more units, hence the margins will be higher. This, in turn, may lead to an increased innovation causing the technical capabilities of component players to surpass those of full-stack developers. Lastly, due to higher volumes, this approach may also increase standardisation through adoption.

Here, again, we compare to the classical computer market, where adoption and diffusion of both Windows and Intel unified the PC market and provided a common set of application programming interfaces for all Intel-based PCs. This has the following bandwagon effects: Firstly, due to a common standard in programming, software developed on the Wintel system could immediately be implemented on the complete set of Wintel devices, leading to a large installed base. This juxtaposes with the proprietary architectures, such as that of NEC or Sun Microsystems, that were incompatible with the competition. Once the Wintel platform gained traction, this led to a tipping effect due to the larger network externalities associated with it as compared to the competing closed operating systems. Both Sun and NEC were inadequate in reacting to the Wintel platform, leading to their demise [90, 105]. For quantum computing, this means that any full-stack developer will have to carefully manage interfaces and monitor industry trends for standards. Moreover, the Wintel combination of compatible architecture and operating system provides an argument for quantum hardware and software developers to collaborate beyond their nearest-neighbours in the stack.

This brings us to the constitution of QC’s value proposition: The need for alignment of key actors in the ecosystem. The topic of alignment has been treated extensively by Ron Adner [40, 49]. He illustrates the need for propositional coherence between actors with the failure of Michelin’s PAX tires, which were ill-adopted due to Michelin’s failure in getting repair shops to partake in the value proposition. Alignment of various parties in the value proposition means educating the end-users on quantum computing. One interviewee said that almost 99% of people that are not in quantum have one of two main, but opposing, misunderstandings. Firstly, about half of the potential end-users does not believe in the existence of quantum computers, thinking that they are science-fiction and, if they exist, that they are still out by at least 20 years. The other group believes that quantum computers are simply a better performing computer, on which they can simply run the existing code and algorithms that they run on classical computers. They view quantum as a buzzword that’s been added to signify an incremental step in computing capabilities. Hence, educating and correcting misunderstandings about quantum computing were a significant portion of this interviewee’s job. This signifies that there is a discrepancy in the value proposition for quantum computing from the end-user side versus the rest of the industry, and this may lead to a lack of alignment of parties. Therefore, educating end-users is paramount in order for the value proposition to take form.

4.4 Analogies with Neighbouring Industries

Interestingly, several analogies within various industries came to light during the interviews. Studying these industries may provide new insights into predictions for the quantum computing industry.

First and foremost, the microchip sector and semiconductor industry were mentioned several times. Especially with superconducting and spin qubits, this analogy seems obvious, as these qubit platforms build on semiconductor technologies. In one interview, the semiconductor sector were said to have taken off mainly when the IT sector started requesting it to produce and scale, after the interfaces got well-defined and abstracted enough for large-scale diffusion of IT technologies. The expert believed that this will also be the case for the quantum computing hardware sector, as they believe that quantum computing will be a part of the existing IT industry. In another interview, the state support in the constitution of semiconductor manufacturer TSMC was compared to the EU's funding in quantum technologies. They said that due to the EU's antitrust policies, not willing to invest a lot of capital into a single company, their capital is much less efficient and they may lose to the US, where capital is out the door much more quickly. Furthermore, the subsidy calls within the EU for quantum technologies were compared to the calls of the CHIPS Act in the United States, in which lobbying and a good network were said to be deciding factors in whether or not firms can win a competitive call.

Two more industries came to light in the comparison with tender and subsidy calls in the QC industry. The political nature of the EU investments was compared to that of the nuclear energy sector. In another interview, large full-stack players in the QC industry were compared to the aerospace industry. It was said that due to heavy subsidising and the strategic nature thereof, large firms may end up integrating components from many suppliers, like with Airbus and Boeing in the aeroplane manufacturing industry. As subsidies in the aircraft industry have been the subject of quite some studies, this might provide an interesting analogy for further research [106].

Moreover, in one interview, the QC market has been compared to the cloud access market, as it is most likely that it will serve as an extension of this. In this market, Europe has failed to facilitate timely innovation, and as a result has become dependent on major firms in the US for this. The expert argued, that the goal of the European Union should not be to have completely independent value chains, but instead promote increasing mutual dependence. However, they mentioned that the key to establishing a significant quantum platform in Europe would be the existence of a large system integrator, which is not currently present.

