# Paving the Way towards Mass Diffusion of Quantum Processors

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*"Do you guys just put the word 'Quantum' in front of everything?"*
- Ant-man, 2018 [1]

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# Summary

The promise of quantum computers seems never-ending: improving the healthcare and life sciences industries by accelerating drug discovery and molecular modeling, revolutionizing the fight against climate change, uprooting the finance sector by efficiently performing Monte Carlo risk analysis, and many more to come.

However, at present, the development of quantum computers is just in the embryonic phase. Most quantum processors currently produced do not possess computing powers beyond what is classically possible. Regardless, we are now on the brink of the next phase of possibilities: Noisy Intermediate-Scale Quantum (NISQ) computing. This phase will allow for calculations that are impossible to achieve in a reasonable time with classical computers, thus entering a never-before-accessed realm of possibilities.

Nevertheless, any calculation made on quantum processors produced in the near future, NISQ or not, will be contaminated by noise, and thus only the surface of potential algorithms is scratched. Only once the majority of this noise can be mitigated and the scale of logical qubits rises substantially will we be able to enter the next revolutionary Universal Fault-Tolerant Quantum Computing era, in which the highly anticipated applications of quantum simulation and chemistry, breaking cryptography and quantum optimization will become reality.

This study provides the basis for an extended version of the existing Technological Innovation System framework from a company perspective. This framework identifies the bottlenecks that will have to be overcome before quantum processors will live up to their promise and can theoretically start mass diffusing in society by structuring them into seven distinct building blocks.

The process of creating the expanded version of the Technological Innovation System framework can be divided into three distinct phases. The preliminary phase, whose main goal is to build a solid foundation and scope, upon which the other phases can rest. The iterative phase, in which several potential versions of each building block are explored, based on various inputs to ensure the building blocks become mutually exclusive and collectively exhaustive insofar as this is possible. And lastly, the suitably called final phase, which merges the preliminary models into one final version. The decision for the final cut of the Key Performance Indicators is based on the successful compliance of a Key Performance Indicator with five consecutive demands. Each definitive Key Performance Indicator can be considered a bottleneck (red), a small impedance (yellow), or well-developed enough (green) for mass diffusion to reasonably occur. The final division of the building blocks into categories and Key Performance Indicators for the quantum processor market are visualized in figure 1

The first two building blocks have been analyzed in more detail up until the final phase to determine where the current bottlenecks of quantum processors lie. The first building block of quality is severely impeded on three out of five of its crucial Key Performance Indicators: the gate fidelity, coherence time, and quantum volume of quantum processing units are all considered to be below par.

The second building block is deemed more promising, as only the variable cost is currently rated red. This Key Performance Indicator is expected to increase quickly once the quantity produced increases, which would effectively upgrade the rating of the entire building block to yellow.

Suggestions for the categories and Key Performance Indicators determining the performance of the other five building blocks are provided, but future research will have to establish their thresholds and present values to ultimately determine the biggest bottlenecks across all seven building blocks.

The extended version of the Technological Innovation System framework, as presented in this study, is expected to translate well to other emerging industries. Four out of seven building blocks, the *product profitability*, the *production system*, the *network formation and coordination*, and lastly, the *innovation-specific institutions*, translate directly to diverse industries as they are considered to be product-agnostic. The building block of *customers* might have to be tweaked slightly, whereas the building blocks of *product performance and quality* and the *complementary products and services* will both have to be completely reassessed, even for adjacent products.

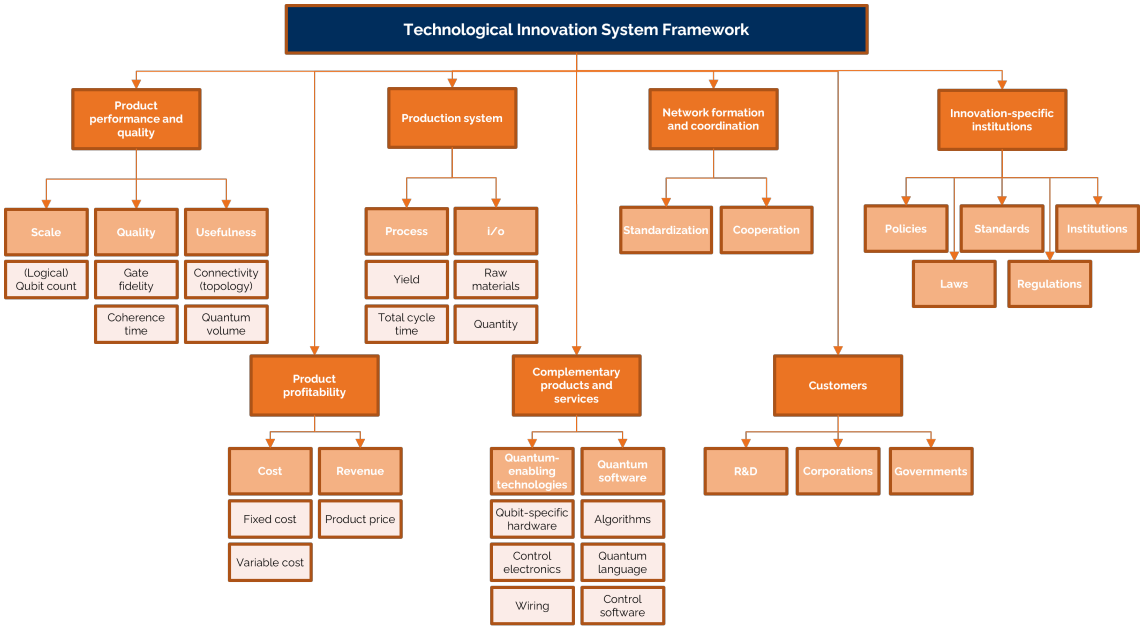


*Figure 1: The final version of the Technological Innovation System model for quantum processors from a company perspective, including all seven building blocks, 19 categories, and 18 Key Performance Indicators.*

Overall, this study identifies and structures the clouds of uncertainty that currently shroud the development path of quantum processors. Only once a significant amount of this uncertainty on all seven aspects of the quantum processor market is resolved can these clouds give way to reveal which way should be paved to achieve mass diffusion of the quantum processor.

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# Acronyms

**AI** Artificial Intelligence.

**CLOPS** Circuit Layer Operations per Second.

**FLOPS** Floating-Point Operations per Second.

**FTQC** Fault-Tolerant Quantum Computing.

**HPC** High-Performance Computing.

**i/o** input/output.

**IP** Intellectual Property.

**IQP** Instantaneous Quantum Polynomial.

**KPI** Key Performance Indicator.

**NISQ** Noisy Intermediate-Scale Quantum.

**NV** Nitrogen-Vacancy.

**OQS** Orange Quantum Systems.

**QAOA** Quantum Approximate Optimization Algorithm.

**QPU** Quantum Processing Unit.

**QS** Quantum Systems.

**QV** Quantum Volume.

**R&D** Research & Development.

**RSA** Rivest, Shamit and Adleman.

**SCQT** Superconducting Qubit Tools.

**SME** Small and Medium-sized Enterprise.

**SPAC** Special-Purpose Acquisition Company.

**SPAM** State Preparation and Measurement.

**TIS** Technological Innovation System.

**TRL** Technology Readiness Level.

**TWPA** Travelling Wave Parametric Amplifier.

**UFTQC** Universal Fault-Tolerant Quantum Computing.

**UV** Ultraviolet.

**VC** Venture Capital.

# Chapter 1.
# Introduction

## 1.1 Quantum Computing Background

Significantly improving the current healthcare system by accelerating the speed at which drugs are designed, modeling molecules and enzymes and the initiation of personalized medicine, revolutionizing the fight against climate change, drastically altering the finance sector by optimizing portfolios and efficiently performing Monte-Carlo risk analyses and restructuring satellite-based communication [16].

These visionary innovations may seem unrelated, but they can be achieved by a single underlying technology: quantum computing. While these applications are not possible yet, the first impactful changes to industries such as the pharmaceutical, financial, chemical, and sustainable energy industries are expected within five years [12].

Despite its novelty sound, the fundamental idea behind quantum computing was born over forty years ago, when the famous physicist Richard Feynman first mentioned it in 1981 [17, 18]. Although Feynman's concept was solely theoretical at first, the hype surrounding the potential of quantum computers became substantial in 1994, when Peter Shor introduced the now famous *'Shor's algorithm'*, which can find the prime factors of any integer number astronomically faster than any algorithm run classically [19].

As will be explained in section 1.1.5, this proposed a major threat to practically all applications of encryption today, immediately putting a spotlight on the strategic value of quantum computing. This made the industry gain the necessary momentum to kickstart its development and reach the remarkable amount of hype and investment seen today.

This chapter provides a short overview of the basics of quantum computing. First, in section 1.1.1, the distinction between the three types of quantum technologies is explained. Thereafter, the main principles behind quantum computing are explained in section 1.1.2. In section 1.1.3, the difference between classical computing and quantum computing is highlighted. Section 1.1.4 underlines when useful applications of quantum computers are expected and highlights the difference between the Noisy Intermediate-Scale Quantum (NISQ) computing era and the universal Fault-Tolerant Quantum Computing (FTQC) era. Consequently, the three main categories of universal fault-tolerant quantum computing applications are described in section 1.1.5. The following sections delineate the scope of this thesis 1.2, its relevance 1.3, and lastly, the research questions 1.4.

### 1.1.1 Quantum technologies

Quantum technology is a very broad term used to describe any technology using quantum principles. The overall quantum technology sector can be divided into three distinct parts: quantum communication, quantum sensing, and quantum computing. This thesis will solely focus on the third sector: quantum computing.

Within quantum computing, a division into five different specializations can be made: component manufacturers, hardware manufacturers, software developers, services, and applica-

tion developers. Orange Quantum Systems belongs to the component manufacturers division, and its customers belong to the hardware manufacturers division. The divisions of the quantum technology sector are visualized in figure 1.1.

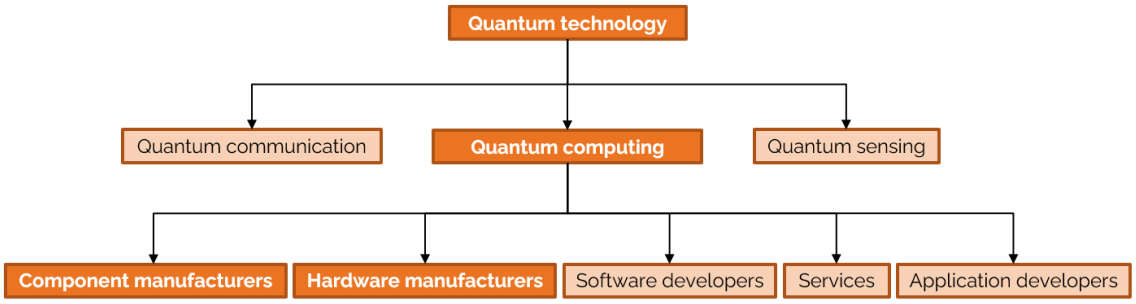


*Figure 1.1: The quantum technology sector can be subdivided into three main divisions, of which the quantum computing division, in turn, has its own five subdivisions. Quantum processors are produced by the hardware manufacturers. Orange Quantum Systems falls in the subdivision of component manufacturers.*

### 1.1.2 Quantum computing principles

Two essential qualities separate a quantum computer from a classical one: *superposition* and *entanglement*. These two unique characteristics are elaborated upon further below.

Where classical computers operate using bits, representing either a 0 or 1, quantum computers operate using quantum bits or qubits for short, denoted as $|0\rangle$ and $|1\rangle$. Qubits can be in the state $|0\rangle$ or $|1\rangle$ or a *superposition* of the two, meaning there is a certain probability of measuring the qubit as either $|0\rangle$ or $|1\rangle$. However, following the quantum principles, a measurement of the qubit destroys the superposition. In other words, all subsequent measurements give the same result as the initially obtained result [2].

The principle of superposition and the collapse of the state following a measurement can be explained more clearly using the analogy of color [2]. Say the $|0\rangle$ state is represented by the color yellow and the $|1\rangle$ state is represented by the color red. A superposition of the two states $|0\rangle$ and $|1\rangle$ would then be represented by a color somewhere on the gradient shown in figure 1.2.




*Figure 1.2: Visual representation of the $|0\rangle$ state by the color yellow and the $|1\rangle$ by the color red. Any superposition of the two states $|0\rangle$ and $|1\rangle$ is represented by a shade of orange somewhere on the gradient.*

A fifty-fifty superposition of the two states would result in the color orange. However, various shades of orange are possible, representing various mixtures between 0% and 100% of the yellow and red states.

But, due to the inability to measure quantum states, a measurement of any superposition of colors will always result in either of its primary colors. The initial shade of Orange can be determined by repeating the measurement. If the initial shade consisted of 20% yellow and 80% red, the frequency with which these colors are measured will accord those percentages if enough measurements are taken[2].

Instead of a color gradient, a Bloch sphere is generally used to visualize superposition, probabilities, and the effects of measurement. The north and south poles of the Bloch sphere represent the $|0\rangle$ and $|1\rangle$ states, respectively. A fifty-fifty superposition of the $|0\rangle$ and $|1\rangle$ states is then represented on the equator of the sphere, as shown in figure 1.3. Any operation performed on a qubit can be visualized as some rotation around either the x-, y-, or z-axis of the Bloch sphere [2].

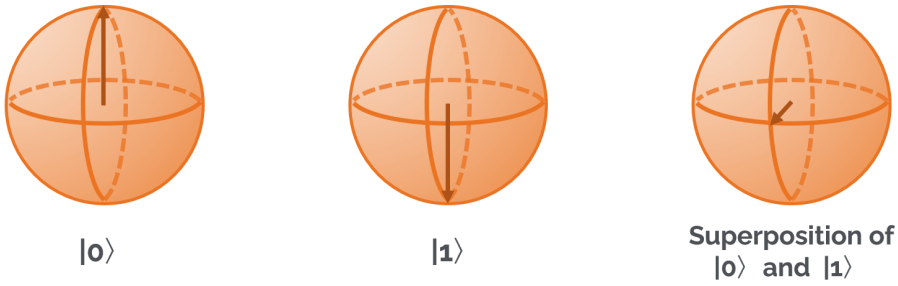


*Figure 1.3: The Bloch sphere representation of the $|0\rangle$ and $|1\rangle$ states respectively, and a fifty-fifty superposition of these two states. Based on [2]*

The quantum property of a state collapsing as soon as a measurement is applied seems to make the process too laborious to create a competent computer. However, this cumbersome attribute is negated by a second unique quantum characteristic: *entanglement*. If a measurement is performed on a qubit, which is entangled with a second qubit, the state of that second qubit is known instantaneously [2].

If the underlying principles are known, why is quantum computing so difficult? The main problem in developing a quantum computer lies in the collapse of qubits to a classical state when measured. A slight disturbance of any kind can cause a qubit to collapse. Therefore, a reliable process can only be created by keeping the system perfectly isolated from the outside world while simultaneously keeping the ability to control the system to perform calculations [20].

### 1.1.3 Quantum computers

To explain the astronomically different computing power quantum computers have compared to their classical counterparts, the difference created with just 11 qubits is visualized in figure 1.4. A classical computer of $n$ bits can represent $n$ states. The states a quantum computer with $n$ bits can represent scale with a factor $2^n$ [2].

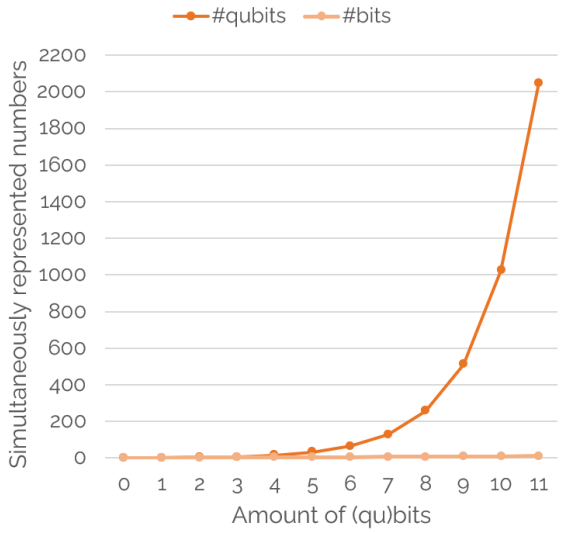


*Figure 1.4: The numbers which can be represented with up to eleven bits and qubits. Based on [2]*

The scale difference this represents becomes more clear when increasing the amount of qubits even further. The memory capacity of supercomputers used today is maximized at 50 qubits. One step further, 51 qubits requires two supercomputers. An even more mind-boggling number is the fact that it would take just 300 qubits to simultaneously represent a number larger

than the amount of all atoms present in the universe [2].

Nevertheless, one measurement can still only represent one result. Therefore, algorithms that can both take advantage of the unique combination of superposition and entanglement and ensure legitimate results will need to be developed. In reality, the accuracy of measurements is far from 100%. Thus, algorithms need multiple runs and will provide a range of answers instead of a single answer [2].

This variety is one of the main reasons why it is unlikely that quantum computers will fully replace conventional computers for ordinary tasks such as addition or running web servers. Instead, quantum computers will be used for a variety of problems that regular computers cannot solve, mainly due to time restrictions. These applications are further elaborated upon in section 1.1.5 [2].

### 1.1.4 Useful quantum computing

As mentioned in section 1.1.2, quantum processing units are highly sensitive to noise. Noise sensitivity can be overcome by better isolation, but better isolation can compromise the amount of control one has. The solution to this apparent deadlock of control and isolation can be found in a process called quantum error correction. Error correction can only be achieved by using many additional physical qubits, which means a reliable quantum correction is still a couple of years away. However, before this error correction era, useful calculations could already be achieved in an intermediate phase called the Noisy Intermediate-Scale Quantum (NISQ) era [20].

The NISQ era is defined as using 50 to several hundreds of qubits, which are not entirely error corrected but do operate above the error correction threshold, hence 'noisy'. The lower boundary is set at 50 qubits because this is the maximum that can be simulated by brute force using classical supercomputers [2, 20]. The error correction threshold is generally assumed to be around $10^{-2}$ [21]. The NISQ era is visualized in figure 1.5. Whilst the 50-qubit threshold has been broken repeatedly, and the error correction threshold has been broken by Google on a large hero device, the boundaries have not been consistently outperformed at the same time, making it hard to say with certainty that the NISQ era has officially been heralded [22, 21].

First, Google laid claim to *quantum supremacy* in 2019 by solving a problem that no classical computer can solve in any feasible amount of time with their Sycamore processor.

However, there is an important distinction between *quantum supremacy* and *quantum advantage*, which even the literature sometimes confuses. *Quantum supremacy* indicates any calculation which cannot be solved in a reasonable amount of time on a classical computer. This calculation does not have to be useful in order to be quantum supreme [20, 22]. *Quantum advantage*, on the other hand, requires a calculation to both be undoable in reasonable time on a classical computer (thus automatically also being quantum supreme) *and* to be useful at the same time [23].

The subsequent and last distinct period of Universal Fault-Tolerant Quantum Computing (UFTQC) era requires several thousands of qubits, which are significantly better error corrected. The order of magnitude at which this era starts remains a fuzzy boundary somewhere around $10^5$ - $10^6$ physical qubits, as visualized in figure 1.5. The main reason for these orders of magnitude in difference and the uncertainty it brings with it can be explained through the concept of physical versus logical qubits [2, 24].

To be able to perform error correction, which is needed in the UFTQC era, several tens of physical qubits are combined together to form one logical, error-corrected qubit. The underlying principle here is that a currently unknown number of qubits can work together to correct each other's mistakes, to act as one unified logical qubit, which is significantly less prone to errors. The large amount of uncertainty is introduced because the ratio of physical **:** logical qubits needed to perform error correction on a large scale is currently unknown, resulting in the fuzzy boundaries of the UFTQC era [2, 24].

The applications mentioned in section 1.1.5 will only become feasible once this era is reached, which is expected to happen around 2030 at the earliest [25].