Lastly, the deep niche strategies that are recently pursued by several quantum startups were compared to the beachhead strategy of Commodore International, which released early home computers. These computers were criticised for not being universal, but their usefulness in the gaming niche and affordability made them extremely desired. For quantum computing, finding these niches may generate significant sales early on, even if the quantum computer is not a universal one. Approaches such as non-universal photonic quantum computers, or D-Wave's quantum annealers may not be able to run every quantum algorithm, but practical niche applications could still be found. Similarly, the expert argued that niche strategies such as focusing on a single hardware platform or software vertical, such as finance, may give startups an early edge. This could be seen in Infleqtion, a quantum software startup that focuses only on a single hardware backend and a single software vertical with the financial sector. These niche introduction strategies are alike the ones advocated by Ortt and Kamp, which can be used prior to large-scale diffusion [83]. However, the obvious risk in this is that, with the large uncertainties in application and technology, betting on the wrong technology or application may end up disastrous. Hence, this provides another interesting area for future studies.

4.5 Discussion

The work in this thesis encompasses a multitude of related fields including competitive strategy, ecosystems and alliances, and discusses the quantum computing industry from a standpoint of the technology providers and developers. Although these topics have been treated extensively, we will indicate several areas for improvements.

First and foremost, the sample size was small, as we were only able to interview four participants in the time-frame of the thesis. This was due to long waiting times to get interview approval from the TU Delft and low participation rate. Lack of sample size may increase bias, reduce rigidity and consensus, and will therefore reduce the overall validity of the conclusions. Additionally, SME interviewees came from companies within the EU. As government subsidies and tenders are a very large portion of firms's revenue and capital income, the geographical differences in politics might have a large effect on the investment landscape. Interviewees already mentioned differences in governmental investments between the US and the EU, which were mostly based on the governance aspects associated with the tenders. Investigating this difference could add valuable insights to the work in this thesis. As a starting point, the difference in the time between the appropriation of a budget by the government and the actual funds being delivered, for various governmental bodies (such as within the EU, US, etc.). This should provide insights into the efficiency of capital allocation by the governments and might help explain the differences in, and attractiveness of, investment landscapes of various locations. Moreover, only a single person from each company was interviewed, but obtaining various views from within single companies might also be interesting. Therefore, future research could use this thesis as a starting point for conducting more interviews, to strengthen the conclusions and implications of the research, and to obtain additional insights.

Secondly, we draw several parallels with the advent of the classical computer. This provides several bridges and allowed us to contextualise the appropriability-adoption dilemma, decisions of vertical integration and platform leadership. However, three key differences exist between the current state of the quantum computer landscape and the landscape of the classical computer at the historical moments we compared to. First, the current quantum computing industry is still very much infant and, therefore, the sales volumes are currently much smaller for quantum computers than for classical computers at the moments discussed. Second, as presently no viable commercial applications exist yet, end-users are only engaging out of exploratory reasons and large-scale diffusion is not seen yet. And third, the value proposition largely complements that of classical (super)computing. Therefore, the industry that comes out of this quantum paradigm might potentially simply extend the current IT industry, instead of spawning a completely novel one. This is supported by the myriad of incumbent classical computing companies that chime into quantum computing. As a result, industry architecture might be more rigid than this thesis makes it out to be. Despite this, ecosystem formation will still take place, and both SMEs and the larger incumbents will have to find their place in the value proposition. It is also entirely possible, however, that significant use cases for quantum computers will be invented once the technology is there, which may result in a completely separate industry nonetheless. In comparing to the standards battles in microprocessor architectures, there is a key difference in market dynamics: Where the adoption of RISC versus CISC was facilitated by a demand-pull market - millions of units were sold at the time [51] - the current quantum computing market is mostly characterised by a technology-push. It is therefore a question to which extend a bandwagon effect will be observed in the QC case, as the low volumes may decrease the positive feedback loop that is seen in adoption and rate of innovation. The same things can be said about our classical-quantum comparison in standardisation and distribution of (open-source) software. Note, however, that this does not change our conclusions much. Despite technology-push dynamics, the ecosystem formation is still taking place and, hence, embedding oneself in this is as important. Moreover, although the mechanism driving standardisation will currently be different than during the time when standards battles in architectures for microprocessors were taking place, adoption of leveraged technologies is paramount nonetheless. Lastly, with such a growing market, the scale advantages that currently play less of a role might start differentiating firms in the near future already. Additional research would be needed to uncover the exact extend to which the parallels apply.