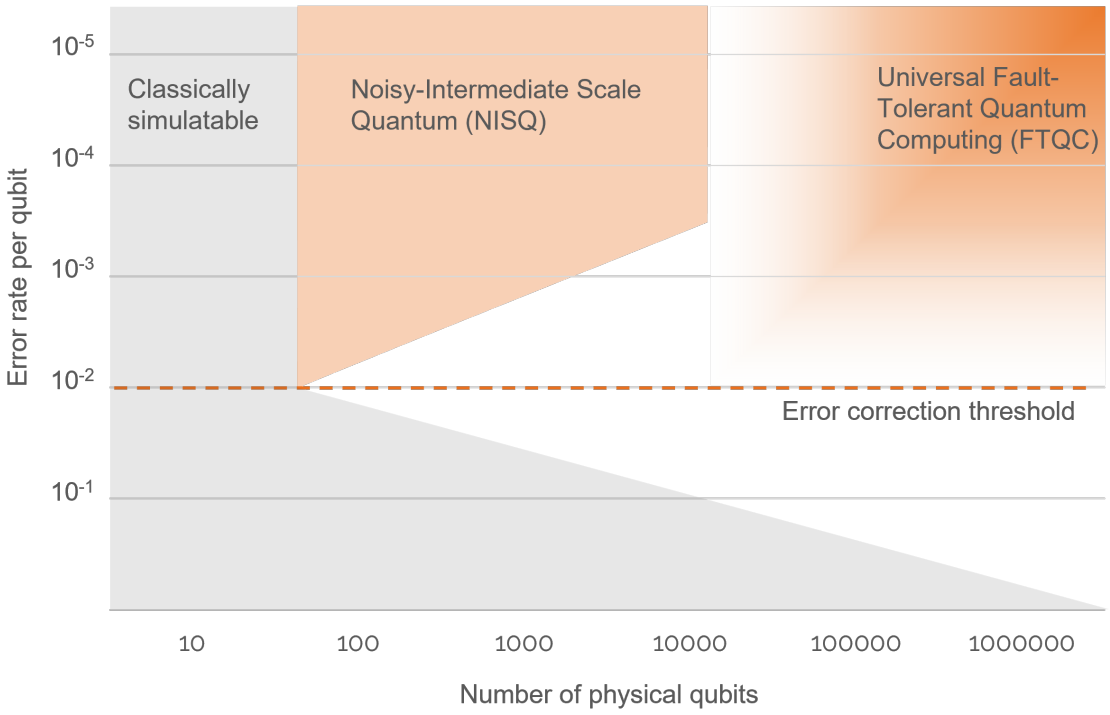


*Figure 1.5: The error rate per qubit and the amount of physical qubits required for the NISQ era and the Universal Fault-tolerant era. The NISQ era starts >50 physical qubits and above the error correction threshold. The exact boundaries of the UFTQC era remain vague but are estimated around $10^5$ - $10^7$ physical qubits and somewhere above the error correction threshold. Based on figure provided by Orange Quantum Systems.*

#### Industry prospects

The industry is making impressive promises for the future. IBM announced to try and solve the scaling problem by developing a modular system to bypass physical scaling limits, as well as the first chip to surpass the 1.000 qubit threshold this year[1]. Furthermore, their latest announcement slightly postponed their 100.000 physical qubit goal towards 2033[2].

Google's roadmap claims to have a fully functional error-corrected quantum computer with 100 logical qubits, or 100.000 physical qubits, by 2029[3]. Psiquantum[4], a photonics start-up, projects to release a million-qubit quantum computer as soon as 2025. This potentially impressive leapfrog over Google and IBM could be possible because they use a different technology to produce their qubits, allowing them to scale up spectacularly faster [26].

### 1.1.5 Applications

The expected applications of quantum computing once the universal fault-tolerant quantum computing era has been reached can be subdivided into three categories [27]:

- **Quantum simulation**. Simulating molecules is potentially one of the most exciting applications of quantum computing due to the incredible breakthroughs it might provide in chemistry, pharmaceutics, and material science. Quantum simulation will provide, amongst others: a re-design of chemical processes, leading to significantly more efficient factories, estimations of the effects of new medicine, a solution to the carbon emission problem created by artificial fertilizers, or the discovery of new semi- or superconducting materials [12, 28].

[1] https://research.ibm.com/blog/ibm-quantum-roadmap-2025
[2] https://research.ibm.com/blog/100k-qubit-supercomputer
[3] https://blog.google/technology/ai/unveiling-our-new-quantum-ai-campus/
[4] https://psiquantum.com/

- **Breaking cryptography**. One of the most concrete useful applications found for quantum computing so far is Shor's algorithm, which was already published in 1994 [29]. Shor's algorithm is a relatively efficient way of cracking the Rivest, Shamit and Adleman (RSA) encryption, one of the most widely used forms of encryption worldwide [29].
- **Optimization**. Optimization problems are the broadest application category but also the category with the most unknowns. It will most likely become relevant for a myriad of disciplines, such as operations research, finance, manufacturing, logistics, weather forecasting, and potentially many more. Despite this expected variety, no quantum optimization algorithm has yet been proven. However, 'quantum speedups', meaning algorithms requiring fewer elementary steps than their classical counterparts, such as the Grover algorithm, have been found [28].

## 1.2 Scope

This thesis will not focus on the entire spectrum of quantum computing but instead operate within a few boundaries, excluding some 'anomalies' of the industry. Furthermore, the focus is not on a quantum computer in its entirety but only on the Quantum Processing Unit (QPU). The choice for the QPU by itself is made because of its importance for the functioning of a quantum computer and because the computer as a whole contains too many separate parts, each with its own distinct innovation path, thus making it harder to distinguish a single route towards mass diffusion.

The wording *quantum processing unit* instead of *quantum computing chip* is chosen deliberately because the term QPU implies there is some sort of application in mind, whereas the quantum computing chip does not necessarily include this appliance.

Within quantum processing units, a lot of variety exists. For various reasons elaborated below, analog quantum processing units and photonic- and topological qubit-based processing units are excluded from the scope of this thesis if no further scientific breakthroughs in these fields occur.

### Analog vs digital quantum computers

There are two different types of quantum computers. There are *quantum annealers* or *analog quantum computers*. They make use of the principles of superposition and entanglement and therefore count as a quantum computer, but they represent a much more limited version, only capable of running optimization algorithms. Nevertheless, quantum annealers will provide a substantial improvement compared to classical computers when calculating optimization problems and will, therefore, still prove useful within their own niche. The most famous quantum annealers are those produced by D-Wave [5].

The second type of quantum computers is *universal quantum computers* or *digital gate-based quantum computers*. This type of computer is able to run not only optimization problems but the entire potential spectrum of quantum computing. Digital gate-based quantum computers actively manipulate the states of qubits and can be seen as similar to the existing general-purpose computers. To be considered a universal quantum computer, it should fulfill all five of the DiVincenzo criteria, as described in section 3.2.3. Currently, the most famous universal quantum computers are those manufactured by IBM, and Google [5].

Due to their more limited criteria, quantum annealers are not within the scope of this thesis. When a quantum computer, quantum processing unit, or quantum computing chip is mentioned in this thesis, it concerns a universal/digital gate-based quantum computer, quantum processing unit, or quantum computing chip.

### Qubit platforms

Interestingly, a dominant design for qubits has yet to exist. There are several technologies to create qubits, which can be grouped into seven categories:

- Superconducting qubits, based on the difference in Cooper pairs between two islands of a Josephson junction. Superconducting qubit technology is currently the most researched form of qubits, pursued by, amongst others, IBM, Google, and Rigetti [30].
- Spin qubits or quantum dots are based on the electron spin of a semiconducting nanoparticle [31].
- Defect-based qubits, where a spin defect in an atom represents the qubit. The most well-known defect-based qubit is the Nitrogen-Vacancy (NV) center in diamond [32]
- Trapped ions, where each trapped ion represents a qubit [33].
- Neutral atom-based qubits, where neutral atoms are manipulated by light, of which the most well-known form is a Rydberg atom [34, 35].
- Photonics-based qubits, which use photons as information carriers in a photonic waveguide. Photonic-based quantum computers do not yet fulfill all of the DiVincenzo criteria because two-qubit gates remain a critical challenge. Nevertheless, photonic qubits are ideal for quantum communication [36].
- Topological qubits based on Majorana fermions are the most recent potential qubit platform. This qubit type remains largely theoretical. Therefore, not all of the fundamental DiVincenzo criteria have been fulfilled [37].

The model described in this thesis is designed to predict mass diffusion in quantum processing units and is, therefore, not necessarily restricted to one or several of the aforementioned qubit platforms, although for some KPIs the desired values differ per qubit architecture. However, as further elaborated upon in section 3.2.3, the DiVincenzo criteria are a widely accepted prerequisite for the functioning of a quantum processing unit. Therefore, photonic-based qubits and topological qubits are currently deemed unfit for the model described here. However, a scientific breakthrough resulting in compliance with the DiVincenzo criteria for either of those qubit platforms will automatically lead to their inclusion in the proposed model.

## 1.3 Relevance

Successfully reaching the Universal Fault-Tolerant Quantum Computing era will unleash a revolution in an astonishing amount of industries. It will significantly improve the Research & Development (R&D) process of pharmaceuticals, radically change the finance world, and some say it may even (partially) solve climate change [26].

Be that as it may, universal fault-tolerant quantum computing is currently still some months, years, or potentially even decades away. No one really knows how long the developments needed to reach the UFTQC era will take, due to the vast amount of incomplete or missing variables regarding the functioning of such fault-tolerant quantum computers, as will be demonstrated in chapter 3. Only once the majority of these missing variables have been supplemented the orders of magnitude of uncertainty that currently cloud the development path can give way to reveal which way should be paved with certainty. Therefore, claiming that this thesis will pinpoint exactly how many months or years from now mass adoption of quantum processors will start is unrealistic, to say the least.

Instead, this thesis will use existing development models regarding the birth of new, radical, high-tech technologies to create an approximation of the expected path of development for quantum processing units. In doing so, the goal is to define the very building blocks essential to the success of this industry and use these building blocks to create a model with certain

thresholds that need to be reached before large-scale diffusion will be anywhere near possible.

## 1.4 Research Question

The main objective of this study is twofold: first, to find a suitable framework for the forecasting of mass diffusion in nascent technologies and to apply it specifically to the emerging quantum industry, and second, to expand upon this framework in a manner that can be generalizable and applied to diverse industries. The following research question can frame the overarching objective of this thesis:

- *What are the bottlenecks before mass diffusion can reasonably occur in the quantum processing unit market, and what insights can be derived from this analysis that are applicable across diverse industries?*

This main question is broken down into a number of subquestions to facilitate a more comprehensive understanding and contextualize the answer. First of all, a more thorough understanding of what a quantum processing unit is, what its applications are, and what the market currently looks like are necessary as a basis for answering the main questions. Thus, the following subquestions are formulated:

- *What is a quantum processing unit?*
- *What are the applications of a quantum processor?*
- *What are the current trends seen in the overall quantum computing market?*

In the second place, an existing model explaining when mass diffusion can reasonably occur is required. This model must be applicable to nascent markets such as the quantum market. Furthermore, the model must be able to provide guidance and clarity, preferably in the form of thresholds that can be translated to the quantum industry. To this end, the following questions are devised:

- *What are existing models to predict the development of nascent markets, and which is best suitable for the quantum industry?*
- *Which building blocks and accompanying key performance indicators can be identified as indispensable for the quantum processor market?*
- *What are the specific thresholds within these building blocks and key performance indicators that need to be reached in order for them to be considered sufficiently developed for mass diffusion to become feasible?*

Lastly, after the selected forecasting model has been applied to the quantum industry, this study will explore whether the lessons learned from this specific application are more broadly applicable to other industries as well. Therefore, the last subquestion is posed as follows:

- *To what extent does the expansion of the TIS framework contribute to its prospective application in other industries?*

# Chapter 2.
# Methodology

Numerous scholars have attempted to construct forecasts of nascent technologies in various forms. However, the trustworthiness of such forecasts remains disputed, as various unforeseen technical, economic, and political barriers can significantly delay or even prohibit mass diffusion, thus rendering the forecast nonsensical. Nevertheless, under the assumption that such unforeseen circumstances are relatively rare and given the vast economic incentives to predict when a product becomes widely adopted, even an attempt at forecasting remains extremely valuable to companies and is, therefore, continuously improved upon by scholars.

Four overarching theories attempting to predict the trajectories of products in the very early stages of their life cycles are explored, and a historical analysis of the adjacent semiconductor industry focused on Moore's law is provided to determine which method, or which methods combined, are most applicable to the complex case of the Quantum Computing industry. The theories which were explored but ultimately deemed unfit for this research specifically can be found in appendix C.

The four theories are the Hype cycle model as described in section C.1, the concept of Technology Readiness Levels and other forms of readiness levels as described in section C.2, (pre-)diffusion patterns in section C.3, and lastly the Technology Innovation Systems framework in section 2.2. A historical analysis with a focus on Moore's Law is also provided in section 2.1. To conclude, in section 2.3, a choice is made for the method that will be used for further research in this paper.

Furthermore, the overall process used in this study is elaborated upon in section 2.4. This is done by first providing an overview of the general process, briefly clarifying the inputs used, and lastly further highlighting the final process.

## 2.1 Historical Analysis: what happened in the semiconductor industry?

Strictly taken, a historical analysis of events in similar industries is not a research model. Nevertheless, history can always provide valuable lessons and is known to generally repeat itself. Therefore, a short analysis of the developments in the adjacent semiconductor industry is provided to potentially learn a lesson for the upcoming quantum industry.

An incredibly detailed account of all inventions starting from the development of the thermionic valve in the early twentieth century to early semiconductors, transistors, and the start of the integrated circuit, such as described in [38] could be provided to search for parallels with the upcoming quantum computing industry.

However, such a detailed account is only deemed relevant when there is certainty the quantum industry will behave in a relatively similar manner to the semiconductor industry. Many believe similar behavior is reasonable. Nonetheless, scientific proof for this similarity is lacking and can most likely only be demonstrated in hindsight, not as a forethought. Therefore, an analysis of the rise of semiconducting devices in the form of Moore's law will suffice for this thesis. For future research, a more detailed dissertation might be deemed necessary.

### 2.1.1 Moore's Law

In 1965, only six years after the introduction of the first commercial transistor, Moore observed that the number of components roughly doubled every year. Extrapolating this trend, he predicted the availability of chips with 65.000 components by 1975 [39]. The central principle of Moore's law was based on economics. It was mainly intended to prove that integrated circuits were the only way toward significantly cheaper products. The initial curve of Moore's law was merely the substantiation of the remarkable decrease in minimum cost per component caused by manufacturing improvements he encountered in his work [3].

Ten years later, in 1975, Moore elaborated his theory further by breaking down the complexity curve into its three main contributing factors, which he established in hindsight [3]:

- the **die size contribution**: as the size of a single die grew, so did the amount of components that could fit on a single die;
- the **dimension reduction**: the shrinking of separate component dimensions, or put differently, the increase in component density;
- the **contribution of device and circuit cleverness**: squeezing out 'waste space' on a chip, the riddance of isolation structures, and several other improvements that do not fit the first two factors.

The first two factors multiplied represent a curve that shows the combined effect on complexity growth. The resulting Moore's law is shown in figure 2.1.

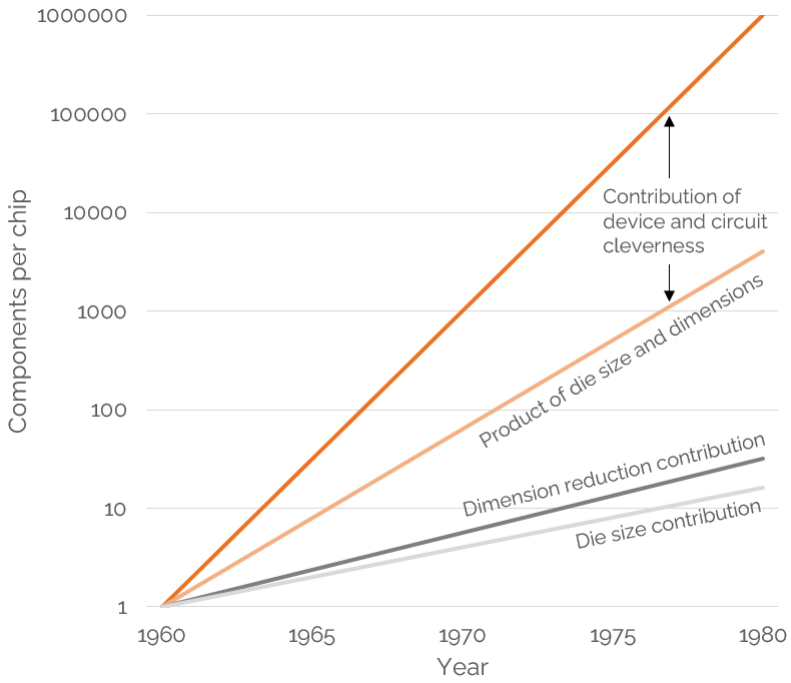


*Figure 2.1: Moore's law broken down into its three components: die size contribution, dimensions reduction contribution, and contribution of device and circuit cleverness. Based on [3]*

Moore altered one aspect of his theory in 1975. The contribution of device and circuit cleverness would soon run out, thus leading to a doubling every two years instead of every year, increasing the reliance of Moore's law on the die size and the minimization of the dimensions [3].

Do these three factors translate to quantum computing, and if they do, how? Researchers are currently figuring out whether scaling up the production of QPUs would be possible using semiconductor manufacturing principles, thus resulting in potentially similar scaling laws [40, 41]. Therefore, one could argue that metrics such as smaller die size, dimension reduction, and overall design cleverness all contribute to the improvement of quantum chips in a similar manner.

However, an important distinction adding extra layers of complexity, is that for QPUs, it is not just the volume of components that is important. One of the main bottlenecks is the fault tolerance of the chips. One can create a chip with a large number of components, but if the fault tolerance is low, it will still not be able to calculate anything useful. Vice versa, a chip with a smaller amount of qubits, which are all fault-tolerant, can easily outperform the former [2, 20].

Therefore, simply applying Moore's law one-on-one to the quantum computing realm is not considered to be possible. However, more general underlying principles can help determine if a different formulation of Moore's law specific to quantum can be created.

To do so, first, the reason *why* Moore's law continues to work needs to be determined. The most widely accepted reasoning for the continuous success of Moore's law is that it has become a self-fulfilling prophecy: companies have realized that if they are not able to 'stay on the curve', they will fall behind [39, 42].

A second interpretation of the longevity of Moore's law is the theory of technology push vs. market pull [39, 42]. According to Moore, the technology push drivers are the three initial contributions as seen in figure 2.1: the increasing chip area, decreasing feature size, and design cleverness.

The market pull drivers are the economic drivers. Despite the push and pull drivers being co-dependent, the economic drivers always dominate. Silicon devices have been manufactured at a virtually constant cost over time, assuring a constantly shrinking cost per transistor, creating guaranteed financial success by following Moore's law. However, the most compelling economic benefits of Moore's law do not rely on the increasing number of transistors but on the ability to enter new mass markets by producing moderately functional chips at incredibly low prices [39].

Mack claims, however, that even though the self-fulfilling prophecy and the technology push vs. market pull theories show *why* Moore's law holds true, it does not explain *how* [39, 43]. The *how* potentially finds its origin in learning curve theory.

Learning curve theory states that *" the learning curve expresses a constant percent improvement in some performance metric each time the cumulative number of trials, or practice attempts, is doubled [39]."*

Thus learning curve theory predicts that plotting this performance metric as a function of the cumulative output on a log-log scale will result in a straight line. For the semiconductor industry, the performance metrics are *memory size* and *transistor size*. The cumulative output of the industry can either be seen as the *cumulative area of silicon produced* or the *cumulative industry revenue* [39]. Since the cost per area of processed silicon has remained practically constant, the cumulative area of silicon and the cumulative industry revenue are proportional [39].

If applying the more neutral learning curve theory to quantum to determine whether a similar trend could emerge, a translation of the performance metric and the cumulative output metric used by learning curve theory is required. A more detailed translation is further elaborated upon in section 2.1.2.

### 2.1.2 Quantum Moore's Law

Several attempts have already been made by the industry to create the quantum equivalent of Moore's law:

- **IBM** has developed a new metric to convey the performance of the chip better. This quantum-specific metric is called the *Quantum Volume (QV)* and takes into account the fault tolerance, the amount of qubits, and the connectivity of the qubits, as further elaborated in section 3.2.4[1].

  The fault tolerance is expressed as the circuit depth. A larger circuit depth allows for a larger number of calculations. The circuit width expresses both the amount of and the

[1] https://research.ibm.com/blog/quantum-volume-256

connectivity between these qubits. A larger circuit width translates to higher memory. These two metrics together create the volumetric benchmark [44].

This metric could be used to create a new Moore's law, as done by IBM for their own quantum processing units, as seen in figure 2.2 [4, 45]. Time will have to tell whether the exponential growth of the quantum volume will remain sustainable in the future, thus resulting in Moore's law's quantum counterpart.

- A second attempt was made by Geordie Rose, the founder of **D-Wave systems**. Rose's law suggests that the quantum development relationship is much more simple and similar to the original Moore's law and should be coined as *"the amount of qubits should double every two years"* [45]. However, this law was devised specifically for D-wave's quantum annealing computer. Therefore, Rose's law is not deemed suitable for universal quantum computers and thus beyond the scope of this study [45]. Furthermore, no other mention of Rose's law can be found in the literature, and after its initial mention, no further records of Rose's law have been made by D-Wave either. Thus, due to its limited scope and the little (scientific) attention it reached, Rose's law is most likely incorrect.
- A third attempt at quantum's Moore's law is proposed by Hartmut Neven, the director of **Google's Quantum AI Lab**, suitably called Neven's Law. Neven's Law states that *"quantum computing is improving at a doubly exponential growth compared to conventional computing"*. This is the exponential of Moore's Law, or the power of the power of two $(2^2(4), 2^4(16), 2^8(256)$ [45]. However, complexity and noise might not be considered sufficiently in this prediction. This law was proposed with universal quantum computing in mind. However, it has not been mentioned further since its emergence in 2019 either [46]. More data points are needed to be able to confirm or deny Neven's law fully.