Thirdly, the use of public statements of companies raises the question of how truthful companies are in their reporting. Oftentimes there is a benefit to be gained by the reporting company to either undermine or exaggerate their statements. For example, there is no telling in the weight added to the IonQ's statements regarding their (alliance) strategy. Although they report five bullet points for both general and cooperative strategy, it might be that a few are much more important to them, or they are leaving out important (business) strategies. Caution should therefore be taken with regards to conclusions drawn from these public statements.

Fourthly, this thesis is ambiguous in who it ascribes strategies to. In the introduction, the landscape is described to consist of both small-to-medium enterprises and large corporations (such as IBM and Microsoft), and the strategies between these categories of firms will be different. Cooperative strategies connected to raising capital will most likely be much more important to SMEs than to large corporations which can finance projects completely from their own budget. It is therefore left up to the reader to decide whether a described strategy is interesting for a large or a small firm. It would be beneficial for future works to investigate the differences in strategy between large and small corporations in the quantum business landscape.

Lastly, currently only quantum computers are considered in the business proposition, leaving out quantum networks, cryptography or sensors. Although little use-cases are currently known to involve both quantum computers and quantum networks, there might be a potential value added from including this. Like in the classical case, where not just computers, but their inter-connectivity constitute a large portion of the value, quantum might have hidden applications that involve networking. Furthermore, recent literature argued that quantum communication might reach commercial use sooner than its computational counterpart [107]. Therefore, the inclusion of these additional quantum-related topics, as well as perhaps hybrid quantum computing approaches, will provide a more detailed view on the quantum industry as a whole.

Notes

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Chapter 5

Conclusions

In this thesis, we explicated the use of cooperations in the quantum computing context, linking it to managerial literature on strategy, alliances and ecosystems, and providing analogies with neighbouring industries. We set out to answer the main research question: *What alliance strategies are present in the quantum computing hardware ecosystem, and how could they help firms to achieve competitive advantage?* In order to answer the main question, we first go over the following sub-questions:

1. *What does the quantum computer business ecosystem look like?*
   (a) What actors, activities and architectures can be identified?
   (b) What (kinds of) alliances are seen?
2. *Looking at literature on cooperative and competitive strategy, which roles and strategies described in literature can we see in the QC market?*
3. *What benefits can be expected from the identified strategies, and what risks are tied to them?*

In order to answer these three questions, we reviewed literature on quantum computing, ecosystems and alliances, and used expert opinions to constitute a notion of the ecosystem. From this, a value proposition was constructed which contained five components: Hardware providers, cloud service providers, quantum software providers, managed services providers and end-users, each with its own set of challenges and strategies attached to it.

Secondly, two technology strategies pursued by firms can be identified: an open innovation approach and a full-stack approach. On the cooperation side, we identified the use of licensing, standards agreements, business networks, joint marketing, selling and offering agreements, consortia, strategic partnerships, mergers and acquisitions, and joint ventures. Next, the actors and strategies were linked to managerial research in neighbouring industries, among which alliance blocks in adoption of microprocessor architectures, vertical integration of Intel into complementary markets, open interfaces in operating software, and capital procurement by startups in the biotechnology industry.

And lastly, we turned to the expert interviews. In the interviews, several other parallels with neighbouring industries came up, which could be used as starting points for future works and are provided in the outlook. Moreover, the interviews showed that, at least for SMEs, alliances through bidding consortia, formed for tenders and subsidies, are the main use of cooperation. Strategies herein are the acquisition of capital, reduction of R&D costs, speeding up product development, and staying in the loop for technological decision making on standards. Other partnerships were aimed at figuring out relationships with other firms in the industry, as currently the value chain has not clearly formed yet, and fostering standardisation through the release of open-source software. Additionally, we contextualised the strategic differences between the full-stack and open innovation approaches that are seen within the ecosystem. Where firms in the former are challenged by technical inflexibility, low sales volume and vast investment costs, firms in the latter need to balance the appropriability-adoption dilemma, create sufficient alignment with their value proposition and use extensive cooperation to ensure compatibility and modularity.

The aforesaid helps us in answering the main research question: *"What alliance strategies are present in the quantum computing hardware ecosystem, and how could they help firms to achieve competitive advantage?"* In short, we identified two categorical strategies for the use of alliances: Acquiring capital and networking. Where the strategic implications of additional capital are trivial, those of networking benefit the firms in two ways. First, networks allow firms to stay in the loop on information and changes in standards and trends. Second, strategic partnerships allow the firms to embed themselves in the quantum computing ecosystem - a necessary constituent for their survival. It should be noted, however, that differences in strategies exist in the acquisition of capital through cooperations, which is a result of the limitations put on various kinds of project funding, such as tenders and subsidies.

As a result, this thesis provides a contextual overview of alliances in the QC ecosystem, which should aid managers in evaluating their strategic position in the ecosystem and in drafting cooperation strategies. In addition to strategies, we identify a lack of alignment of end-users as a key inhibitor to the constitution of the value proposition. From an academic perspective, this research provides, to our knowledge, the first managerial study of the quantum computing provider market. Furthermore, the parallels between the case of quantum computing and neighbouring industries provide a contextual basis for future studies. Lastly, the findings of this thesis can be seen as a first confirmation of the speculations made by Ortt and Kamp in the outlook of their paper about the drivers of strategies in the pre-adaptation phase [83]. This will be elucidated in the outlook below.

5.1 Outlook

Although this thesis covers many facets of the use of alliances in the quantum computing context, there are a few limitations to the research, as put forward in the discussion. These are mainly related to the sample size and composition, which consisted of only four experts, and the infant state of the QC market. The former makes that differences in strategy between firms in different parts of the stack, different locations and firms of different scale - SME versus large firms - are poorly understood. The latter raises the question to which extent the parallels with the classical computing industry hold, for now. In order to improve the validity of the conclusions, more interviews with a large and varied sample of experts would be ideal. Furthermore, this could extend the use of alliances and strategies per type from merely a qualitative one to more quantitative. Lastly, this could also help in exposing the geographical and value-chain positional nuances in the strategy formulations and evaluations of firms.

Two of our experts brought up disadvantages in funding received from the European Union, which, due to its bureaucratic nature, was said to be slower and less effective than the governmental funding instantiated by the United States. With the considerable influence of institutional investment into quantum technologies, understanding differences in funding efficiency between countries and regions, such as the EU and US, is paramount both for firms and policy makers. Hence, one topic for future research could be the geographical differences in public funding for quantum technologies. For instance, studies could look at the time between the appropriation of a budget for certain technological developments and the moment it reaches the actors developing the technology, as this should give some indication of the time-efficiency of capital.

Research could also cover the industry comparisons that came out of the expert interviews. This includes diffusion of microchip in the semiconductor industry, influence of state funding in the constitution of TSMC, influence of lobbying and network in acquiring public subsidies and the influence of subsidies on the ecosystem and system integration of the aeroplane manufacturing industry, Europe's participance - or lack thereof - in the cloud access industry, and beachhead niche strategies by home computer developers such as Commodore.

Moreover, for now the ecosystem is in an emerging state. This provides opportunities for studying the emergence of platforms and the role of strategic alliances herein. This work identifies that, to constitute the value proposition, end-user engagement is necessary, which is currently challenged by the lack of commercial advantages offered by quantum computing, as well as end-user awareness and knowledge of quantum technologies. Future works could therefore characterise the differences in engagement of end-users based on the industry in which quantum computing is applied. With varying applications and varying technological requirements of the quantum computers to enable these applications, milestones could be defined at which the various groups of users are expected to benefit of and, hence, engage in QC.

Furthermore, the findings in this research support one of the hypotheses in the outlook of Ortt and Kamp's TIS framework paper [83], about the phase prior to the adaptation phase studied in their paper. Here, they speculate that in this innovation phase, firms' strategies might be aimed at constituting the TIS building blocks, which they identified in their paper. Examples they provide are lobbying and networking strategies aimed at building supply networks and R&D investments to improve product performance. This is precisely in line with the two main categories identified in this work: acquisition of capital through R&D subsidies and tenders, and networking in order to constitute a beneficial value chain. Future works could therefore further develop this link and look at firms' strategies in relation to the seven building blocks identified in their framework. Studying this subject could allow us to understand the drivers of emerging ecosystems.