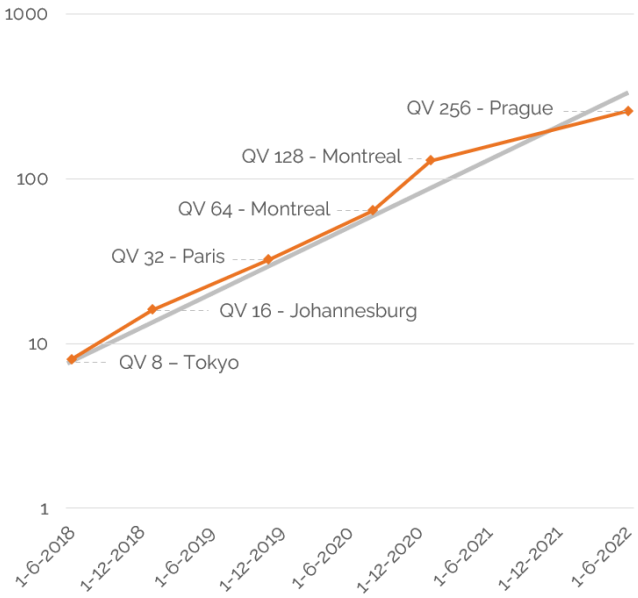


*Figure 2.2: The quantum volumes IBM has achieved over time. An exponential curve similar to Moore's law could emerge based on these points. Based on [4].*

## 2.2 Technological Innovation System (TIS) framework

The mass diffusion of quantum processing units cannot be treated as a single, detached event. Instead, there is a wide variety of actors and factors surrounding the QPUs, which all influence the rate of adoption. To include this influence, the QPU should be considered with its surrounding socio-technical system. A socio-technical system can be defined in various ways. For the case of QPUs, a variation called the Technological Innovation System is best suited, as it includes all actors and factors involved in a particular technological innovation. The Technological Innovation System can be mapped using the Technological Innovation System (TIS) framework.

The foundations for the TIS framework were laid by Carlsson and Stankiewicz [47] and further elaborated upon by the papers of Bergek [48] and Malerba [49]. Bergek added structural components to the original model in the notion of four distinct building blocks: the technology, a network of actors, supporting institutions, and the demand side, making the model significantly more concrete and user-friendly [48].

However, Bergek's model does not align with the company perspective this thesis aims to take but instead uses a policy perspective [48]. According to the paper of Ortt and Kamp [50], this difference in perspective does not invalidate the model. Instead, a simple subdivision of the building block *technology* into *product performance and quality, product price, the production system* and *complementary products and services* is proposed to change the perspective [50].

This, in combination with rephrasing the other building blocks to suit the perspective better, results in the following seven company-specific building blocks [50]:

- **Product performance and quality**. The product should be a new, high-tech product with a sufficiently good performance and quality now or in the near future.
- **Product price**. Often the initial price of new technologies is extremely high compared to alternatives. Various costs such as switching costs, transaction costs, and simply time are needed to acquire the new technology.
- **Production systems**. The new technology needs to be delivered at high quality and in large quantities to enable mass diffusion.
- **Complementary products and services**. Support for the entire value chain in terms of development, production, distribution, adoption use, repair, maintenance, and disposal is needed. When these are unavailable, incompatible, or too expensive, they can hamper innovation.
- **Network formation and coordination**. This can refer to various types of actors, such as suppliers, producers, distributors, and those providing any of the aforementioned complementary products and services. Especially coordination and a shared vision between these actors are vital.
- **Customers**. It is important to identify who the potential customers are early on and to make these potential customers aware of the innovation and ensure they have the knowledge, means, and willingness to acquire and use it.
- **Innovation-specific institutions**. This includes government policies, laws, standards, and regulations.

These seven building blocks are deemed relevant to create a model to predict when large-scale diffusion of quantum computers can start. The second part of the framework by Ortt and Kamp [50] mentions the influencing conditions that dictate which niche strategies can be pursued when one of the seven building blocks is still lacking. As this study focuses on the state of the building blocks and not on the subsequent strategies they imply, these niche strategies are not further elaborated upon in this paper. Nevertheless, it should be noted that these strategies provide a fruitful foundation for a follow-up study.

## 2.3 Definitive methodology

Four different models to approach the development of a new high-tech product were explored briefly, three of which can be found in the appendices C.1 - C.3, as well as a brief historical analysis of Moore's law based on the adjacent semiconductor industry.

Section C.1 describes Gartner's Hype Cycle model, which in itself lacks scientific proof, but might be considered valuable in combination with the diffusion of innovations model as described in section C.3 and its proposed additions in the form of quantitative approaches, such as seen in the trends of section B.1. However, due to the lack of scientific evidence for the fundamentals of this theory, it shall not be pursued in this thesis.

As described in section C.2, the second method of technology readiness levels and its complementing other forms of readiness levels are considered too experimental for this research and will thus not be pursued.

Section C.3 shows that quantum computing is still in the pre-diffusion phase, more specifically, depending on the definition, in either the innovation or adaptation phase. Due to the relatively early position of quantum computing in the (pre-)diffusion phase, it is considered untrustworthy to base a prognosis of the technology on the diffusion of innovation approach for now. Once quantum computing chips have developed further, this will be a very interesting path to study, and it is thus highly recommended for future scholars.

Section 2.1 dissects Moore's law. When divided into its sub-components, it becomes clear that Moore's law cannot be translated to the quantum realm one-to-one. However, the underlying theories behind Moore's law could potentially be applied to quantum computing and create an interesting new version. Nonetheless, this theory by itself would only provide information for one aspect of the development of QPUs. Moreover, a physically correct analogy of Moore's law in quantum has not yet been found, as described in section 2.1.2. Therefore, Moore's law will not be used further in the final model. Nevertheless, once a correct physical analogy has been found, it is expected to incorporate smoothly into the Technological Innovation System (TIS) framework.

The last section on the Technological Innovation Systems (TIS) framework 2.2 is considered useful and well-suited for the current maturity of the quantum computing industry. This method is used as the foundation on which this thesis is built. The overall decision for which methods are and are not used is visualized in figure 2.3.

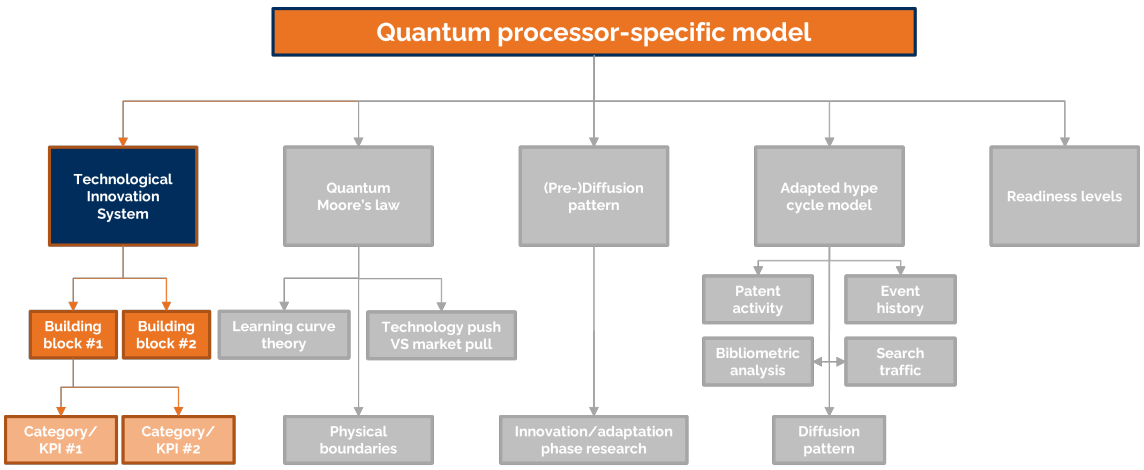


*Figure 2.3: Visual representation of the methods which will be used and their underlying theories. Shown in grey are the methods which were explored but will not be used.*

## 2.4 Process

This section describes the process this study used to determine the final expanded Technological Innovation System (TIS) framework for quantum processors. First, a general overview of the process divided into three distinct phases is provided in section 2.4.1.

To avoid subjectivity as much as possible, the supporting elements are co-designed and iterated with the help of experts in the field. This is achieved by using three varieties of input. Literature, a workshop, and expert interviews which are elaborated upon briefly in sections 2.4.2, 2.4.3, and 2.4.4 respectively.

Thereafter, the rationale behind the KPI selection is explained in more detail in section 2.4.5, and finally, the definition of the red, yellow and green thresholds is provided in section 2.4.6.

### 2.4.1 Process overview

From start to finish, the process of determining the final categories and KPIs for each of the building blocks can be subdivided into three phases, as visualized in figure 2.4.

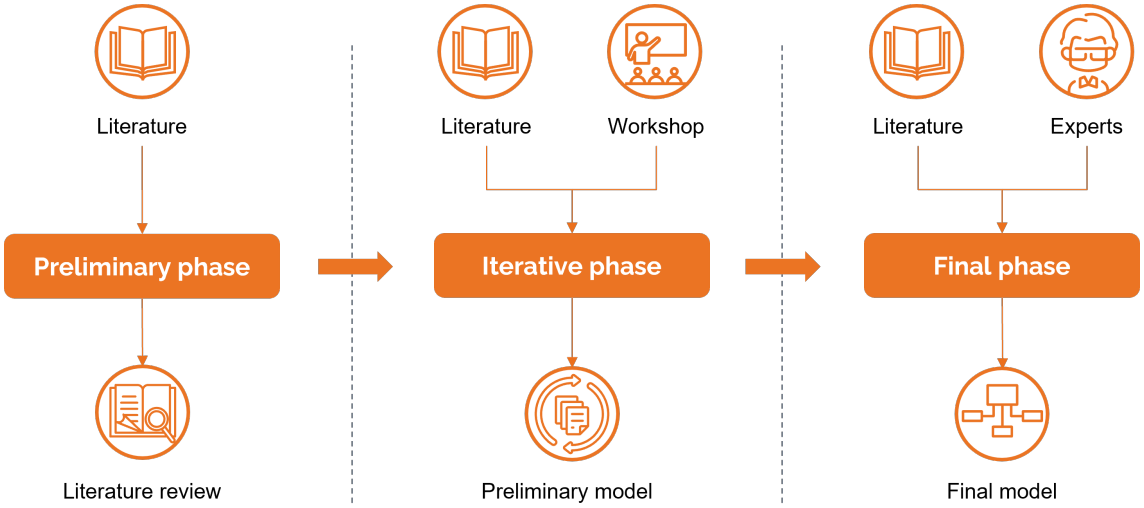


*Figure 2.4: The process of determining the categories and KPIs for each of the building blocks of the Technological Innovation System framework consists of three phases: a preliminary phase, an iterative phase, and a final phase. Each phase consists of a distinct in- and output.*

Each of the three phases consists of a distinct goal, input and output:

- The **preliminary phase**. The goal of this phase is to be sufficiently familiar with the product or industry to which the extended Technological Innovation System framework will be applied and to determine the definitive scope of the analysis. Determining the exact scope is especially vital to the product-specific KPIs, because they can alter drastically due to minor scope changes. For example, if the scope of this research would have been extended slightly to quantum computers as a whole, the *complementary products* building block would no longer contain the entire *quantum enabling technologies* category.

  The input for the preliminary phase consists entirely of literature but could potentially be enhanced by talking to industry experts to gain a more comprehensive understanding if desired. The output of this phase consists of a literature review and a strictly defined scope, which translates to chapters 1 and 2.

- The second phase is the **iterative phase**. The goal of this phase is to gather insights for the construction of the categories and KPIs for each of the seven building blocks. Various renditions of the model will result from various sources.

  The input for this phase consists of more in-depth literature research and additionally can consist of a workshop given to experts within the field, as further elaborated upon in

section 2.4.3. The latter is mainly recommended to determine which KPIs are potentially suitable for the product-specific building blocks. The output of this phase consists of various preliminary models resulting from the various sources used, which correspond to sections 3.1 - 3.2.3, and 3.4 - 3.8.

- The last phase is suitably called the **final phase**. The goal of this phase is to merge all various renditions of the created building blocks into one final version and to determine the thresholds for each of the identified KPIs.

  The input of this phase consists of both expert interviews to ensure the thresholds for the KPIs are set according to the state of the art, and more literature review to determine which KPIs are vital to mass diffusion and which are not. A more detailed description of the reasoning behind which KPI should be included in the final model, and which KPIs should not, will be provided in section 2.4.5.

  Note that in this thesis, this final phase was undergone solely for the *performance and quality* and *product profitability* building blocks, corresponding to section 3.2.4 - 3.3.

### 2.4.2 Literature

The main source of information for this thesis is existing literature. However, it should be noted that this thesis contains an above-average amount of so-called 'grey literature'. This 'grey literature' is necessary to describe advances in the quantum field that are too recent to be described in (peer-reviewed) academic literature. Due to the erratic and dynamic nature of the quantum industry and the fact that the success of this model depends greatly on its novelty and knowledgeability, it cannot do without this grey literature.

For more well-established topics, such as the foundations of the theories mentioned in the unused methodologies in the appendices C.1 - C.3, grey literature is avoided where possible.

### 2.4.3 Workshop

A short workshop was conducted to see how experts would subdivide the first building block *Product performance and quality*. The workshop was created using basic brainstorming principles. A group of 15 quantum experts with various backgrounds and job titles participated in this brainstorming session. The session itself is divided into two parts. Before the first part of the session, the participants are not given any context, meaning they do not get any explanation regarding the TIS framework, nor the subject of this research. This is done to assure as little bias as possible is introduced. Only after finishing the first round a brief introduction of the extended TIS framework is given, as this is necessary to converge toward the final model.

The first part of the workshop consists of an individual brainstorming session. This first session is not done in groups because research points out that allowing participants to brainstorm individually beforehand in the diverging phase increases the quality of the generated ideas [51].

The aim of the first part is to make use of divergent thinking, creating as many ideas as possible [52]. Therefore, without context, the participants are asked to write down as many Key Performance Indicators (KPIs) as necessary to determine either the performance or the quality of a quantum processor.

Furthermore, research shows that brainstorming is done more effectively when a constraint is provided when the participants are in the divergent phase. Here, the chosen constraint is a time limit of ten minutes[52].

The second part of the workshop is conducted in groups of two as this is indicated to be the optimal group size [53]. The aim of the second part is to use convergent thinking to bring ideas together and create an all-encompassing but feasible model.

The participants have now been provided with the basics behind the TIS framework. They were shown the seven building blocks and an empty model, indicating the two additional layers of supporting elements and sub-elements.

The participants are asked to categorize the KPIs from the first session. These categories should be mutually exclusive and collectively exhaustive, meaning there is no considerable overlap between categories whilst still covering the entire topic. The participants are allowed to add new KPIs or not use all KPIs from the first session if they think this improves their model overall.

In case the participants did not understand the division into categories or the difference between category names and KPIs, an entirely unrelated example of the model completed for a coffee machine is shown. This unrelated example is chosen to minimize the odds of creating bias.

Both the slides used in the workshop and the digitized results of the workshop are attached in Appendix D.

### 2.4.4 Expert interviews

To both verify and iterate upon the created models, expert interviews are used. Due to the qualitative nature of this research, these experts are selected via purposeful sampling. Purposeful sampling is especially useful in this case because it allows for a relatively small sample size (can be useful starting at n=1) and because its purpose is to select outstandingly information-rich cases that will illuminate the questions under study [54].

There are various different purposeful sampling strategies. In this case, *snowball or chain sampling* will be used. Snowball sampling is done by asking knowledgeable individuals who they would identify as an expert on a certain topic. A few key names will be mentioned repeatedly, thus identifying the most important information-rich individuals for this research [54, 55].

The individuals selected through purposeful sampling are asked for their opinion on the thresholds of one specific KPI. Because the quantum computing field is incredibly competitive, exact values for most of the KPIs present in this thesis are classified as highly sensitive information. This sensitivity also leads to very little information regarding the values of KPIs in the literature, making the thresholds highly dependent on the knowledge of experts. Due to this sensitivity, experts are reluctant to share any critical information anonymized in person as well.

To still be able to gain some understanding of the quantum computing field's boundaries, experts are only asked to describe the boundaries of the ranges they consider to be red, yellow, and green for the entire quantum field. This also rules out any unwanted specificity regarding the qubit architecture they are working with, thus reducing the odds of either the experts' or their company's values being identified. An anonymized list of the experts interviewed can be found in appendix E.

### 2.4.5 KPI selection

Potentially relevant KPIs are initially selected in the iterative phase through various methods to ensure nothing is forgotten, and biases are avoided where possible. To ensure the final selection of KPIs is all-encompassing, each KPI should be elaborated upon in more detail. Thereafter, five consecutive questions must be answered to establish the overall importance of the KPI for the building block, as shown in figure 2.5. Note, that it is possible to obtain more or less than three preliminary models, depending on the amount of sources available. Furthermore, potential iterations within the preliminary models are not shown in figure 2.5 for the sake of simplicity, but might be present nonetheless.

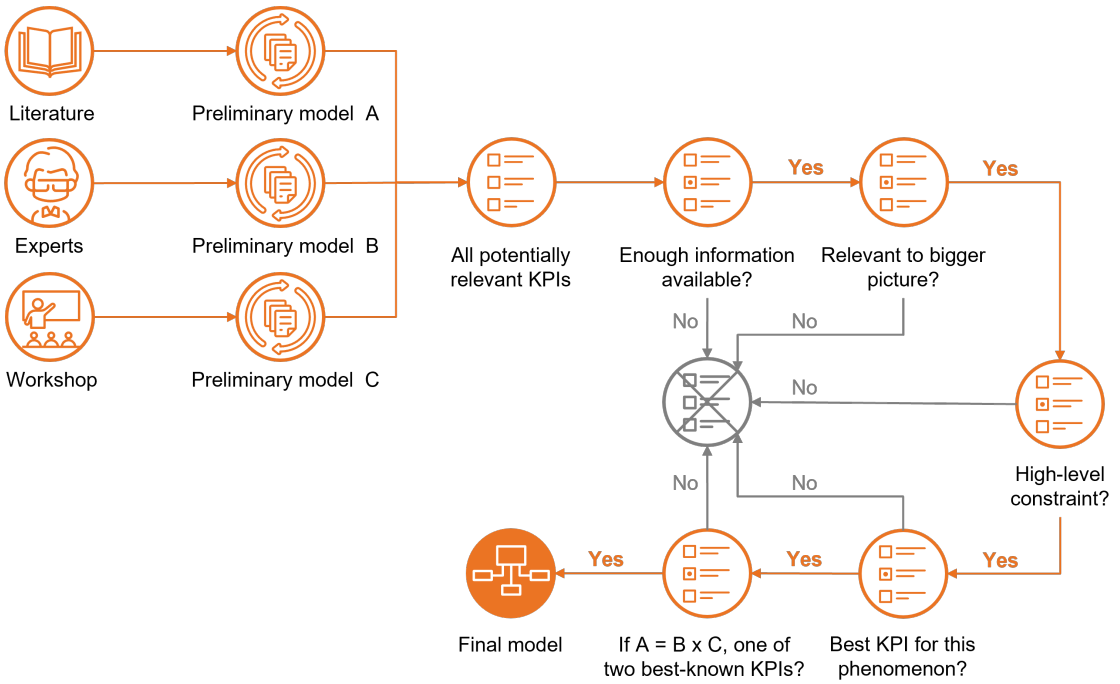


*Figure 2.5: Various preliminary models stem from various sources, which together provide a list of all potentially relevant KPIs. To determine whether a KPI is fit for the final model, five consecutive questions must be answered with 'yes'.*

The five demands which must be fulfilled for a KPI to reach the final model on which the questions are based are the following:

- There must be **enough information available**. A KPI might be identified but remain relatively uncertain due to a lack of knowledge regarding the optimal value of this KPI. This can be the case for KPIs describing a fully functioning product that does not yet exist. Ideas regarding the approximate boundaries for this KPI might already exist in this case but cannot be set with certainty. Unique to this demand is that these KPIs can be included later on, once the development of the product in question is sufficient. Therefore, this demand provides only a temporary constraint. In the case of the quantum processor, three KPIs are (temporarily) determined unfit due to this demand. These are the *initialization fidelity*, the *measurement fidelity*, and lastly, the *stability*.
- A KPI must be **relevant to the bigger picture**. A KPI might be relevant for only a limited amount of time. For example, if the KPI describes a process relevant to early-stage development activities only. For quantum processors, this is the case for the KPI *CLOPS*.
- A KPI **cannot** merely be a **technical or otherwise low-level constraint**. Some KPIs are considered to be checkboxes that need to be checked in a fundamental phase before development can occur at all. Such KPIs can often be seen as yes or no questions, and without their presence, establishing a functioning product is unthinkable. A KPI can also be considered too low level if it merely describes a basic aspect of the product which will always be present, such as a size. In the case of quantum processors, the KPIs *chip size*, the *operating temperature* and *quantum-classical interaction* are determined to be too low level.
- The KPI must objectively be the **best at describing this phenomenon**. If this is not the case, evidently, the other KPI should be preferred. For quantum processors, this is the case for the *algorithmic performance* and the *off-on ratio*.
- If three KPIs can be linked together directly, **one out of three KPIs becomes redundant** because the model should be kept mutually exclusive and collectively exhaustive where possible.