Finally, future works should study whether, and how, the high-flexibility of open innovation will win or lose from the propriety and control in full-stack development.

Appendix A

Porter's Structural Analysis of Industry

A discussion of business strategy would not be complete without the inclusion of the work by Michael Porter [44], who established the most widely adopted framework for competitive strategy. Along the lines of Porter's five forces model, the company environment is divided into five categories, depicted in figure A.1. Interactions between and within these categories determine the profitability of a firm's position in an industry. Structural analysis of each of these components is a necessary basis for gauging the state of the industry, and the drivers of change.

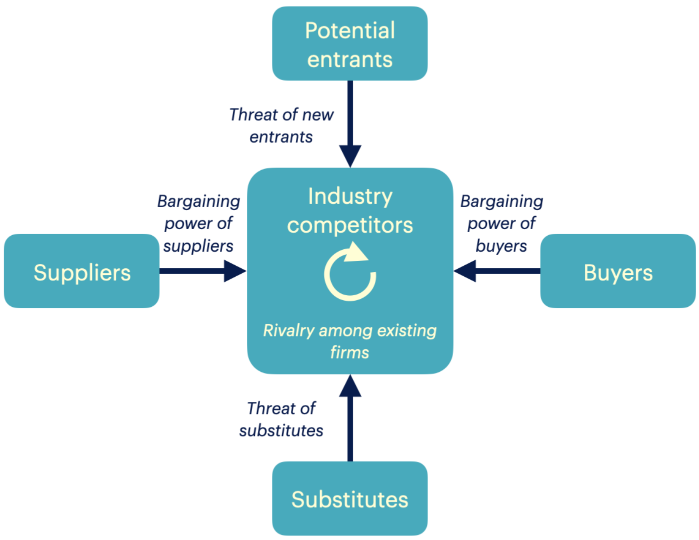

Figure A.1: Porter's model of industry forces that drive competition [44].

What business managers need to know about drivers of change is the capability of these drivers to affect the industry structure, as well as the value chain of the business. Predicting the drivers of change, and their effect in the business context, is at the heart of a business' future: inadequate reaction to change, which brings about or elevates new sources of competition to the forefront, is detrimental to a business' competitive advantage and its success in the long run. Especially disruptive changes, which demand a complete change of the value chain and lead to large shifts in industry structure and competition, are to be anticipated lest the business is surpassed by competitors [26]. At the same time, timely recognition of a disruptive change in industry drivers can provide opportunities for a firm to overthrow current industry leaders, and build a sustaining competitive advantage. Due to the complexity of the environment's dynamics, managers must revert to 'mental models', which are simplified representations and heuristics that describe their business environment, and are based on managers' past experiences. Mental models are therefore extrapolative in nature, hence frequently rendering business managers inapt at reacting to disruptive changes and discontinuities. Literature on strategy therefore not only aims to accurately describe the environment, but also to develop the mental models of managers for the better [108]. In the following sections, the elements that make up Porter's model are treated separately for the QC industry and specifically for the superconducting qubit platform, with other qubit technologies treated as substitutes.

A.1 Buyers

An overview should be established of current buyers of quantum computing technologies. For these buyers, the value chain of the product offering should be analysed, in order to assess unique selling points (USPs). Buyer preferences also give insight into product strategy: What do buyers look for in the product, and in the company selling it? Possible answers are trust (brand identification, product service), low costs (cost leadership) or product ecosystem (complementaries, product service, network externalities), all of which can be used by the firm to gain an advantage over its competitors. Current buyers are mostly research institutes and other component firms that are looking to develop their respective products.

However, product market is not static, and buyer segments can even be created. Hence, potential future buyers should also be identified. The discovery of a new kind of buyer can also be a disruptive innovation, and first-mover advantages can allow the discovering firm to become a leader in new segments. In the QC market, future customer segments can be classified by their technology readiness trigger: the point at which they will start to consider adoption of quantum technologies to advance their own position or products. These triggers are based on the (complexity of the) intended application and a buyer's perceived value in this application. Some buyers will simply be monitoring developments, ready to implement it in their business once the technology becomes available, while others are actively seeking to pursue its development itself. The attitude of future buyers will depend on how much added value the application might potentially bring, the extend to which early development will provide the buyer competitive advantages and the advantages that can be achieved by developing in-house, as opposed to investing in the QC market. Furthermore, as QC is still in its infancy, other useful applications might still be discovered. This provides two stances, where new buyer markets can become available with the discovery of new applications by quantum algorithm developers. This will lead to a technology-push in case the current QC market develops the application, and a market-pull when interested firms develop the application in-house.