In other words, when certain KPIs are related to each other in such a way that $A = B * C$, only two out of the three KPIs are required in the model, as the third value of *KPI A* will automatically be considered 'sufficient' if the values for *KPI B* and *KPI C* are considered to be satisfactory. Therefore, an arbitrary choice for two out of the three KPIs can be made. It is recommended to choose the two KPIs with the most accurately known values.

For example, in the case of quantum processors, this is the case for the KPIs of *gate fidelity*, *gate operating speed* and *coherence time*. These are directly related to each other via the simplified formula: $Gate\ fidelity = Gate\ operating\ speed / Coherence\ time$. Due to less information available, the choice was made not to include the *gate operating speed*. Similarly, *crosstalk* is not included because it is directly dependent on the *gate fidelity*.

### 2.4.6 Determining the thresholds

Once the desired KPIs have been selected, a threshold to determine when the labels red, yellow, and green are allotted has to be established. To do so, the following definitions are applied:

- Red indicates that the KPI is underdeveloped and currently severely hindering the odds of mass diffusion and thus seen as a bottleneck.
- Yellow indicates that the KPI is not fully developed yet, but not in a desired state either. The possibility of mass diffusion is slightly impeded.
- Green indicates the KPI is within the desired boundaries and thus does not provide any hindrance for reaching mass diffusion whatsoever.

The exact implication of these boundaries have to be reassessed depending on the context for each KPI separately.

# Chapter 3.
# Results

This chapter will further elaborate on the seven building blocks of the TIS framework and establish their elementary categories and corresponding KPIs for quantum processing units specifically. The aim is to both create a generalizable, more detailed version of the TIS framework from a company perspective as proposed by Ortt and Kamp [50] and to use the detailed framework to make a well-informed, adjustable forecast for the start of mass diffusion of quantum processing units.

This chapter first describes several dichotomies within the seven building blocks and their corresponding implications for the amount of detailed appropriate per building block in section 3.1.

Thereafter, each of the seven building blocks is explored with varying levels of scrutiny. In light of the limited timeframe of this research, as explained in section 4.2, exclusively the first two building blocks are treated more in-depth due to their relatively high importance. The latter five building blocks are briefly touched upon but should be further explicated in future research.

The first industry-specific *product performance and quality* building block is conceived for quantum processors by analyzing three different sources and combining the results into one final subdivision, consisting of three categories in section 3.2.

Secondly, an amendment of the second building block from *product price* to *product profitability* is proposed and highlighted for the quantum processor market specifically in section 3.3.

Thereafter, the five less-detailed building blocks are briefly touched upon. Firstly, the final directly product-related building block of *production systems* is subdivided into the process- and input/output-related KPIs in section 3.4. Consequently, the suggested categories and sub-categories for the four indirectly product-related building blocks of *complementary products and services*, *network formation and coordination*, *customers*, and *innovation-specific institutions* are provided in sections 3.5, 3.6, 3.7 and 3.8 respectively.

Lastly, the overall generalizability of the model for other industries is addressed in section 3.9.

## 3.1 The TIS Framework from a Company Perspective

The original Technological Innovation System (TIS) from a company perspective as devised by Ortt and Kamp [50] formulated seven equally weighted building blocks. When further investigating them, several dichotomies within the building blocks appear.

First of all, a dichotomy based on the (in)direct relation of the building blocks to the product appears, as shown in figure 3.1. This distinction is further manifested in their quantitative and qualitative nature. Another apparent distinction is whether the building blocks are product-agnostic or not. The building blocks *product performance and quality*, *complementary products and services*, and partially the *customers* building block are product-specific and will have to be adjusted every time the scope is altered. The other building blocks are product-agnostic.

The first four building blocks are grouped as directly product-related and can generally be considered quantitative in nature. This group consists of the *product performance and quality*, the *product profitability*, the *production system*, and the *complementary products and services*. These four building blocks are subdivided into categories, which in turn have distinct, measurable KPIs, underwriting their generally quantitative nature.

The second group consists of the building blocks *network formation and coordination*, *customers*, and lastly *innovation-specific institutions*. These KPIs are indirectly related to the product in the sense that they are undoubtedly necessary for mass diffusion to occur, but they are not fundamental for the sole functioning of the product, in this case, the QPU itself. These indirectly product-related building blocks are characterized by their generally more qualitative nature if seen from the perspective of the product. They can be considered checkboxes as they are significantly more difficult to capture in a numerical value. Either a dominant design has been established, customers of a certain group already exist, or laws have been put into place.

The exception that proves the rule is that for each of those building blocks, the total amount can be captured in a numerical value. Only for the *customers* building block, the case could be made that a higher amount also implies a better value. For the other two building blocks, the amount is not considered to have any relevant value. Thus overall, the second group of building blocks is considered to be qualitative in nature.

The dichotomy between direct, quantitative, and indirect qualitative building blocks mainly manifests itself in the amount of detail. The former contains detailed KPIs with complicated thresholds, whereas the latter does not.

Another apparent distinction is whether the building blocks are product-agnostic or not. The building blocks *product performance and quality*, *complementary products and services*, and partially the *customers* building block are product-specific and will have to be adjusted every time the scope is altered. The other building blocks are product-agnostic.

This dichotomy manifests itself in the amount of work needed to determine the categories and KPIs for the implementation of the framework to a new product. The product-agnostic KPIs will not have to be redetermined, whereas the product-specific KPIs will need to undergo the entire process again.

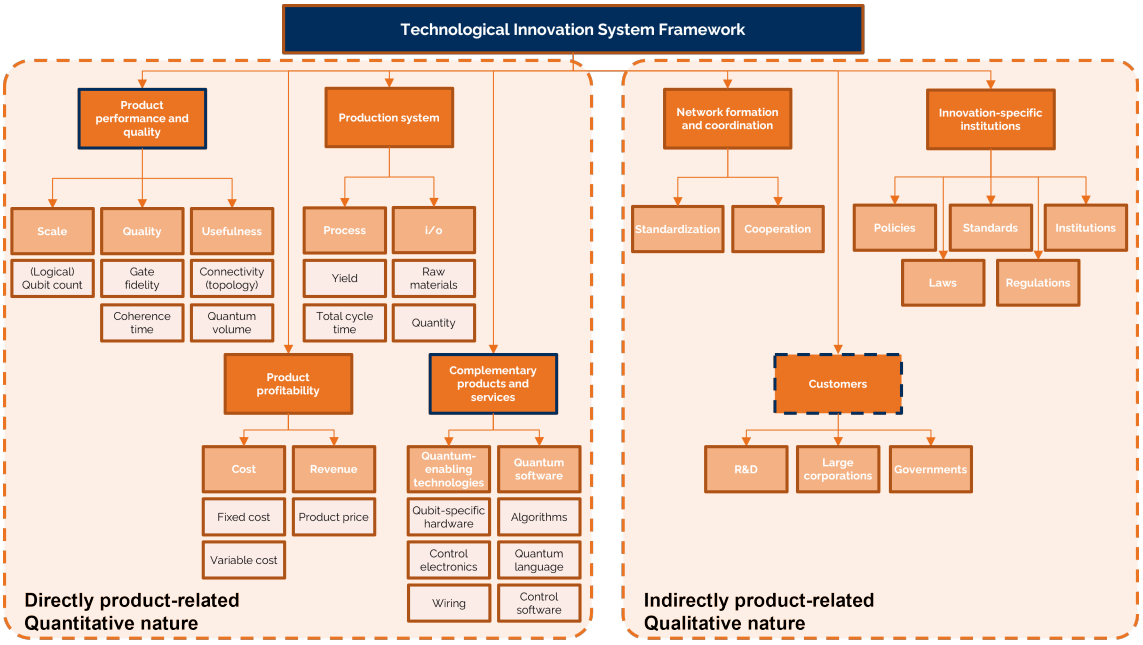


*Figure 3.1: The full Technological Innovation System Framework including the dichotomy between direct, quantitative, and indirect, qualitative product-related building blocks and product-specific (marked by a dark blue outline) and product-agnostic building blocks.*

## 3.2 Product Performance and Quality

The factors contributing to the performance and quality of quantum processing units are the most complex of the seven building blocks. This is mainly due to the fact that the industry itself is still torn on which criteria best capture all aspects of a functioning QPU. This section describes all relevant criteria needed to determine together whether the industry is ready to create quantum processing units which are of sufficient performance and quality.

First, the result of the workshop is discussed in section 3.2.1. Here, an initial version of the various KPIs needed for the performance and quality of a quantum processing unit are categorized. Secondly, in section 3.2.2, another version of the building block *product performance and quality* is proposed, based on a categorization proposed by market leader IBM. Thirdly, the DiVincenzo criteria and their fundamental importance to a useful quantum computer are provided and elaborated upon in section 3.2.3.

Thereafter, a short summary of all metrics mentioned in the workshop, the IBM model, the DiVincenzo criteria, and any additional required criteria derived from literature is provided in section 3.2.4.

To conclude, the three proposed models derived from the workshop, IBM, and the DiVincenzo criteria plus any additions from the literature are merged into one model, which is the final subdivision of the building block *product performance and quality*.

### 3.2.1 Workshop results

As mentioned in section 2.4.3, 15 participants split into eight groups were asked to create their version of the building block *performance and quality* in a two-step process. The various resulting *performance and quality* building blocks can be found in appendix D.

Some of the KPIs mentioned by the participants are named slightly differently but are considered to be the same KPI, such as qubit count and #qubits. Furthermore, there are a lot of non-relevant KPIs in the results, such as KPIs related to the costs, which belong to another building block. To differentiate between those KPIs which are relevant and those which are not, only those mentioned in at least three out of the eight building blocks created are considered. These relevant KPIs are then grouped together in three categories, *capacity, performance* and *usefulness*, as seen in figure 3.2. The categories were chosen based on their greatest commonality in such a way that the least possible amount of categories was necessary to encompass all KPIs. Details on what each metric entails and when a metric is considered to be developed 'enough' are described in section 3.2.4.

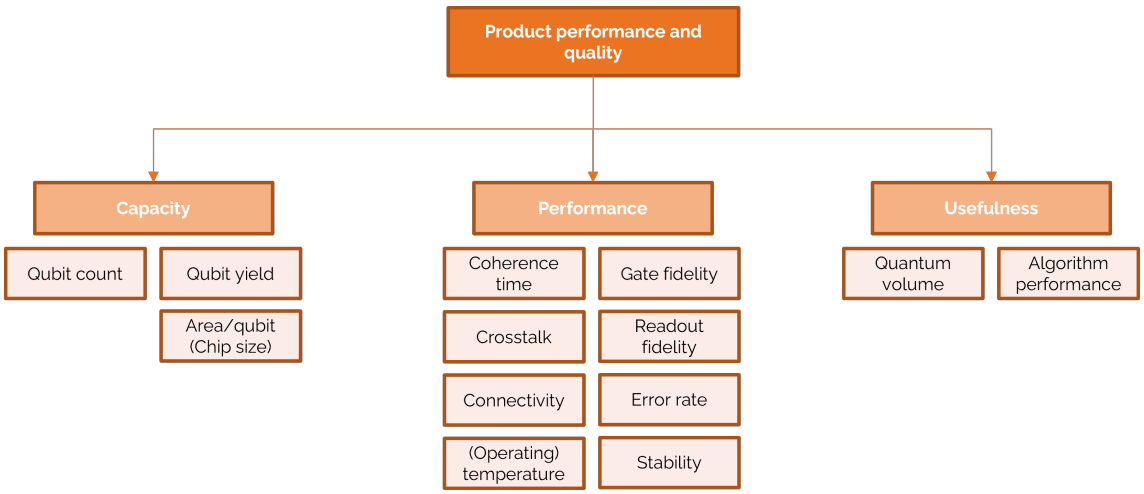


*Figure 3.2: A summary of the relevant KPIs of the workshop on product performance and quality, grouped into three different categories.*

### 3.2.2 IBM's metrics

IBM is currently considered to be the frontrunner in quantum computing. Their latest 433 qubit chip *Osprey* is currently the market leader[1], and their roadmap is promising to scale towards 100.000 qubits from as early as 2033 onwards[2]. Therefore it is not surprising that some of the industry's key metrics were proposed by IBM as well. IBM has created its own division of key metrics, which together encompass the total package of *product performance and quality*. Their division, highlighted in an interview [5] and a paper [56] consists of three categories, *scale, quality* and *speed*, as visualized in figure 3.3.

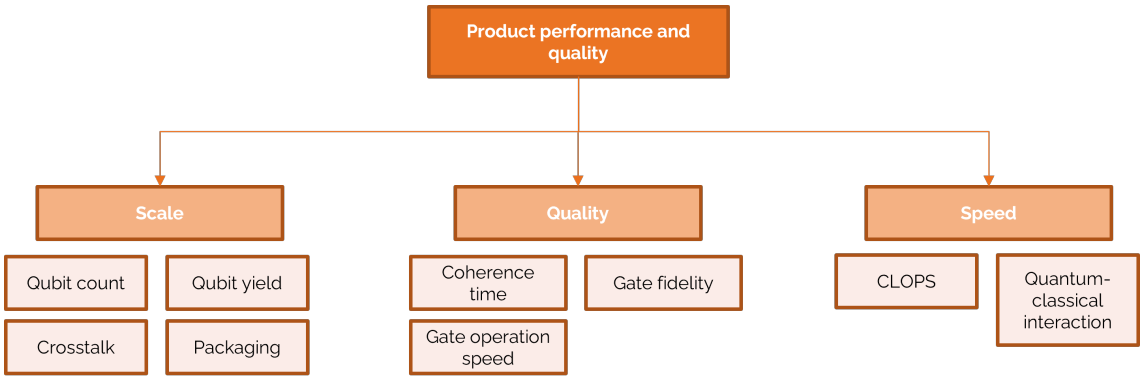


*Figure 3.3: The subdivision of the relevant key metrics for quantum processing unit performance and quality, as devised by IBM [5]*

The first key metric of **scale** is not solely concerned with raising the *amount of qubits* on a chip. If only a small amount of the qubits manufactured is of satisfactory quality, large-scale production remains unfeasible. Therefore, it also takes into account the *fabrication yield* on a chip. Furthermore, increasing the amount of qubits creates a lot of new technical- and fabrication challenges, which can mainly be captured in the KPI of *crosstalk* reduction. Other technical- and fabrication challenges, such as the packaging, for which 3D integration and multi-level wiring are necessary, are not incorporated but nevertheless required to function properly [5, 56].

The second key metric of **quality** needs to improve to be able to make use of this increase in scale and thus become useful. By increasing the *coherence time* simultaneously with the *gate operation speed*, the number of gate operations that can be performed before noise masks the results are increased. To define the quality of operations done within this time period, the *gate fidelity* is added to complete the quality metric. A more holistic metric for the quality is the quantum volume, which indicates how faithfully a quantum circuit can be implemented into a quantum computing system. The quantum volume is dependent on the other three quality metrics and, therefore, not incorporated separately [5, 56].

The final key metric of **speed** is mainly determined by the Circuit Layer Operations per Second (CLOPS), a metric created by IBM to try and capture the full dependencies of circuit executions across both hardware and software. One of the big advantages of this metric is that it is system agnostic, creating the opportunity to compare, for example, transmon qubits to spin qubits. Simplified, it determines how fast users receive the results of their calculations [5, 56]. Lastly, IBM points out that for the foreseeable future at least, quantum computers have to cooperate with classical computers to generate input and utilize the output. Therefore, these quantum-classical interactions are likewise crucial to sustain computation speed [5].

IBM does point out in a 2021 paper [56] that mainly the latter two categories of quality and speed are intrinsically linked and that they can both be viewed from three different levels of complexity; that of the device, the subsystem, and lastly in a holistic view [56]. The bottom tier

[1] https://newsroom.ibm.com/2022-11-09-IBM-Unveils-400-Qubit-Plus-Quantum-Processor-and-Next-Generation-IBM-Quantum-System-Two
[2] https://research.ibm.com/blog/100k-qubit-supercomputer

of device-level benchmarks provides more complexity but creates a less accurate description of the overall performance of a quantum chip. The upper tier of holistic benchmarking, on the other hand, captures the overall performance well but does so at the cost of its specificity [56].

IBM visualizes the linkage of these different complexity levels in a so-called 'benchmarking pyramid' [56]. However, it should be noted that despite providing an appealing visualization of the metrics, no scientific reasoning behind the formation of the pyramid is given, nor how their third category of scale fits into this theorem. Furthermore, no explanation of what the boundaries between the layers mean is given in the paper either. Because of this lack of explanation, this 'pyramid' visualization will not be used in this research.

Another important note to be made on the viewpoint of IBM on a quantum processing unit's performance and quality metrics is that their way of phrasing metrics and the benchmarks they have created themselves, like the Quantum Volume and CLOPS, have been created with IBM's QPUs in mind. Therefore, some bias is present in their formulation of the metrics, which seems to be confirmed in a recently published paper [57]. This bias is also apparent in one of the papers IBM published regarding their performance metrics [56].

Note that this does not mean that, for example, the Quantum Volume is a bad metric at all, as endorsed by its widespread use. It merely implies that a bias is probably present in IBM's subdivision of key performance metrics. Therefore, these metrics will not be simply copy-pasted as a base for the performance and quality building block but instead be compared to other findings in the literature and expert opinions to check if the proposed benchmarks are indeed the best options and whether any other criteria might have been conveniently omitted or added.

Details on what each metric entails exactly and when a metric is considered developed 'enough' are described in section 3.2.4.

### 3.2.3 DiVincenzo's Criteria

DiVincenzo was one of the first physicists to propose five plus two basic criteria which need to be met for a quantum computer to be of sufficient performance and quality and thus be considered a quantum computer, now fittingly called the DiVicenzo criteria. The first five criteria are concerned with the computational nature of quantum computing. The latter two criteria are related to the transmission of information [6]. The five plus two DiVincenzo criteria are visualized in figure 3.2.3.

These criteria will not be mentioned in the model directly because most of DiVincenzo's criteria are not concrete KPIs. This does not undermine the importance of these criteria in any way. Instead, they can be seen as foundational 'checkboxes' that need to be ticked off before a 'quantum computer' can be considered a quantum computer. The exception to this rule is the criterium of a long enough *coherence time*, which is mentioned in the model explicitly.

Due to the foundational nature of the criteria, they are mostly captured in other KPIs, which means they are, in fact, present in the model, be it indirectly. The original DiVincenzo criteria are the following [6]:

#### A scalable physical system with well-characterized qubits

Here, a *well-characterized qubit* is defined as having accurately known physical parameters, which translates to a well-defined Hamiltonian. Furthermore, a scalable physical system is required, which means not one but multiple qubits can be controlled simultaneously [6]. Currently, particularly the scalability of this criterion remains the hardest to solve for all qubit architectures [58].

This criterium will not be used in the model directly due to its intrinsically foundational nature. Therefore, it is implicitly present in almost all of the *performance and quality* KPIs.

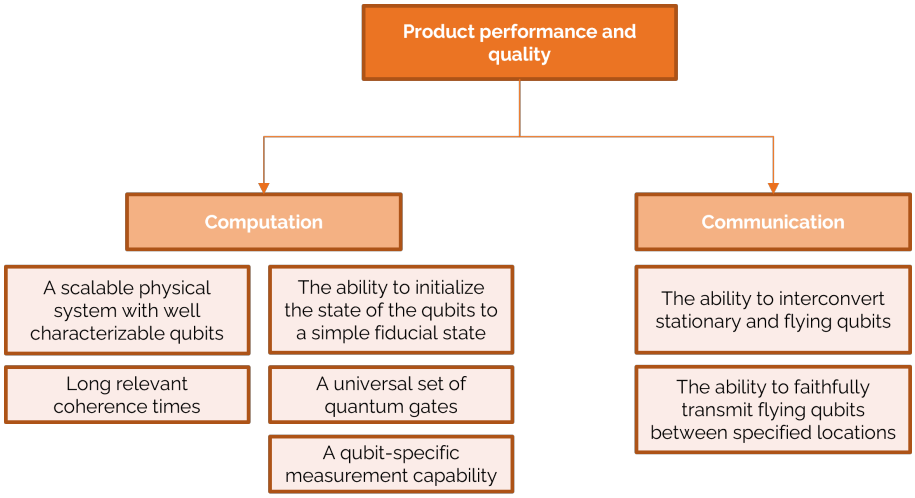


*Figure 3.4: Visualization of the seven DiVincenzo criteria necessary to successfully build a quantum processing unit. Based on [6].*

### Initialization of the qubits to a simple initial state

This is necessary for two reasons: first of all, the registers should be initialized to a known value before computations can start, and second, a 'continuous supply' of zeroes is mandatory for the proper execution of quantum error correction. The latter means that either the speed at which qubits can be 'zeroed' needs to be either substantially faster than gate-operating times or something like a qubit 'conveyor belt' removing the qubits from the computational area and returning them once they have initialized will be essential [6].