By forecasting the timing of these additional future buyers, a QC firm at the lower end of the stack can profit by strategically timing new product development and releases, as well as from targeted marketing and timing production efforts. Furthermore, by heightening switching costs, such as arise due to platform incompatibility, costs of (re-)educating personnel, costs of ancillary equipment for a new product, etc., buyer dependence can be strengthened further. However, it should be noted that within a qubit platform, switching costs are likely to be less, such as is the case by switching QPU suppliers within a superconducting qubit platform.

A.2 Suppliers

A firm at the lower end of the stack will most likely have large cross-industry suppliers for its components. For example, a superconducting quantum processor manufacturer is dependent on material suppliers, for silicon wafers and other materials that are used in the manufacturing process, as well as suppliers of the machines, and potentially facilities, that are used to build the quantum chips. Here, risk of those actors vertically integrating into the focal firm's space is small. However, firms that rent time in fabrication facilities have a more favourable bargaining position if they are a large customer, if switching costs are minimised or if the firm has the means for backwards integration.

A.3 Substitutes

This is especially applicable in the QC industry, between different qubit platforms. The two largest platforms in the industry are based on superconducting and trapped ion technologies, but recently there has been an emergence of other platforms as well, such as qubits based on spins in silicon [24], photons [21] and more [104]. Platform adoption depends mostly on the current performance and potential of the underlying technology. Hence, differentiation strategy is key. On top of that, positive network externalities can be seen, for example, when cloud-service providers adopt a certain platform and provide access to end-users.

The lack of a dominant design and little standardisation make that platforms are unlikely to be compatible easily, which leads to high switching costs. Furthermore, their high specificity means that employees will need retraining if the switch is made to a different platform. On top of that, expensive ancillary equipment is often necessary when switching, e.g. from trapped ion technologies to superconducting qubits.

A.4 Competitors

Since the industry is more specifically selected as just superconducting qubit manufacturers, other qubit platforms are substitutes, rather than direct competitors. However, even within this single technology platform we can identify multiple competing actors. This entails firms that are creating components fulfilling similar roles. Although some firms will seem like less direct competitors, mostly if they are supplying full-stack versus just components, these can be treated as a direct competitor based on their influence on sales of the focal firm's ecosystem.

A.5 Potential Entrants

For a firm operating in superconducting qubit manufacturing, several potential entrants can be identified. Analogous to the classical computers, where vertical integration is ubiquitous, any other player in the stack could be a potential entrant, based on their wishes to integrate. Furthermore, as a dominant design emerges for the quantum computer, players working on other platforms, which currently are substitutes, may change technology. Lastly, chip manufacturers in the semiconductor industry, like TSMC or Intel, may enter into the QC market in order to expand their portfolio. In order to raise entry barriers, firms should focus on leveraging their intellectual property, and to build expertise.

Appendix B

Quantum Computing Companies

B.1 Qubit Providers

Table B.1 shows a list of various companies that are developing qubit technologies, and the technological platform that they are pursuing.

Table B.1: Various qubit providers and the respective technological platforms that their qubits are based upon.

Firm	Platform
ALIBABA	Superconducting
Alice & Bob	Superconducting
Anyon Systems	Superconducting
AQT	Trapped ion
Atlantic Quantum	Superconducting
Atom Computing	Neutral atoms
BAIDU	Superconducting
Bleximo	Superconducting
C12 Quantum Electronics	Superconducting
Coldquanta	Trapped ion
D-Wave	Annealing
Diraq	Silicon spin
Eeroq	Electron-Helium
Google	Superconducting
IBM	Superconducting
Infineon	Silicon spin
Intel	Silicon spin
Ionq	Trapped ion
IQM	Superconducting
Nord Quantique	Superconducting
Orca computing	Photonic
Origin Quantum	Superconducting
Oxford ionics	Trapped ion
Oxford quantum circuits	Superconducting
pasqal	Neutral atoms
photonic inc	Silicon spin
planqc	Neutral atoms
psiquantum	Photonic
qilimanjaro	Superconducting
quandela	Photonic
quantinuum	Trapped ion
quantum brilliance	Diamond
Quantum circuits inc	Superconducting
quantum motion	Silicon spin
quantum source	Photonic
Quantware	Superconducting
qudoor	Trapped ion
QuEra	Neutral atoms
rigetti	Superconducting
seeqc	Superconducting
silicon quantum computing	Silicon spin
Turinq	Photonic
universal quantum	Trapped ion
xanadu	Photonic