This criterium translates to the *initialization fidelity* KPI as mentioned in section 3.2.4.

### Long coherence times

A long coherence time is at least significantly longer than the gate operation time. If the coherence time is not 'long enough', the desired calculation cannot be completed and thus renders the QPU useless [6].

The *coherence time* is the only 'original' DiVincenzo criteria that can directly be considered a KPI and not a preliminary 'checkbox'. Therefore, it is used directly in the final model. More details on the coherence time are given in section 3.2.4.

### The implementation of a universal set of quantum gates

A 'universal gate set' means that when the gates are put together, they express any Boolean function. This gate set can approximate any unitary transformation, which is a transformation that preserves the inner product [6].

These universal quantum gates do not directly translate to one of the KPIs in the final model. This is mainly due to the intrinsically elementary nature of this KPI. Without a universal quantum gate set, a quantum chip cannot be controlled whatsoever.

### The ability to perform qubit-specific measurements

The result of the computation performed on a QPU must be read out to know the result. This requires the ability to measure the results of each of the qubits. In an ideal measurement, the quantum efficiency would be 100%. However, in reality, this will always be less. A useful parameter to summarize this criterion is the single quantum-efficiency parameter. Fortuitously, useful computations can be performed with a quantum efficiency as low as 1%, by ingeniously performed gates or by simply rerunning the calculation multiple times [6].

This criterium translates relatively directly to the *measurement fidelity* KPI as described in section 3.2.4.

#### The ability to interconvert stationary and flying qubits & the ability to faithfully transmit flying qubits between specified locations

For computation alone, the aforementioned five criteria suffice. However, to provide information-processing and thus make use of the computations, two closely related additional criteria are required. The term 'flying qubits' used in these two criteria refers to any qubit which is not stationary and can therefore be transmitted between two quantum computers [6, 59].

The first criterium is *the ability to interconvert stationary and flying qubits*. This is important because, in classical computers, several different physical resources co-exist, making it probable that a similar co-existence will occur in future quantum computers [59].

The second criterium *the ability to faithfully transmit flying qubits between specified locations* is necessary for exchanging information without decoherence [6].
Since the latter two criteria are mainly necessities for quantum computation/communication and are not necessarily needed for the production of a functioning QPU, as also endorsed by DiVincenzo himself [6], these two criteria are not taken into account in the final model.
In a subsequent paper co-written by DiVincenzo, three additional metrics are mentioned: the *off-on ratio*, the *gate fidelity*, and the *measurement fidelity*. These are further elaborated upon in section 3.2.4

### 3.2.4 Performance and quality metrics

This section will provide a short explanation for each KPI related to the performance and/or quality of a quantum processor unit mentioned in the workshop, the IBM metrics, and any other notable mentions in the literature. For each KPI, a brief justification of whether it will be included in the final model is also provided.

The metrics further elaborated upon in this chapter are *algorithm performance*, *chip size*, *CLOPS*, *coherence time*, *connectivity/topology*, *crosstalk*, *error tolerance*, the fidelities, being the *gate fidelity*, *initialization fidelity* and the *measurement or readout fidelity*, *gate operation speed*, *off-on ratio*, *(operating) temperature*, *quantum-classical interaction*, *qubit count*, *quantum volume*, *qubit yield* and *stability*.

All metrics mentioned in either the workshop, IBM's metrics, or the literature are mentioned separately for the sake of completeness. However, because of this, some metrics have a significant amount of overlap. Where necessary, these overlapping metrics will refer to one another and only be fully elaborated upon once.

#### Algorithm performance

The performance of quantum algorithms is a KPI mentioned in the quantum expert workshop described in section 3.2.1.

Quantum algorithms must be able to run on a quantum processor, or else it is rendered useless. However, the performance of quantum algorithms itself is not taken into account in the final model for several reasons. First of all, *algorithm performance* is not a KPI in itself but an overarching category. Secondly, there is no single unambiguous KPI to measure the overall performance of algorithms on quantum processors. To still be able to determine whether a certain algorithm can hypothetically be run on a quantum processor, the quantum volume, described in section 3.2.4, is generally used instead. Whilst this metric does not capture everything, it is the best metric available at this moment. Given the relative novelty of metrics describing the performance of quantum algorithms, such as the quantum volume, a more suitable metric might be devised once the industry develops further.

#### Chip size

The chip size refers to the area used per qubit and is a metric mentioned in the workshop results as described in section 3.2.1. This metric is relevant in the sense that the area per qubit cannot be infinitely large, especially for those architectures restrained by the size of the existing cryostat.

Nevertheless, the chip size is considered to be more of a technical constraint and does not directly influence the performance or quality of the QPU. Therefore, the chip size is considered too low level to be used as a KPI in the final building block.

#### CLOPS

Circuit Layer Operations per Second (CLOPS) is a holistic metric created by IBM as described in section 3.2.2, correlated with the amount of quantum volume (QV) circuits a quantum processing unit can execute per unit of time [56]. Formally it is defined as *"the number of QV layers executed per second, using a set of parametrized QV circuits, where each QV circuit has* $D = log_2 QV$ *layers. Circuit execution time includes updating parameters to the circuit, submitting the job to the QPU, executing on the QPU, and sending results back to be processed. CLOPS is then calculated as the total number of QV layers divided by the total execution time* [56].

IBM acknowledges the difficulty in finding an accurate and representative 'average' circuit that allows for enough quality, thus questioning the metric themselves [56]. Furthermore, the industry does not seem particularly keen on CLOPS either, given how little it has been mentioned in literature since its introduction in 2021, creating a stark contrast to its counterpart, the quantum volume.

The goal of this model is to provide a more accurate prediction of the start of mass diffusion for QPUs, which will most likely not take place in the NISQ era, but only once universal fault-tolerant quantum computing is reached. However, the CLOPS metric is only relevant for the NISQ era, further nullifying its potential in the bigger picture.[3] Therefore, CLOPS will not be used in the final model.

### Coherence time

The coherence time is mentioned by both IBM 3.2.2 and the expert workshop 3.2.1 as one of the key performance indicators for QPUs. The coherence time of a qubit measures how long the qubit can maintain its quantum state before being subjected to errors created by interaction with the environment. The longer the coherence time, the more gates can be performed, thus the more useful the computations which can be done become.

A minimal threshold for the coherence time has been established at the order of "$10^4 - 10^5$ times the execution time of a single quantum gate" [6] for error correction to be successful. At present, there is a vast difference in the orders of magnitude of the gate operating speed per qubit architecture. Trapped ion-based qubits operate in the microsecond regime, around $10^-3$ - $10^-4$ microseconds, whereas superconducting- and spin-based qubits typically have operating times in the nanosecond regime instead, around $10^-3$ - $10^-4$ nanoseconds, thus three orders of magnitude more [60].

Therefore, coherence times of around $10^-7$ - $10^-9$ seconds are required for superconducting- and spin-based qubits, and trapped ion-based qubits need a significantly longer coherence time of around $10^-6$ - $10^-8$ seconds for error correction to be successful. This error correction threshold for the coherence time is seen as the minimum requirement to reach the yellow predicament [60]. This threshold has not been reached for any of the qubit architectures yet, thus, the coherence time is currently labeled red, as seen in table 3.1.

However, for useful quantum computing applications such as quantum chemistry and factorization problems, much higher coherence times are necessary. The coherence times for superconducting- and spin-based qubits move up to $10^-2$ - $10^0$ seconds, and for trapped ion-based qubits, even to $10^-1$ - $10^1$ seconds. As these applications fall into the UFTQC era, these are considered to be the green values [60].

For other types of qubit architectures, the desired values for the yellow and green thresholds could not be found in the literature. Further research will have to determine their specific threshold values.

[3] Based on an expert interview with interviewee A.

*Table 3.1: Definition of the red, yellow, and green thresholds and when they are expected to be reached for the KPI coherence time. Currently, the coherence time is considered red.*

| Coherence time | |
|---|---|
| **Red** | |
| **Threshold** | **Reached in** |
| Anything below the error correction threshold, which is below $10^-7$ - $10^-9$ seconds for superconducting- and spin-based qubits and below $10^-6$ - $10^-8$ seconds for trapped ion-based qubits. | Unknown |
| **Yellow** | |
| **Threshold** | **Reached in** |
| Anything above the error correction threshold, but below the times needed for useful applications | Unknown |
| **Green** | |
| **Threshold** | **Reached in** |
| Anything above $10^-2$ - $10^0$ seconds for superconducting- and spin-based qubits and above $10^-1$ - $10^1$ seconds for trapped ion-based qubits. | Unknown |

### Connectivity/Topology

The connectivity is deduced from the expert workshop 3.2.1. The connectivity or chip topology describes in what manner the qubits are connected to each other. There are various possible topologies, which are divided into four categories as shown in figure 3.5.

Within these categories, a subdivision could be made, as a square lattice is arguably better than a hexagonal lattice. However, for the sake of simplicity, the differences between square, hexagonal, and other thinkable shapes are considered irrelevant to this research.

Next to the visual differences, the various topologies can also be described using the *average qubit connectivity*, which describes the number of other qubits one qubit is connected to [61]. The four distinguished categories are [4]:

- **1D**. The qubits are only connected in a straight line, as shown in figure 3.5 (a). This significantly hampers the possible use of most types of algorithms and is therefore considered very unsatisfactory. The average qubit connectivity is $< 2$. This topology is considered to be below the lowest threshold, and thus considered red.
- **1D+**. The qubits are connected in a second dimension, however, only in a circular shape, and they do not have any other connections outwards as shown in figure 3.5 (b). It is a slight upgrade compared to the latter category, but it is still considered very undesirable. The average qubit connectivity is 2. Due to the fact that 1D+ connections are only marginally better than 1D, it is also given the predicament red.
- **2D or nearest neighbour connected**. This is the most commonly found topology at the moment in superconducting qubits. The qubits are generally aligned in a square or hexagonal lattice, as shown in figure 3.5 (c), but other shapes are also possible. The average qubit connectivity is $3+$. Most algorithms can be run on this topology, and it is therefore considered to have the predicament yellow.

[4] Based on an expert interview with interviewee A.

- **3D or all-to-all connected**. Shown in figure 3.5 (d) is an all-to-all connection for a square lattice. The bigger the lattice, the harder it becomes to create an all-to-all connection. The average qubit connectivity is $4+$. The all-to-all connectivity is considered the most preferable because all algorithms can be run on it. Therefore, the 3D connectivity is considered green.

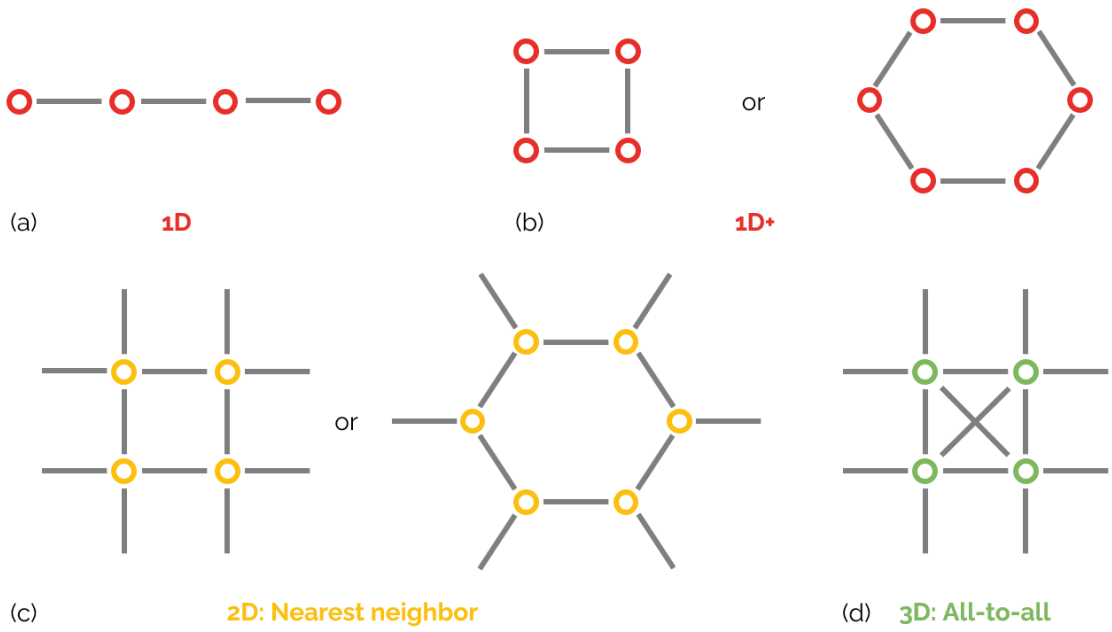


*Figure 3.5: The four distinguishable categories of possible topologies, 1D, 1D+, 2D or nearest neighbor and 3D or all-to-all. The circles represent qubits, and the grey lines represent their connections.*

Generally speaking, superconducting qubit manufacturers make use of a 2D or nearest neighbor connection in their devices, thus gaining the predicament yellow. IBM, for example, used to have a (partially) all-to-all connection in their earlier designs but switched to a less connected self-proclaimed *heavy-hex lattice* due to undesired frequency collisions. This *heavy-hex lattice* is drawn in a hexagonal shape to appear to have a 'classical' nearest neighbor design. However, it has extra, less connected qubits in between the corners of the hexagon, effectively further demoting their overall average qubit connectivity to only $2.1$[5]. Google's Sycamore processor also makes use of nearest-neighbor connections but in the form of a square grid, thus achieving a higher average qubit connectivity.[6] Spin qubit-based quantum chips have been created with a nearest neighbor connection as well, be it only on a small scale [62].

Trapped ion manufacturers, such as Honeywell, generally make use of 3D or all-to-all connected qubits, thus gaining the predicament green[7]. For other, less-researched qubit architectures, no conclusive information regarding the average connectivity of the qubits could be found.

[5] https://research.ibm.com/blog/heavy-hex-lattice
[6] https://quantumai.google/hardware/datasheet/weber.pdf
[7] https://www.honeywell.com/us/en/company/quantum/quantum-computer

*Table 3.2: Definition of the red, yellow, and green thresholds and when they are expected to be reached for the KPI connectivity/topology. Currently, the connectivity/topology is considered yellow for superconducting and spin qubits and green for trapped ion-based architectures.*

| Connectivity/Topology | |
|---|---|
| **Red** | |
| **Threshold** | **Reached in** |
| 1D or 1D+ connectivity, regardless of the shape. The average qubit connectivity is $\leq 2$. | - |
| **Yellow** | |
| **Threshold** | **Reached in** |
| 2D or nearest neighbor connected. Average qubit connectivity of $\pm 3$. | Current average connectivity for superconducting and spin qubit-based architectures. |
| **Green** | |
| **Threshold** | **Reached in** |
| 3D or all-to-all connected. Average qubit connectivity of $4+$. | Current average connectivity for trapped ion-based architectures. |

### Crosstalk

Crosstalk is mentioned as a separate metric by both IBM 3.2.2 and the expert workshop 3.2.1. It can be defined as *'unwanted interactions between coupled qubits on a quantum chip'*[63]. Among all possible sources of gate errors, crosstalk is the most common form for almost all qubit architectures [30, 63, 64, 65]. Because crosstalk is a form of gate error, it is captured in the gate error rate. The gate error rate is directly translatable to the gate fidelity via the formula $gate\ fidelity = 100\% - gate\ error\ rate$ [66], as described in section 3.2.4. Therefore, crosstalk is not separately included in the final model.

### Fidelities and error rates

There are three types of fidelities relevant to determine the performance and quality of a QPU: the *gate fidelity*, the *initialization fidelity*, and the *measurement or readout fidelity*. The latter two are sometimes combined in literature in the State Preparation and Measurement or *SPAM fidelity* [67]. The fidelities are directly related to the error rates of a QPU through the following equation [66]:

$$Fidelity = 100\% - Related\ error\ rate$$

The related error rate depends on the type of fidelity asked. The gate fidelity is connected to the single- and dual-qubit gate error rates, the measurement or readout fidelity is related to the measurement/readout error rate, and the initialization fidelity is related to the initialization error rate. Due to their interconnectedness, the fidelities and their respective error rates are often used interchangeably in the literature [66]. Currently, the gate error rate is responsible for the lion's share of the overall error rate of qubits in almost all architectures, rendering the current influence of measurement and initialization errors almost negligible. Once the field advances further toward the UFTQC era, these types of errors might become significant, but to what degree remains difficult to predict at this moment in time. Therefore, the current version of the model will only include the gate fidelity or gate error rate.

### Gate fidelity or Gate error rate

Gate fidelity is mentioned in the expert workshop 3.2.1 and the only fidelity mentioned in IBM's metrics 3.2.2. It is a measure of how accurately a quantum gate can be implemented. Therefore, a high gate fidelity indicates that the gates operate as expected, with minimal error and/or noise. The gate fidelity is considered to be the most important and influential of all three fidelities [66].

The gate fidelity $F$ encompasses most types of error that could occur, for example, due to loss of coherence or crosstalk as described in section 3.2.4. More specifically, $1 - F$ is an error probability relevant to the fault-tolerant operation of the quantum computing chip. It measures the occurrence of an error during actual coupled operation. Therefore, the desired value of $F$ is as close to 1 or 100% as possible [68].

Quantum gates cannot be implemented perfectly and will thus demonstrate two types of errors that affect gate fidelity. The first type of error is random errors, which are inherent to quantum and can only be resolved using error correction. Initially, the tolerable error correction threshold for the magnitude of these random errors was thought to be in the same order of magnitude as the decoherence threshold: $10^-4$ - $10^-5$ per gate operation[6]. However, later research showed that certain 2-D architectures exist that can relax this boundary to approximately $10^-2$ [69]. Current error rates for qubits are generally still below the error correction threshold except for some notable outliers [70], and thus the gate fidelity is currently classified as red, as seen in table 3.3. Anything consistently performing above the error correction threshold is considered yellow.

The second type of error, systematic gate errors, should be practically eliminated by careful calibration. The tolerance for systematic gate errors is significantly smaller (approximately the square of the tolerance for random errors); however, certain types of computation can tolerate very high levels of systematic error [6].

It is estimated that error rates in the range of $10^-6$ - $10^-9$ are necessary to run quantum circuits capable of solving industrially relevant problems, on top of a greatly increased qubit count [70]. This range is therefore considered to be green. However, with increasing the amount of qubits, the potential for a qubit to create an error naturally increases, thus also increasing the error rate. Therefore, lower error rate ranges can only be achieved in a different way: through applying error-correcting surface codes. Google recently published the first paper, which was convincingly able to successfully apply a surface code, thus outperforming the error rate with a greater qubit count [70].

*Table 3.3: Definition of the red, yellow, and green thresholds and when they are expected to be reached for the KPI gate fidelity. Currently, the gate fidelity is considered yellow.*

| Gate fidelity / Gate error rate | |
|---|---|
| **Red** | |
| **Threshold** | **Reached in** |
| Anything below the error correction threshold of $10^{-2}$ | Current value |
| **Yellow** | |
| **Threshold** | **Reached in** |
| Convincingly overcoming the error correction threshold $\pm 10^{-2}$ | Except an outlier[21], not reached yet |
| **Green** | |
| **Threshold** | **Reached in** |
| Error rates around $10^{-}6 - 10^{-}9$ are estimated to be capable of running quantum circuits which can solve industrially relevant problems | Unknown |

### Initialization fidelity

The initialization fidelity is not mentioned explicitly in either IBM's metrics or the workshop. Instead, it is mentioned by DiVincenzo as an additional minimal criterium for QPUs to function as described in section 3.2.3. The initialization fidelity refers to the degree to which a qubit can be prepared in a desired quantum state. The initialization fidelity is connected to the second DiVincenzo criterium of *initialization of the qubits to a simple initial state* [66].

The initialization fidelity or initialization error rate is currently not incorporated into the model because the share of the initialization error rate to the overall error rate is negligible. Therefore, it is hard to estimate what desired values for the initialization error will be once they do become significant. Accordingly, once more knowledge regarding the desired value range for the initialization error is attained, and its share becomes substantial, the initialization fidelity should become part of the model.[8]

### Measurement or readout fidelity

Measurement fidelity, also called readout fidelity, refers to the accuracy with which classical information can be extracted from a qubit and is derived from the expert workshop 3.2.1. The desired value of the readout fidelity is as close to 100% as possible [68].

Similarly to the initialization fidelity, the share of the measurement fidelity and, thus, the measurement error rate is currently negligible compared to the gate error rate. Therefore, the measurement fidelity or error rate is not considered to be part of the model for now. Equivalently to the initialization fidelity, the measurement fidelity should be included in the model once its results become significant.[9]

### Gate operating speed

The gate operating speed is mentioned as crucial by IBM in 3.2.2. It addresses the average time to perform one gate operation. The slower the gate operating speed, the fewer total gates can

[8] Based on an expert interview with interviewee A.
[9] Based on an expert interview with interviewee A.

be performed before the QPU decoheres and, thus, the less useful the QPU becomes. The gate operating speed is directly related to the coherence time and the gate error rate via the following simplified formula:[10]

$$Gate\ error\ rate = \frac{Gate\ operating\ speed}{Coherence\ time}$$

Because the gate error rate and the coherence time are separately incorporated into the model, it is not deemed necessary to also include the gate operating speed, as it naturally follows by defining the other two metrics.

### Off-on ratio

The off-on ratio is not mentioned in the expert workshop or IBM's metrics, but derived from a later paper by DiVincenzo, describing the ratio as crucial to the minimum functioning of a QPU, as mentioned in 3.2.3. A programmed sequence of gate operations, or specific coherent couplings between specified qubits, are necessary to run a quantum algorithm. This coupling should be equal to zero when there is no operation specified. The off-on ratio $R$ measures the extent to which these couplings can really be turned off. Therefore, a high-quality quantum computing processor has a desired value of $R$ as close to 0 as possible [68].

This KPI is not used in the final model for two reasons. First of all, this KPI is intrinsically linked to the initialization fidelity as described in section 3.2.4. If the initialization fidelity is high, the off-on ratio automatically is low, as they describe the same process. Secondly, the initialization fidelity is used instead of the off-on ratio because it is more widespread in the literature. The off-on ratio is mentioned rarely except for the paper it originated from [68].

### (Operating) temperature

The operating temperature is a metric that arose from the expert workshop as described in section 3.2.1. The operating temperature varies significantly between qubit architectures. NV center-based qubits function at room temperature, whereas spin qubits need around 100 mK - 1K, and superconducting qubits operate at an even less sustainable 15 mK. Such cold temperatures are relatively hard to achieve for a large amount of space, thus obstructing the scaling potential of quantum processors [71].

Nevertheless, the operating temperature is not incorporated into the final model for several reasons. First of all, the temperature necessary for qubits to operate is achievable for a space large enough to fit current quantum processor sizes. Furthermore, the operating temperature is not directly a measure of the well-functioning of a quantum processor. It is merely a checkbox to be ticked off for the processor to work.

Despite this, the importance of continuous development of cryostats large enough to fit upcoming quantum processors cannot be denied. Therefore, this development is incorporated into the *complementary products and services* building block.

### Quantum-classical interaction

This metric is mentioned by IBM in section 3.2.2 as foundational for the speed and, thereby, the usefulness of a quantum computer. This is indisputable because a quantum processing unit is worthless unless it is controlled in some form by a classical computer. The elementary nature of this orchestration is also seen in most of the DiVincenzo criteria. This renders the quantum-classical interaction not a concrete KPI but instead a checkbox inherent to the functioning of a QPU. Therefore, this criterium is not used in the final model.

[10] Based on an expert interview with interviewee A.

### Qubit count

The qubit count is considered to be a vital metric by both IBM and the expert workshop, as mentioned in sections 3.2.2 and 3.2.1, respectively. The threshold for the number of qubits above which quantum computing becomes useful is dependent on the application and whether the goal is to run NISQ applications or to wait until the universal fault-tolerant era has begun. Furthermore, the number of qubits necessary to run a certain algorithm can be reduced by applying error correction. This requires several tens of physical qubits that combined become one logical qubit. Because the so-called 'code rate', the ratio of X physical qubits : 1 logical qubit required is yet unknown, the order of magnitude of physical qubits required for fault-tolerant quantum computing is uncertain.[11] A visualization of the NISQ and universal fault-tolerant era and their relation to the qubit count and error rates is given in figure 3.6.

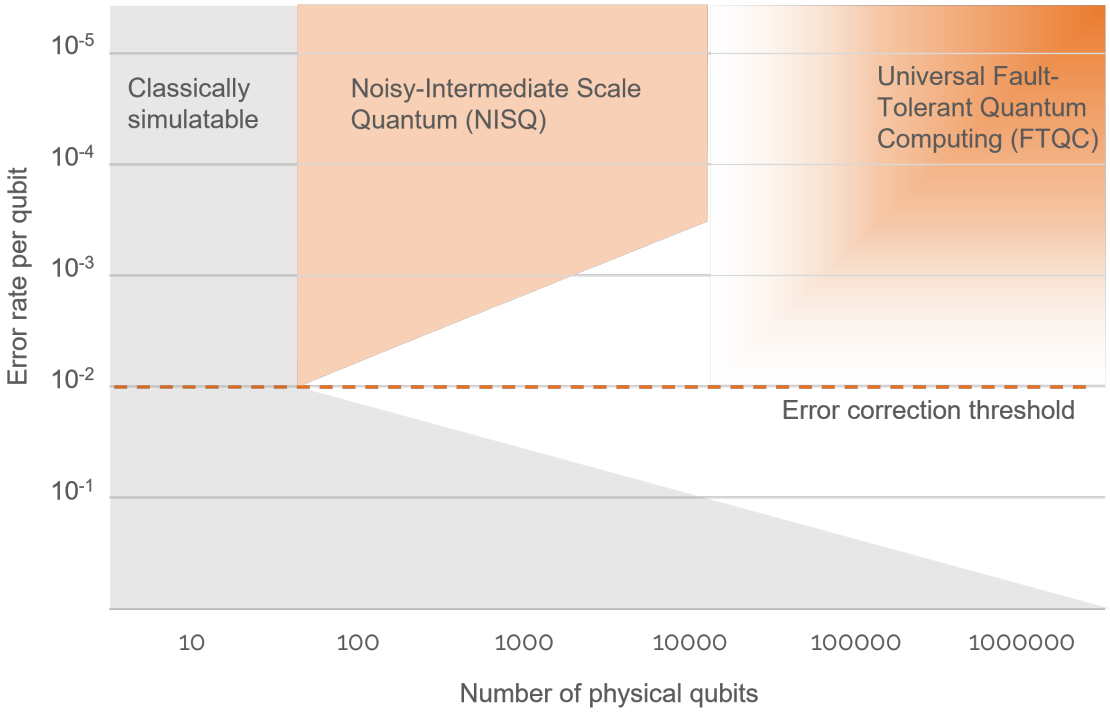


*Figure 3.6: The error rate per qubit and the amount of physical qubits required for the NISQ era and the Universal Fault-tolerant era. The NISQ era starts >50 physical qubits and is above the error correction threshold. The exact boundaries of the UFTQC era remain vague due to the yet unknown code rate but are estimated to be around $10^5$ - $10^7$ physical qubits and somewhere above the error correction threshold. Based on a figure provided by Orange Quantum Systems*

The maximum amount of qubits that is classically simulatable is a hard boundary at 50 qubits, as explained in section 1.1.4. Furthermore, the error tolerance threshold is also a set boundary at $10^{-2}$ as explained in section 1.1.4 as well. The division into red, orange, and green for this KPI is as follows:
The qubit count is considered to be completely unsatisfactory, and thus red below 50 qubits because this is the classically simulatable boundary. Currently, quantum processing units are entering the NISQ era, thereby entering the yellow status as seen in table 3.4. This is most likely where the QPUs of the coming 5 - 10 years will operate. The qubit count is considered to be satisfactory, or green, only when the universal fault-tolerant quantum computing age has been reached. The roadmap of IBM estimates that the UFTQC era will be achieved in 2033 at the earliest.[12] The various thresholds for the colors are summarized in table 3.2.4.

[11] Based on an expert interview with interviewee C.
[12] https://research.ibm.com/blog/100k-qubit-supercomputer

As mentioned in section 1.1.5, the applications of universal fault-tolerant quantum computing can be subdivided into three main categories of algorithms. For each of these categories, a more specific 'useful threshold' within the universal fault-tolerant quantum computing era can be given:

- The most concrete threshold can be given for the application *breaking cryptography*. To break the RSA-2048 protocol, the famous Shor's algorithm should be run on a quantum computer. Recent research found that this can be done on a noisy quantum computer within eight hours if using 20 million physical qubits [29].
- The category of *quantum simulation* is harder to estimate because of its significantly larger variety of algorithms. However, for one specific problem, the simulation of the $Fe_7MoS_9C$ cofactor, or FeMoCo for short, a specific estimate has been found. This simulation is relevant for significantly reducing carbon emissions in the production of artificial fertilizer. Lee et al. [72] found that this simulation can be run in approximately four days, using around 4 million qubits.
- For the third category of *optimization*, giving estimates of the amount of qubits needed to solve a problem is virtually impossible because the algorithms needed to solve optimization problems have not been developed enough yet.

A more closely reachable threshold is the definitive reach of quantum advantage. As mentioned in section 1.1.4.

A paper published in 2021 established a more concrete threshold, which is reachable in the very near future [73]. The simulations described in this paper would take a supercomputer with $10^(17) - 10^(18)$ Floating-Point Operations per Second (FLOPS) one century to perform, thus officially classifying as 'undoable in a reasonable amount of time'. The exact amount of qubits and gates needed to reach quantum computational advantage is calculated for three families of quantum circuits:

- Instantaneous Quantum Polynomial-time (IQP) circuits would need 208 qubits and 500 gates.
- Quantum Approximate Optimization Algorithm (QAOA) circuits would need 420 qubits and 500 constraints.
- Boson Sampling Circuits, such as optical networks, would need 98 photons and 500 linear optical elements.

*Table 3.4: Definition of the red, yellow, and green thresholds and when they are expected to be reached for the KPI qubit count. Currently, the qubit count is considered yellow.*

| **Qubit count** | |
|---|---|
| **Red** | |
| **Threshold** | **Reached in** |
| Anything which is classically simulatable, which is up to 50 qubits. | Before 2019 |
| **Yellow** | |
| **Threshold** | **Reached in** |
| Anywhere between 50 and $10^3$ - $10^4$ qubits. | 2019 - $\pm$2033 |
| **Green** | |
| **Threshold** | **Reached in** |
| The universal fault-tolerant quantum computing era, which requires around $\pm 10^5$ qubits. | 2033+ |

### Quantum volume

The quantum volume is a metric first devised by IBM as described in section 3.2.2 to convey a more holistic view of the performance of a quantum processor. The quantum volume is a function of two metrics. The first metric is the circuit depth, which is an expression of the fidelity of the processor. A higher circuit depth means more calculations can be performed before the qubits decohere. The second metric of circuit width is related to the number of qubits present on the processor and the way in which they are connected. The circuit depth and width can be expressed on a log scale [7].

Figure 3.7 shows four different scenarios for the development of quantum processors and their corresponding maximum quantum volume as a function of their circuit depth and width.

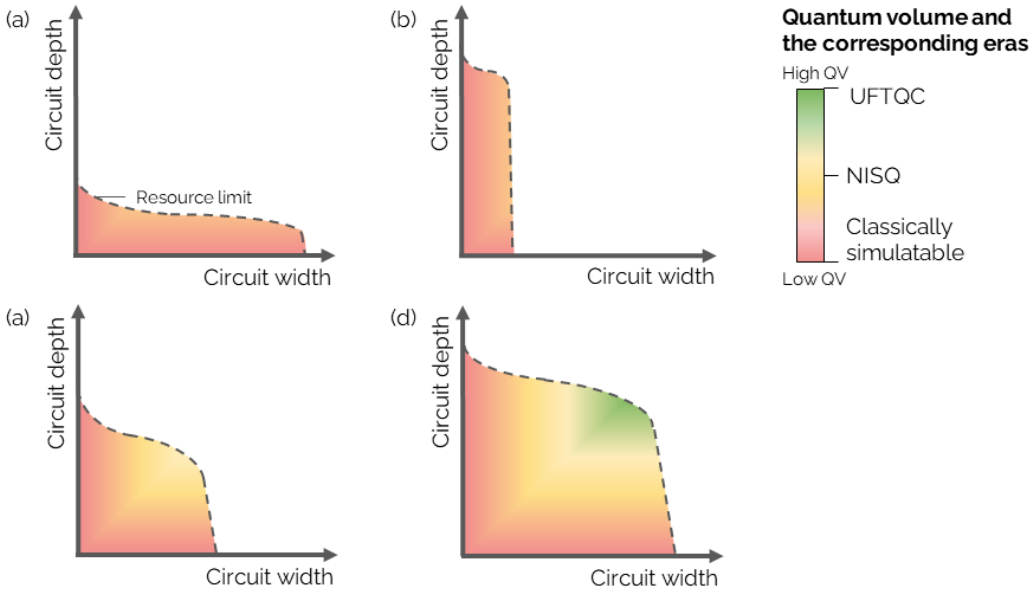


*Figure 3.7: Four different scenarios for the development of quantum processors based on the maximum achievable circuit depth and width. Both (a) and (b) represent an undesirable scenario where either the qubit fidelity (a) or the number of qubits (b) is a severely limiting factor. Scenario (c) represents a slightly better quantum volume. However, development beyond NISQ applications remains unfeasible. Only in scenario (d), the total achievable quantum volume is sufficient to reach the universal fault-tolerant quantum computing era. Based on [7].*

Figure 3.7 (a) shows a scenario where the number of qubits can be increased, but the fidelities of those qubits do not, thus severely limiting the circuit depth and, thereby, the maximum reachable quantum volume. Figure 3.7 (b) shows a scenario where the fidelities of the qubits increase, but the maximum amount of qubits on a processor is a limiting factor, thus resulting in a similar maximum achievable quantum volume as in scenario (a). Both scenarios (a) and (b) are considered to be below the red threshold [7]. Currently, the quantum volume is nearing the end of the red era as seen in table 3.5.

Figure 3.7 (c) represents a more proportionate but still undesirable scenario, where both the qubit fidelities and the number of qubits increase somewhat but not enough to reach the universal fault-tolerant quantum computing era. Scenario (c) coincides with the era of NISQ applications and is given the predicament yellow [7].

Lastly, figure 3.7 (d) represents the most desirable scenario where both the qubit fidelities and the number of qubits can be increased enough to obtain a quantum volume corresponding to the UFTQC era. Therefore, (d) is qualified as the green scenario [7].

*Table 3.5: Definition of the red, yellow, and green thresholds and when they are expected to be reached for the KPI quantum volume. Currently, the quantum volume is considered red.*

| Quantum volume | |
|---|---|
| **Red** | |
| **Threshold** | **Reached in** |
| Either the qubit fidelities, corresponding to scenario (a) of figure 3.7, or the number of qubits corresponding to scenario (b) of figure 3.7 remain a seriously limiting factor to the quantum volume. | Current value |
| **Yellow** | |
| **Threshold** | **Reached in** |
| Both the qubit fidelities and the number of qubits can be improved slightly, but not enough to reach the UFTQC era. The maximum quantum volume achievable remains mediocre. Corresponds to scenario (c) in figure 3.7. | Unknown |
| **Green** | |
| **Threshold** | **Reached in** |
| The qubit fidelities and the number of qubits can be improved significantly, thus enabling quantum volumes large enough to reach the UFTQC era. Corresponds to scenario (d) in figure 3.7. | Unknown |

### Qubit Yield

The qubit yield is emphasized as an important quality metric by both IBM, as described in section 3.2.2, and the workshop, as described in section 3.2.1. In order to create functioning quantum computing chips with a high amount of qubits, it is paramount to maximize both the qubit yield and the chip yield. Logically, the threshold for the qubit yield is as close to 100% as possible. However, due to a wide variety of potential defects, the qubit yield is always lower than 100%. The qubit yield can be defined as [13]:

$$Qubit\ yield = \frac{The\ number\ of\ qubits\ actually\ produced}{The\ maximum\ number\ of\ qubits\ designed} * 100\%$$

Where the number of qubits actually produced is determined via testing to see how many of the planned qubits perform as expected.

To compute the quantum processor yield, the qubit yield is taken to the power of the number of qubits on the quantum processor:

$$Quantum\ processor\ yield = qubit\ yield^{amount\ of\ qubits\ on\ one\ processor}$$

Because of the power in the formula, the qubit yield needs to be incredibly high in order to create a significantly lower quantum processor yield, as visualized in figure 3.2.4. With a qubit yield of $99\%$, the quantum processor yield at 100 qubits is only $37\%$. To be able to achieve a $10\%$ quantum processor yield at 1.000.000 qubits, a qubit yield of at least $99.99977\%$ is required.

An alternative to significantly increases the qubit yield in order to reach quantum computing processors with high qubit counts would be to connect several quantum processors together. In this way, ten processors containing 100 qubits each could create one bigger joint processor

[13] Based on an expert interview with interviewee B.

of 1000 qubits, which is possible with a qubit yield of $97.7\%$ instead of the otherwise required $99.7\%$.

Due to its sensitive nature, quantum manufacturers are reluctant to show qubit or quantum processor yield information. However, a recent paper by Zwerver et al. [74] demonstrated a maximum yield of 98% at room temperature on their best-performing wafer and a lower, unknown yield when testing at temperatures closer to the operating temperature.

Since connecting several quantum processors has not been proven possible yet, the qubit yield is still far from the $99.99977\%$ necessary to create a 1-million qubit processor with a $10\%$ yield rate.

The qubit yield is deemed to be completely unsatisfactory and thus red as long as it remains below $99\%$. This results in a quantum processor yield of $37\%$. Currently, a qubit yield of $99\%$ has not yet been achieved, and therefore this KPI remains red as seen in table 3.6 [14].

The green lower boundary is set at $> 99.9977\%$ because this allows for a quantum processor with 100.000 qubits with a processor yield of $10\%$. If it becomes possible to connect several quantum computing processors together in the future, this lower bound can be lowered drastically [15].

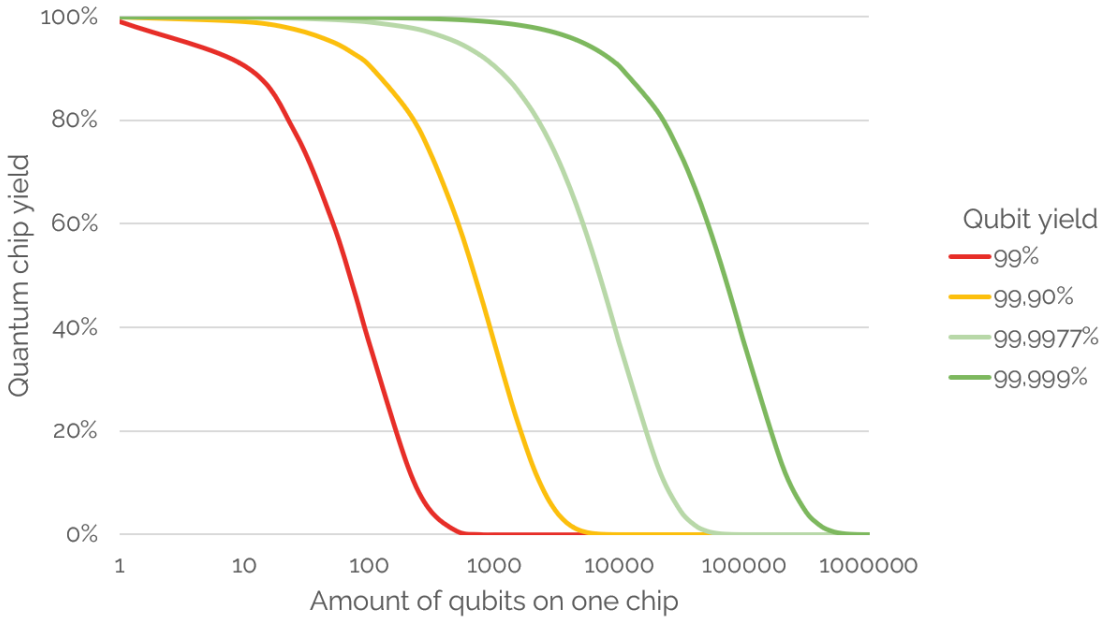


*Figure 3.8: The quantum processor yield in % per amount of qubits per processor. The quantum processor yield is plotted for four various qubit yield factors.*

The semiconductor chip yield follows the same scaling laws and thus exhibits similar behavior, creating one of the biggest bottlenecks in semiconductor chip manufacturing. Reportedly, the yield rates of Samsung and TSMC are around 10%-20% and 60%-80%, respectively, for 3 nm chips[16].

Note that the qubit yield is mentioned in this section because the members of the workshop indicated it as one of the KPIs for the *product performance and quality* building block. Nevertheless, further research indicated that this KPI is a better fit with the *production systems* building block as described in section 3.4 and is therefore included in that section in the final model.