B.2 Quantum Software Providers

Table B.2 shows a list of various companies that are developing software for quantum computers, both for applications and on the firmware side.

Table B.2: Various quantum software providers and their respective focal applications.

Firm	**Platform**
Party	Applications
IBM Compiler, ML, Chemistry, Optimisation, Finance	
1qbit	Finance, ML, Chemistry
Algorithmiq	Chemistry
Quantinuum	Compiler, ML, Chemistry, Optimisation, Finance
Beit	Optimisation
Classiq	High-level quantum programming, Chemistry, ML
Entropica labs	Optimisation, Finance
Exaq.ai	ML
HQS	simulations Chemistry
Jij	Optimisation
JoS	quantum Finance, ML, Chemistry
Phasecraft	Chemistry
QunaSys	Chemistry
Semicyber	
Zapata	Optimisation, ML, Chemistry
Strangeworks	Application platform
Q-CTRL	Quantum Firmware

Appendix C

Company Descriptions

Here, several QC firms are covered in depth, in order to illustrate some of the strategies that they apply, and their incentives to do so.

COMPANY PROFILE: IonQ

IonQ, founded in 2015, is a full-stack quantum computer developer, based on trapped ion technology. They offer complete quantum computing solutions, which are available as hardware, or on a service-basis through cloud services such as AWS Amazon Bracket, Microsoft Azure Cloud or Google's Cloud Marketplace, and contain up to 32 qubits.

Upon launch, IonQ raised $2M in their seed round, with an additional $20M of investments raised in the first three years of its existence[44]. IonQ is one of the first quantum computing startups to go public, together with D-Wave and Rigetti. Through a merger with a special purpose acquisition company (SPAC), they were able to get listed on the New-York Stock Exchange (NYSE) on October 1, 2021[45].

IonQ talks about their corporate strategy in their 2021 annual report[46], where they mention the following five key points for their strategy:

- Leveraging their trapped ion technologies
- Offering Quantum Computing as a Service (QCaaS)
- Selling quantum computer hardware
- Enhancing proprietary position
- Further developing their partner ecosystem

We could characterise the first point as leveraging their technological competitive advantage, the second and third as product visions, and the last two as competitive strategies. Further down in the document, they mention the following goals for entering in strategic partnerships:

- Obtain expertise in relevant markets

- Obtain sales and marketing services or support
- Obtain equipment and facilities
- Develop relationships with potential future customers
- Generate revenue

IonQ has displayed a multitude of competitive and cooperative moves. In order to expand their ecosystem, they partnered with various end-users, like Hyundai, Airbus and the US Air Force Research Lab to co-develop use-cases[47] and engaged in cooperative research activities, like in the paper published by researchers from IonQ, 1QBit and Dow [109], one from IonQ, QC Ware and Goldman Sachs [110], or from IonQ together with FCAT [111]. In their 2021 annual report, they mention the use of patent licensing from Duke University and the University of Maryland. In June, 2021, a strategic partnership was established with Japanese conglomerate SoftBank Group, to develop IonQ's Asian market presence and incorporate the technology into some of SoftBank's portfolio companies[48]. On January 10, 2023, they announced the acquisition of Entangled Networks Ltd., a company looking to provide the coupling between quantum computers[49]. Like stated above, IonQ's technology is available through cloud access, through it's own service but also by cloud service providers such as Microsoft Azure Cloud, Amazon Bracket and Google's Cloud Marketplace. For cloud access, they provide their own API, and are supported by major SDKs like Qiskit, cirq, Q#, et cetera. Lastly, IonQ is a founding member of the Quantum Economic Development Consortium (QED-C).