[14] Based on an expert interview with interviewee B.
[15] Based on an expert interview with interviewee B.
[16] https://www.tomshardware.com/news/analysts-estimate-tsmc-n3-yields-between-60-and-80-percent

*Table 3.6: Definition of the red, yellow, and green thresholds and when they are expected to be reached for the KPI qubit yield. Currently, the qubit yield is considered red.*

| Qubit yield | |
|---|---|
| **Red** | |
| **Threshold** | **Reached in** |
| Qubit yield $< 99\%$ | Current value |
| **Yellow** | |
| **Threshold** | **Reached in** |
| Qubit yield $99\% - 99.9977\%$ | Unknown |
| **Green** | |
| **Threshold** | **Reached in** |
| Qubit yield $> 99.9977\%$ | Unknown |

### Stability

The stability of a quantum processor is one of the key performance indicators that arose from the workshop given to quantum experts, as described in section 3.2.1.

The overall stability of the processor is undoubtedly very relevant to the quality and performance of the final product. However, no single unambiguous KPI to describe the overall stability of a quantum processor exists so far. Instead, the stability of the processor is captured partially in the coherence time as described in section 3.2.4 and the various error rates and thus the fidelities as described in section 3.2.4.

Therefore, despite its relevance, stability is not directly used in the final model. Nevertheless, as the research surrounding quantum chips progresses, the stability might be added separately later as an appropriate KPI is found.

### 3.2.5 Combined model product performance and quality

In section 3.2.4 for each of the KPIs that was mentioned in either the workshop, IBMs metrics, the DiVincenzo criteria, or the literature, a brief explanation of why that specific KPI is or is not considered in the final model, is given. The KPIs that were considered vital for the end goal of *'predicting when mass diffusion of quantum processor units can occur'* are subdivided into three categories:

- **Scale**. The scale is fundamental for a well-functioning QPU, as most useful algorithms need a significant scale-up compared to what is currently on the market before they can be run. Thus the performance and quality of a QPU are highly dependent on the achievable scale. The scale has just one relevant KPI: the *amount of (logical) qubits* a device has.
- **Quality**. Despite the quality already being mentioned in the name of the building block, it is considered to be the most suitable name to express the nature of both of the KPIs for this category. The KPIs are the *coherence time* and the *gate fidelity/gate error rate*. Any other KPIs mentioned in this category are either not yet relevant or can be captured indirectly in either the gate fidelity or the coherence time.
- **Usefulness**. The last category involves two KPIs which are related to how well certain algorithms will perform on the quantum processor. These are IBM's *quantum volume* and the *connectivity* or *topology*.

The three final categories of *product performance and quality*, including the five key performance indicators necessary to allow for mass diffusion of a quantum processing unit, are visualized in figure 3.9.

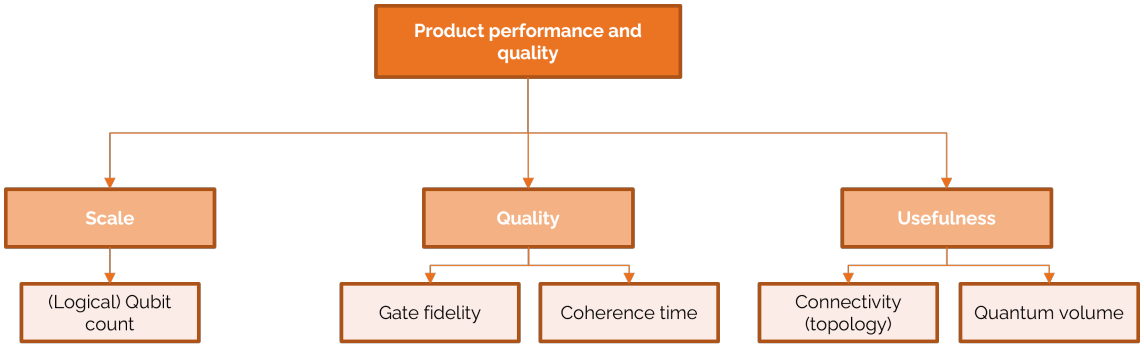


*Figure 3.9: The final model for the building block of product performance and quality, subdivided into three categories and five KPIs.*

### 3.2.6 Bottlenecks within product performance and quality

Multiple bottlenecks for the building block *product performance and quality* were identified. The current amount of (logical) qubits is labeled as yellow, as the amount of qubits that is classically simulatable has recently been exceeded consistently, but it is nowhere near the desired value required for complex applications. Therefore, it is not considered to be a severe impedance but not fully developed either.

The current quality of QPUs is a severe bottleneck for the potential of mass diffusion. Both of the KPIs determining the quality, the gate fidelity, and the coherence time are labeled red due to their inferior performance. As long as both are not improved significantly, the quality and, thereby, the entire building block will remain red for some time in the future.

The last category of usefulness is also still labeled as an impedance to the possibility of mass diffusion because the quantum volume, which is strongly connected to the other KPIs

of scale and quality, is currently inferior. Once the quantum volume is improved, the usefulness will immediately switch to yellow, as the other KPI of connectivity already reached this predicament.

To conclude, the overall *product performance and quality* is severely impeded due to inferior performance of the gate fidelities, the coherence times, and the quantum volume, as visualized in figure 3.10.

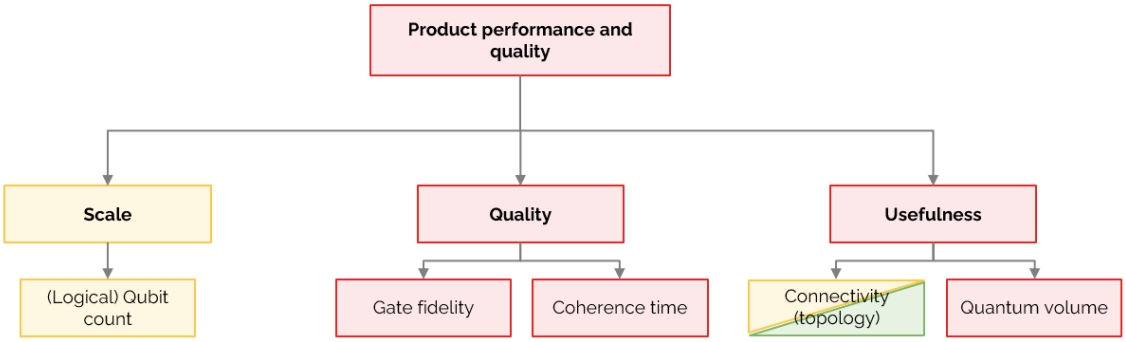


*Figure 3.10: The bottlenecks hampering the overall performance and quality of quantum processors currently are the quality, due to a low gate fidelity and coherence time, and the usefulness, as a result of a low quantum volume. Because the building block is only as good as its weakest component, the product performance and quality is considered red.*

## 3.3 Product profitability

For a product to develop past the pre-diffusion stage, not only the price but also the cost of production is important. As long as these costs remain astronomical, production will lag or remain in the academic research phase, and the product will not be able to start mass diffusing. Therefore, an amendment is made to the original model of Ortt and Kamp [50] as described in section 3.3.1.

After this amendment is clarified, first, the costs of a quantum chip are described in section 3.3.2. Thereafter, the revenue of the chips is described in section 3.3.3, which is in turn divided into the original building block of the product price in section 3.3.3. Revenue is likewise dependent on quantity. However, this metric is part of the production system, as described in section 3.4.

### 3.3.1 Price–cost relationship

Contrary to the relatively predictable downward-sloping cost curve, the price curve is anything but predictable. This is mainly due to the fact that the price of a certain product is generally not much more than a strategic choice made by the company producing the product. The company can decide on various strategies, with the most straightforward strategy being one where an arbitrarily chosen profit can be made from the start.

However, a choice could also be made to start at a considerably lower price point and thus at a loss, knowing that the cost will eventually decrease. There are various reasons for adopting a loss-making strategy. For example, governmental subsidies can help markets to enter the mass-diffusion phase by funding products to create an artificially lowered price point substantially lower than the cost price.

Another reason could be to obtain a large market share quickly or to generate publicity for the company and thus out-compete competitors in the long term. An example of a successful company that has been able to operate at a lower price point in exchange for publicity is Amazon. Using this strategy has allowed them to survive the dot com bubble, and thrive afterward, despite officially never having been profitable [75].

Because of this, the product price does not have a direct relationship with the product cost. Instead, price is dependent on the well-known combination of the supply and demand curve, together with the quantity of the product, as shown in figure 3.13.

Nevertheless, the importance of the cost of production for the overall diffusion of a product cannot be denied. Therefore, an amendment to the original model of Ortt and Kamp [50] is suggested.

Since there is no direct link between cost and price, cost is included as a separate category. To be able to differentiate between the one-off costs of, for example, the infrastructure needed to manufacture chips and the recurring costs, such as resources and man hours, the cost category is subdivided into variable and fixed costs.

As the supply and demand curves show, the price of a product is intrinsically linked to the quantity produced of said product. However, the quantity is covered in the production system of this model, as described in 3.4.

These additions result in the updated version of the second building block. The building block is renamed to *Product profitability* because the product price is already contained in one of the subdivisions. Note that despite the implication that some sort of profit is gained, making an actual profit is not necessary for mass diffusion, as proven by Amazon [75]. The final version of the second building block is visualized in figure 3.13.

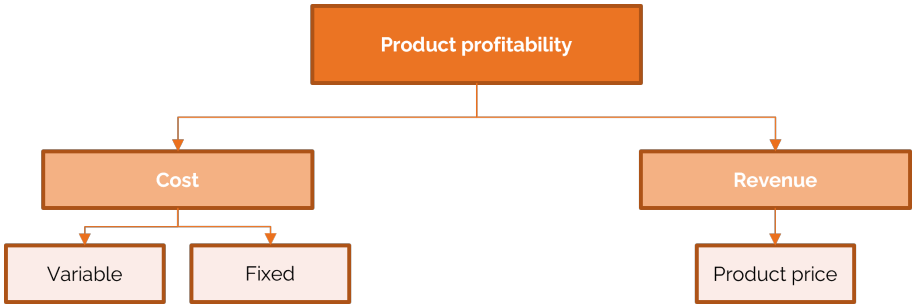


*Figure 3.11: The profitability of a product can be split into the costs, which can either be fixed or variable, and the potential revenues, which are dependent on the quantity and price at which the product is sold.*

### 3.3.2 Cost

The current exact costs per quantum processor are unknown. However, the fixed cost of building a state-of-the-art facility to create chips can be derived from the costs incurred by universities and the statements from the quantum manufacturers who went public, as described in section 3.3.2. Furthermore, the variable costs to produce quantum chips will reduce drastically as more experience is gained according to the experience curve, as described in section 3.3.2.

#### Fixed cost

The incurred costs per qubit architecture differ substantially due to the vastly different manufacturing methods and equipment required. A small-scale facility to manufacture superconducting transmon quantum processing units costs around $40 million, as based on the financial statement of Rigetti [76]. Note that this only includes the fixed cost of building the facility. Costs related to maintenance and daily use are disregarded.

A manufacturer of spin qubits needs, among others, a UV technology-based machine as provided by ASML, which, depending on the version, costs between $150 million and $300 million each [17]. Given that one machine most likely does not provide all functionalities needed, the total cost of a spin qubit manufacturing facility is even higher.

For the other types of chip architectures, ballpark cost figures are more uncertain because there are no public financial statements from companies using other manufacturing methods. However, the order of magnitude of the cost is expected to be comparable to those of manufacturing superconducting or spin qubits.

Currently, expensive manufacturing facilities are only reserved for either highly funded specialized scale-ups (such as Rigetti [76]) or major established corporates such as Google and IBM. However, most future consumers of QPUs will simply buy QPUs instead of manufacturing them themselves. Therefore, only a handful of companies that can afford the appropriate manufacturing facilities are deemed enough because these pioneers can set high initial prices due to their near-monopoly position to earn back their high investments, attracting competition, which will, in turn, ultimately lower the prices.

Thus, despite the high prices, the fixed costs are currently rated green, as shown in table 3.7. Nevertheless, to eventually become profitable, the quantity of QPUs produced and, therefore, the production facilities will have to ramp up significantly.

[17] https://www.reuters.com/technology/intel-orders-asml-machine-still-drawing-board-chipmakers-look-an-edge-2022-01-19/

*Table 3.7: Definition of the red, yellow, and green thresholds and when they are expected to be reached for the KPI fixed cost. Currently, the fixed cost is considered green.*

| Fixed cost | |
|---|---|
| **Red** | |
| **Threshold** | **Reached in** |
| Neither academic labs nor commercial labs can afford a production facility. | - |
| **Yellow** | |
| **Threshold** | **Reached in** |
| Only academic labs can afford limited production capabilities, thus significantly hampering commercial scale-up. | - |
| **Green** | |
| **Threshold** | **Reached in** |
| Specialized manufacturers can afford their own production facilities. | Some specialized players can already afford their own production facilities. |

### Variable cost

The exact variable cost for quantum processing units is unknown but expected to be disproportionally high due to the very limited quantity that is currently being produced, mainly by hand, by expensive, highly specialized professionals. Nevertheless, these costs are expected to reduce drastically in the future. The rationale behind this cost reduction can most easily be explained via the experience curve, also called Wright's Law, introduced by the founder of the Boston Consulting Group (BCG). The experience curve was first formulated in research regarding the cost analysis of a major semiconductor manufacturer[18]. The experience curve is closely related to the learning curve, which is also mentioned as one of the underlying principles of Moore's Law, as described in section 2.1.1.

The experience curve is an explanation for the relationship between knowledge or experience and cost. It shows that *"costs decline by some characteristic amount each time accumulated experience is doubled"* [77]. Surprisingly enough, data shows this decline is rather consistent over time, even from industry to industry [77]. Mathematically, the experience curve can be expressed as [78]:

$$C_t = C_0(P_t/P_0)^{-a}$$

Where:

- $C_0, C_t$ = cost per unit (corrected for inflation) at times $0$ and $t$ respectively,
- $P_0, P_t$ = accumulated volume of production at times $0$ and $t$, respectively,
- $a$ = constant, which reflects the elasticity of unit costs to accumulated volume.

The potential for cost reduction is the greatest in fast-growing industries and industries with strong experience effects [78]. The semiconductor industry is a textbook example of such an industry, as can be seen in the relative manufacturing cost per component in the early days of semiconductor chip manufacturing in figure 3.12 [8]. Due to its likewise fast-growing nature and overall similarity to the semiconductor industry, the quantum industry also has great potential for cost reduction.

[18] https://www.bcg.com/publications/1968/business-unit-strategy-growth-experience-curve

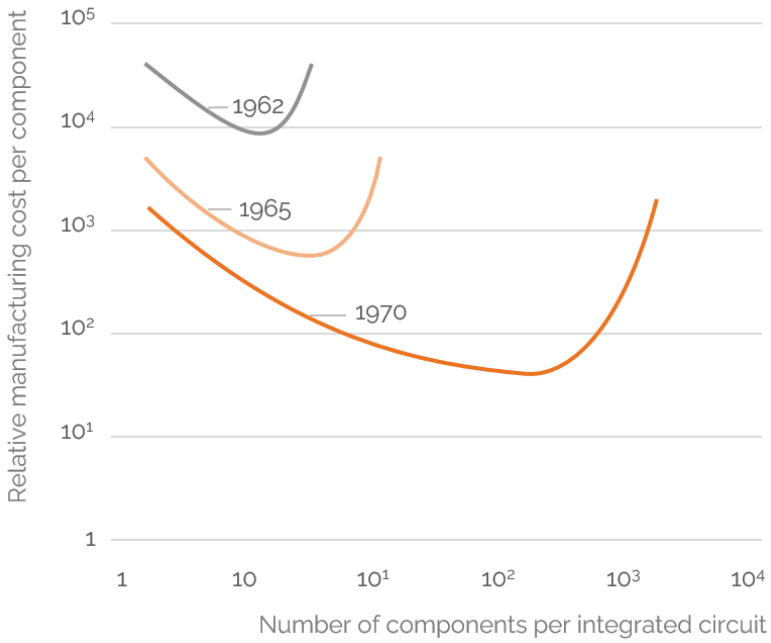


*Figure 3.12: The relative manufacturing costs per component relative to the number of components per integrated circuit for 1962, 1965, and 1970, based on [8].*

The effects of the experience curve can be measured in each stage of the value-added chain, although the strength of the effect differs per stage, with the strongest effects seen in manufacturing and assembly and the weakest effects in R&D and retailing [78].

Several factors responsible for the systematic decrease of cost with accumulated volume can be established [78]:

- Learning. Productivity per worker increases with increased dexterity due to skill development.
- Specialization of redesign and labor tasks. Historically proven, an increase in volume will allow for specialization and standardization of labor, which contributes to overall productivity.
- Product and process improvements such as modifications to the product, more efficient utilization and substitution of materials, and overall manufacturing process improvement, which all originate from the experience that comes with larger volumes.
- Methods and systems rationalization. Adopting a standardization of the process along with opportunities to improve performance by using more up-to-date technology allows for better coordination and, thus, the efficiency of the process.
- Economies of scale or the decrease of the unit cost that comes with a production increase. The main contributing factors to the economies of scale are:
  - Improved technological processes for higher volumes.
  - Resources can only be profitably used at a larger scale.
  - Possibilities arise for integrating manufacturing processes for several different business opportunities for large firms in stable environments.
  - Lowering of shared fixed costs, such as overhead costs.
- Organizational 'tune-up'. A more subtle sign of experience, which expresses itself in overall technological know-how within the company and more well-developed formal systems. Despite being subtle, this organizational tune-up can provide a valuable competitive edge to a firm.

It is important to note that the cost reductions resulting from the experience curve do not 'magically' occur. Despite the aforementioned factors, competent management capable of

continuously improving and providing internal pressure to change is paramount [78].

The variable costs for QPUs are currently labeled as red because the currently insufficient accumulated volumes result in astronomical variable costs per QPU produced, as the benefits of the experience curve cannot be reaped yet. Once the effects of the experience curve start to take hold, this label is expected to switch to yellow quickly, as visualized in table 3.8. The green color will be achieved once variable costs have declined significantly and become almost negligible compared to the fixed costs per chip.

*Table 3.8: Definition of the red, yellow, and green thresholds and when they are expected to be reached for the KPI variable cost. Currently, the variable cost is considered red.*

| Variable cost | |
|---|---|
| **Red** | |
| **Threshold** | **Reached in** |
| Quantum chip manufacturers only produce a handful of chips, resulting in low accumulated volumes and, thus, astronomical variable costs per unit. | Current value |
| **Yellow** | |
| **Threshold** | **Reached in** |
| Accumulated experience has doubled several times, creating a significantly lower but still relatively high variable cost per QPU. | Unknown |
| **Green** | |
| **Threshold** | **Reached in** |
| Variable costs have declined significantly and are almost negligible compared to the fixed costs per chip | Unknown |

### 3.3.3 Revenue

The category of 'revenue' might seem irrelevant for the greater purpose of this model. After all, generating a lot of revenue is not necessarily mandatory for a product to start diffusing at a large scale [75]. However, the importance of the underlying building block of *product price* and the intrinsically linked production system building block of *quantity* cannot be denied. Thus the overarching category of *revenue* is born, as

$$Product\ price * Quantity = Revenue$$

Despite the fact that the current product price of quantum processing units is uncertain, basic economics can still provide some clarity on when prices will become more competitive, as described in section 3.3.3.

#### Product price

Any information regarding the current pricing of quantum processing units is highly sensitive and thus neither publicly provided nor available through expert interviews. Thus, little can be said about the current chip price and its feasibility for potential customers. Therefore, the

product pricing KPI is not based on industry information but instead reasoned from a classical economics perspective.

Ultimately, the question remains when the price of a quantum computing chip is considered 'reasonable enough' to allow for large-scale diffusion. At the moment, prices are unknown, and production costs are astronomical. Nevertheless, chips are already sold sparingly in the R&D field, and some quantum chip manufacturing companies have even been able to go public, be it in a questionable manner[19].

This shows that there is already some demand for quantum computing chips, and as soon as their performance and quality are improved, as described in section 3.2, this demand is expected to rise aggressively due to the wide range of potentially disruptive applications.

The relationship between the demand and the sparse supply can be illustrated with basic economics in the well-known supply and demand curve. However, the supply curve is relatively short and shifted upwards because it is restricted by non-price factors such as a (human) resource shortage, technological lag, and very limited production capacity, as shown in figure 3.13. The demand curve shows no restrictions, as there are little to no anomalies on the demand side[20].