COMPANY PROFILE: Quantum Machines

QUANTUM MACHINES

Quantum Machines is an Israeli startup, founded in 2018, that develops quantum operations and control systems. This includes both hardware and software in what they call their 'Quantum orchestration platform'. Their product line includes quantum control systems, hardware, such as OPX+, OCTAVE, QDAC and QBOX, and their quantum programming language QUA that allows programming of their control systems. Furthermore, since their acquisition of QDevil, they also include cryogenic hardware in their offering, such as filters and sample holders.

Quantum Machines has thus far partaken in three funnding rounds. In November 2018, they raised $5.5M from the two VC firms TLV partners and Battery Ventures in a seed financing round[50]. In their series A round in March, 2020, they raised an additional $17.5M to accellerate the adoption of its orchestration platform[51]. Finally, they raised $50M in series B in September, 2021[52], to which an additional $20M was added in late 2022[53]. This places their total raised capital at $93M. It should be noted, however, that an additional, but undisclosed, amount was invested by Qualcomm and, thus, their real capital might be higher[54].

Competitive and cooperative moves:

1. Q-CTRL partnership for compatibility

2. Q-Devil acquisition
3. Toyota Tsusho
4. Nvidia
5. ARTEMIS european bidding consortium (with Alice&Bob)
6. QED-C, IBM Q network
7. ’Quantum orchestration platform’
8. Active engineering support & social media presence

Through these competitive moves, Quantum Machines displays platform leadership, with its quantum orchestration platform, engineering support, social media presence, vertical integration and compatibility partnerships.

COMPANY PROFILE: IBM Quantum

International Business Machines (IBM) is a computer technology company with an exceptionally long track-record, with its origins tracing back to the 1880s[55]. It played a crucial role in the development of the classical computer, from its introduction of commercial mainframe computers to the IBM PC [90]. IBM is currently also pioneering the development of quantum computing, having the most-qubit quantum processing unit. They offer access to their quantum computers with their cloud services, and work together with many different potential end-users to develop use-cases for quantum computing technologies.

IBM has been involved in the development of quantum computing since the start. In 2016, they launched the first accessible quantum computer with their cloud service, the IBM quantum experience[56]. This quantum computer contained 5 qubits, that were based on the superconducting platform. IBM has since continued this development, launching their 433-qubit chip called ’Osprey’, which is still based on superconducting qubits. According to their roadmap, depicted in figure C.1, they are planning to launch a 1121-qubit chip this year[57].

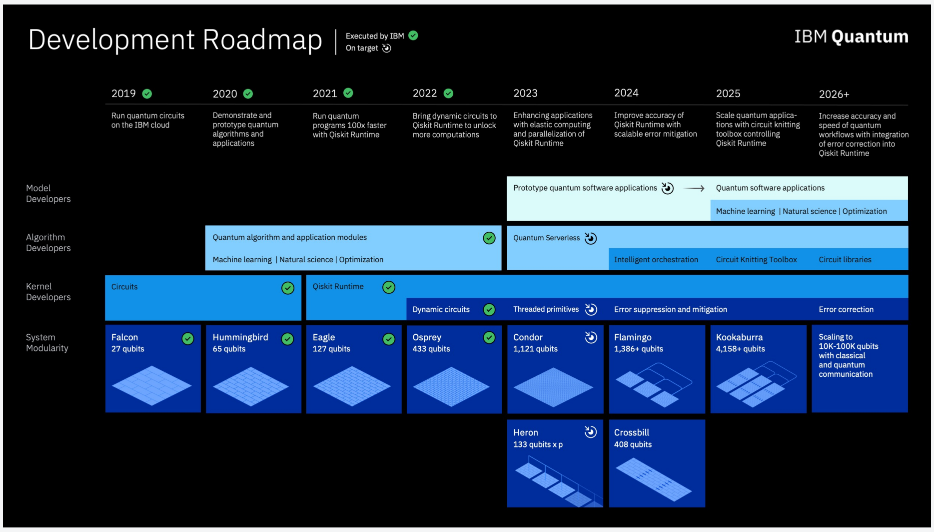

Figure C.1: IBM's quantum roadmap.

Strategic moves by IBM, mostly included by the IBM Quantum Network, which is concealed.

Notes

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