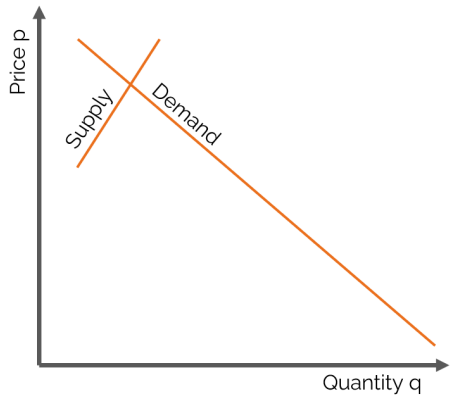


*Figure 3.13: Supply and demand plotted as functions of quantity and price. Adapted from https://www.britannica.com/topic/supply-and-demand.*

Figure 3.13 also shows how these supply restrictions cause the demand to be relatively low at a relatively high equilibrium price, indicated by the junction between the supply and demand curves[21].

At present, some products are already sold, be it in very low quantities. Therefore, there is some supply, but demand still significantly outnumbers the supply, resulting in the current predicament of yellow for the product price, as depicted in table 3.9.

If the non-price factors are compensated for in the future, the supply curve will shift downward, causing the quantity to go up and the equilibrium price to go down simultaneously, creating a significantly more attractive market and thus resulting in the green scenario.

[19] https://www.wired.com/story/quantum-startups-stock-market-dreams-are-decohering/
[20] https://www.britannica.com/topic/supply-and-demand
[21] https://www.britannica.com/topic/supply-and-demand

*Table 3.9: Definition of the red, yellow, and green thresholds and when they are expected to be reached for the KPI product price. Currently, the product price is considered yellow.*

| Product price | |
|---|---|
| **Red** | |
| **Threshold** | **Reached in** |
| Product cannot be sold yet due to astronomical prices. Only used in the academic community or for internal R&D. | - |
| **Yellow** | |
| **Threshold** | **Reached in** |
| Some products are sold, but prices are too high, resulting in a very select group of customers | Current situation |
| **Green** | |
| **Threshold** | **Reached in** |
| Supply curve shifted to the right significantly, price range becomes feasible for many companies. | Unknown |

### 3.3.4 Bottlenecks within product profitability

The building block *product profitability* consists of three KPIs, the fixed and variable cost and the product price. The fixed costs are currently not posing any form of problem for mass diffusion to occur potentially and are thus labeled green. The product price is currently not at the desired level due to the constraints put on the price by the sparse supply. Nevertheless, the price range is not considered to be fully restrictive either and is therefore labeled yellow.

The biggest bottleneck within the *product profitability* is the variable cost or the cost per unit produced. These costs are currently astronomical because the processors are still manually produced in small batches, labeling the variable cost and, thereby, the entire building block red. Nonetheless, Wright's theory predicts that with accumulated experience, the variable cost will go down considerably. Therefore, the variable costs are an easily conquerable bottleneck but a current bottleneck nonetheless. A summary of the final judgment for the product profitability is shown in figure 3.14

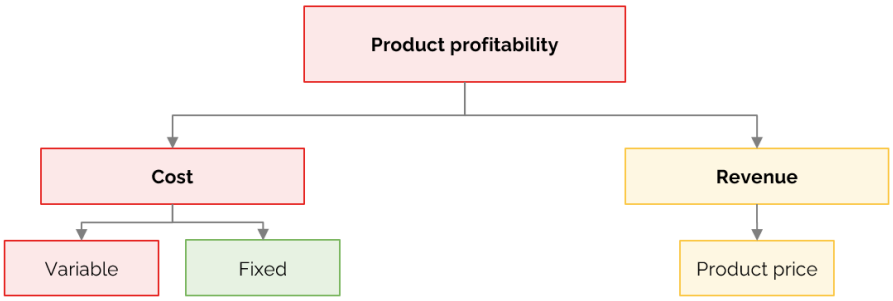


*Figure 3.14: The bottleneck hampering the overall product profitability of quantum processors is the variable cost. The fixed cost is considered fair and thus green. The current price is considered tolerable, thus yellow.*

## 3.4 Production Systems

The definition for the production systems from the paper by Ortt and Kamp [50] is *"The new technology needs to be delivered at high quality and in large quantities to enable mass diffusion"*. However, the goal of this model is to create distinct categories and KPIs with as little overlap as possible with the other building blocks. Given the fact that the quality is covered in the building block *performance and quality* as described in section 3.2, it will not be repeated in this section.

This leaves the quantity produced as the main category for this building block. To be able to reach a certain quantity, standardization and automation of the production methods are paramount. At present, small-scale state-of-the-art QPUs are mostly developed in academic environments and shared facilities, largely by hand, hampering the possibility of large-scale production and increasing the odds of production failure occurring due to human errors [9].

There are two probable ways in which production can both be standardized and automated in order to scale up. The first option is for companies to build their manufacturing facilities for quantum processors from scratch. However, this would require a vast amount of initial capital.

A second option is for current semiconductor manufacturers to convert some of their product lines to become quantum-compatible. However, it is improbable that high-end semiconductor chip manufacturers will do so anytime soon due to the high level of profitability semiconductor chips still provide. As long as Moore's law is continuously extended far beyond anything predicted initially, and the usefulness of QPUs has not been sufficiently proven, semiconductor manufacturers are not expected to take this risk. This effectively turns the availability of manufacturing lines via this second option into a chicken and egg problem, creating a strong interdependency between the *production systems* building block and the *product performance and quality* and *product profitability* building blocks [3, 9, 42, 79].

An interim solution to bridge this 'profitability gap' could be to implement pilot lines through public-private partnerships facilitated by, for example, Research and Technology Organisations (RTOs) and national laboratories. These pilot lines can be used to assess the requirements needed for automation using existing Complementary Metal Oxide Semiconductor (CMOS) production lines. The main goal of these pilot lines is to provide a short development cycle to continuously implement improvements before moving on toward high-volume production [9].

Regardless of whether manufacturing facilities will be built from the ground up or by converting existing semiconductor manufacturing facilities, some sort of standardized process needs to be put in place for the production system to become functional. Automation is not the only way to achieve this, but it is the most self-evident. To capture both the level of automation/standardization and the reduction of human errors without eradicating other, hitherto unexplored ways to manufacture the QPUs, the KPIs *total cycle time* and *yield* are suggested. These are process-agnostic KPIs that will remain relevant for the final product regardless of the manufacturing method.

The total cycle time entails the entire process, thus starting with the raw products, throughout the entire manufacturing process, up until the testing of the system to ensure the manufacturing process has succeeded. Only once the processor is tested en proven ready to use the total cycle time ends.

Because the (qubit) yield is also mentioned as a potential contender for the *quality and performance* KPIs, a more detailed elaboration of the yield and its associated red, yellow, and green thresholds is provided in section 3.2.4.

Next to the process-related KPIs, both the input and output of the process are vital. It is self-explanatory that without input, there will be nothing to manufacture to begin with. Hence the availability of raw materials commonly used in QPU manufacturing, such as rare metals, is imperative.

Furthermore, the quantity produced is intrinsically linked to all other product-related building blocks. The higher the quantity, the lower the relative cost, as predicted by the experience

curve explained in section 3.3.2. Besides positively affecting the cost and making the industry overall more attractive, the quantity produced and its associated experience are more likely to lead to breakthroughs in the overall quality of the product as more development cycles are passed. Despite the strong connection to the other building blocks, the quantity remains most suitable for the *production systems* building block as it is generally considered to be the main measure of production. A summary of the four essential KPIs for the *production system* is shown in figure 3.15.

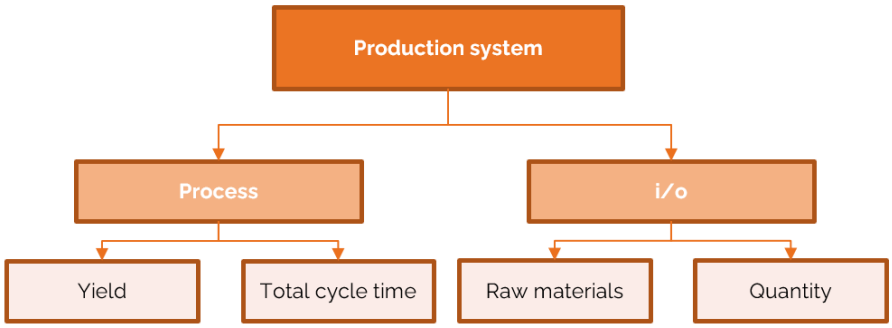


*Figure 3.15: The production system building block can be divided into two main categories: the process-related KPIs of yield and total cycle time and the input/output-related KPIs of the raw materials necessary to produce the QPUs and the number of QPUs produced.*

## 3.5 Complementary Products and Services

The scope of the model created in this thesis is limited to quantum processors, whose main desired function is to operate in a quantum computer. For a QPU to fully function as a part of this bigger picture, a multitude of relevant complementary products is required. Next to that, standardization, integration, and a mature supply chain consisting of high-quality components are paramount.

The various qubit architectures covered by this thesis each have their own distinct, complementary products necessary to create an operational quantum computer. However, the categories should be generalizable and are thus representable regardless of the qubit architectures. Nevertheless, it is inevitable to use architecture-specific KPIs.

Next to a QPU, all types of quantum computers require specific quantum-enabling technologies, such as control electronics, wiring, and architecture-specific hardware, such as cryogenics for those operating at cold temperatures and vacuums for trapped ion and cold atom qubits. Furthermore, quantum software is required to create and run quantum-specific algorithms, including a compiler and emulators, to make the translation from classical to quantum and back. An overview of these categories and an initial suggestion for their generic KPIs is provided in figure 3.16.

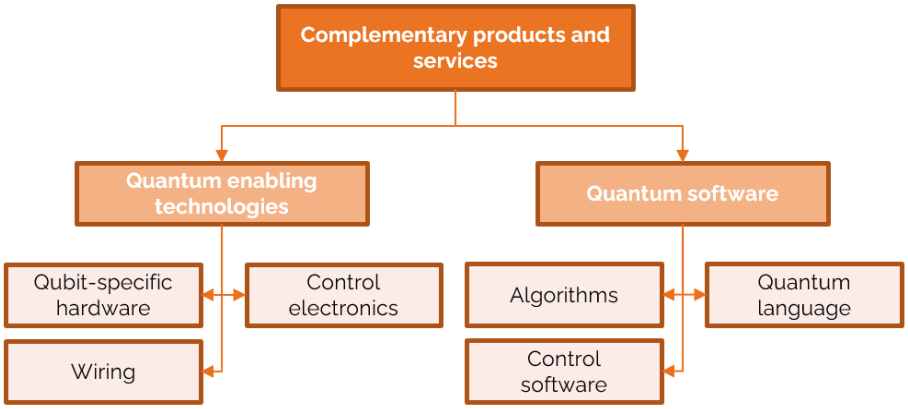


*Figure 3.16: Complementary products and services can be subdivided into two distinct categories: quantum enabling technologies, which include all hardware required to build a quantum computer, the control electronics and the wiring, and quantum software, including the algorithms and language needed to write them and the control software.*

Because qubits based on a superconducting architecture are currently the most researched variety, the complementary products and services necessary for this architecture are provided as an example. Future research is needed to elaborate upon the supply chain necessary for other qubit architectures.

At present, the superconducting qubit-based quantum computing supply chain offers enabling technologies and supporting component solutions sufficient to scale far beyond quantum advantage. Next to a quantum processing unit, it consists of several components, such as a dilution refrigerator to keep the QPU at its operating temperature, close to $0K$. A cryogenic i/o chain capable of connecting the QPU inside the dilution refrigerator to the control electronics. A calibration and control framework, including control software, is necessary to transmit signals to and from the QPU. Lastly, quantum-specific algorithms are needed to run the desired calculations [9]. An overview of the minimum required amount of complementary products and services necessary to build a functioning quantum computer based on a superconducting architecture is shown in figure 3.17.

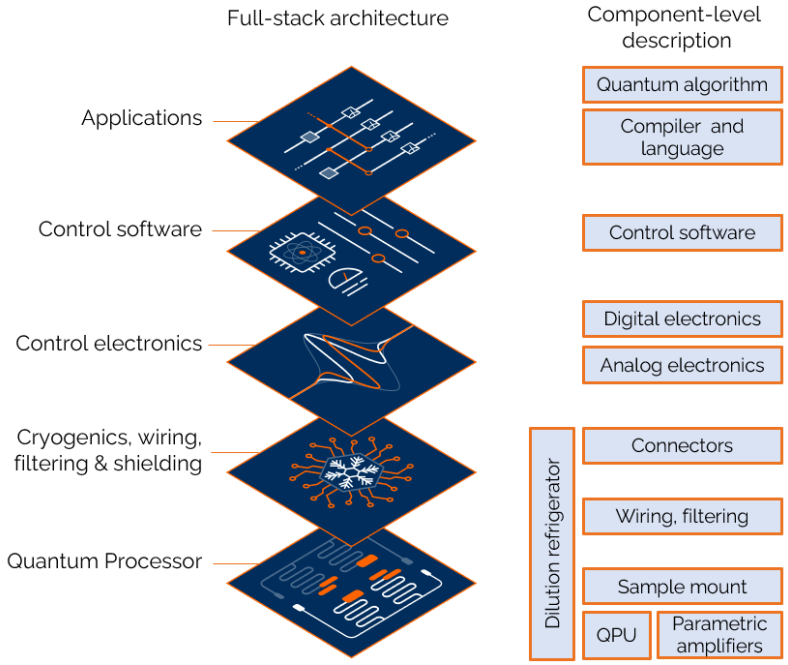


*Figure 3.17: Complementary products and services needed to use the quantum computing chip in a functioning quantum computer, based on a superconducting chip architecture. Adjusted from [9].*

## 3.6 Network Formation and Coordination

There are two distinct approaches to the 'best way' to develop a quantum computer. On the one hand, there are those advocating for a full-stack approach, producing all parts necessary to complete a full quantum computer in a monolithically structured manner. Generally, this approach is preferred by established tech giants such as Google[22] and IBM[23], but some notable start-ups also adopt this approach, such as Rigetti[24] and IonQ[25].

On the other hand, there are those who consider the full-stack approach too arduous and costly a burden for one company to carry. Instead, they suggest bundling forces of separate specialized players in an open innovation approach, each focussing on optimizing their individual strength before combining it into a complete quantum computer to mitigate risks.

This open innovation approach naturally requires various forms of strategic alliances to succeed. Advocates of this approach [9, 80] point to similar forms of partnerships seen in other high-tech environments, such as the aviation and car manufacturing industries. Companies preferring this approach are those specializing in one part of the quantum supply chain, generally start-ups. An example of a strong specialized ecosystem of Small and Medium-sized Enterprises (SMEs) is the quantum community in Delft, consisting of Delft Circuits[26], Demcon[27], Orange Quantum Systems[28], Qblox[29], QuantWare[30], and Pasqal (former Qu &co)[31] who are capable of creating a quantum computer when combining their forces.
Regardless of whether the monolithic development approach or the ecosystem approach is considered better, both are dependent on standardization and cooperation to a certain extent,

[22] https://quantumai.google/
[23] https://www.ibm.com/quantum
[24] https://www.rigetti.com/
[25] https://ionq.com/
[26] https://delft-circuits.com/
[27] https://demcon.com/nl/
[28] https://orangeqs.com/
[29] https://www.qblox.com/
[30] https://www.quantware.eu/
[31] https://www.pasqal.com/

be it one more than the other, resulting in the main categories for the *network formation and coordination* building block as visualized in figure 3.18.

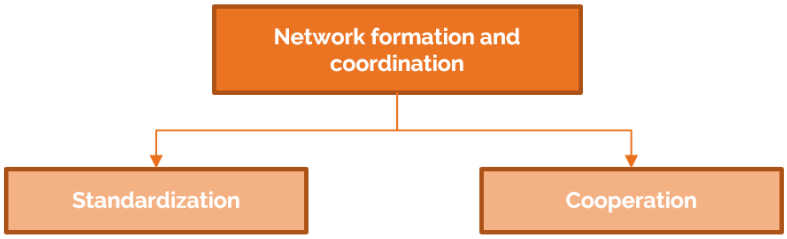


*Figure 3.18: The building block Network formation and coordination can be subdivided into two categories: standardization and cooperation.*

Even considering the monolithic approach, it is highly unlikely that one company will be the supplier, producer, distributor, and provider of complementary products and services. Therefore, coordination and, thus, cooperation is inevitable. However, a KPI capturing the desired degree of cooperation has not been found. Hence, more research into a suitable measurement is essential to complete the model.

Standardization will be necessary to a certain degree, as confirmed by van Deventer et al. [81], to make sure all components combined in a potential quantum computer are compatible with one another, whether one company produces all components or each component is produced by a different one. A prerequisite for standardization is the formation of a dominant design at some point in time. This does not necessarily imply that only one type of qubit architecture can succeed. It is probable that either various qubit architectures will prove useful for various applications, each fulfilling its own niche, or that multiple architectures will ultimately exist together in the same quantum computer.

Nevertheless, this does mean that either on the application level or computer level, eventually, a dominant design will arise. According to Utterback and Suarez [82], the occurrence of a dominant design, in turn, enforces more standardization, positively affecting the production system and complementary products. Furthermore, this leads to effective competition on the basis of cost and scale, as well as product performance, thus affecting all product-related building blocks.

This does give rise to the question: is the network formation and coordination necessary as a separate building block if it influences all other product-related building blocks directly? This question is recommended to explicate in further research.

## 3.7 Customers

In the short-term, partly functional quantum computers operating within the NISQ domain are expected, which mainly cater to the R&D segment of various types of companies and institutions consisting of both commercial and non-commercial players.

The non-commercial R&D segment includes universities, research institutes, and governmental organizations that mainly purchase QPUs to get to scientific breakthroughs quicker or cheaper because it takes years off of their internal development, allowing them to focus immediately on new challenges.

The commercial segment consists of two types of companies. On the one hand, there are full-stack developers who will use the QPUs to further develop and test their complementary products to improve their overall quantum computing set-up. On the other hand, there are those with in-house R&D departments who will mainly use the knowledge gathered from these preliminary quantum computers to give them a headstart once the market matures.[32]

[32] Based on expert interviewee D.

An example of the large variety of interested commercial players can be found in the companies that have joined IBM's Quantum Network. Members of this network include Capgemini, ExxonMobil, Goldman Sachs, Daimler-Benz, Mitsubishi, and approximately 300+ others [33].

In the long term, it is significantly more difficult to accurately predict what the customer base of QPUs will look like, as it is highly dependent on whether quantum cloud computing will become the main modality or the development will be more similar to semiconductor-based processing units and thus become significantly more widespread than anyone could predict around 50 years ago. Some claim that it is likely that quantum computers will partially replace supercomputers in the High-Performance Computing (HPC) market currently used for complex calculations and data management because there are some calculations currently attempted with HPC, which could be performed significantly more efficiently using quantum algorithms [9]. This, combined with HPC providers' experience with a business model which will most likely be similar to that of quantum computers, makes it plausible that HPC providers will constitute a relatively big share of future customers, especially if the main modality of quantum computing will be through cloud computing.

Another option is that fully operational quantum computers will open up a new, unexplored, much larger market of hitherto unattainable calculations, attracting a myriad of large enterprises. The largest players in this market will consist of financial institutions that will benefit from the expected financial applications, large pharmaceutical and life sciences companies due to the expected applications of drug discovery and the overall possibility of modeling intricate molecular structures, and travel, transport, and logistics companies due to the expected improvements in logistics optimization [12]. However, it remains hard to predict whether this segment will ultimately have their own quantum computer and thus become a QPU customer or if they will simply purchase cloud time from the aforementioned group of HPC providers.

Lastly, governments are expected to occupy a smaller yet still significant share of QPU demand due to the potential military applications and safety hazards such as encryption problems, as highlighted in section 1.1.5.

However, these long-term possibilities are likely at least ten years away according to current product roadmaps, such as those of IBM[34] and Google[35].

The subdivision of the *customers* building block into its three distinct categories of R&D, corporations and governments is visualized in figure 3.19

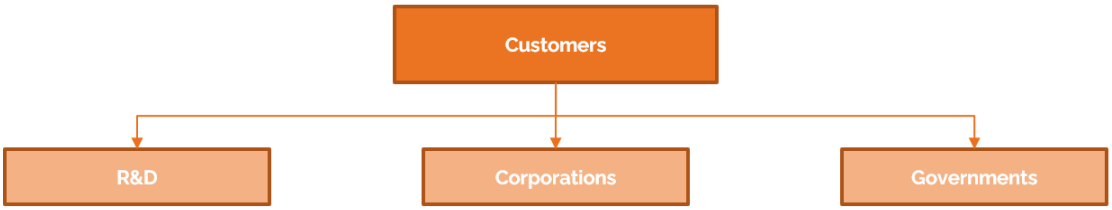


*Figure 3.19: The potential customers for QPUs can be divided into three distinct groups. In the short term, there is both a commercial and a non-commercial R&D segment. In the long term, this is expected to expand towards governments and corporations, such as financial services, pharmaceutical companies, travel, transport, and logistics companies, and other sectors for which the potential new realm of quantum algorithms can give them a competitive advantage.*

## 3.8 Innovation-specific Institutions

According to Ortt and Kamp [50], innovation-specific institutions should include *"government policies, laws, standards, and regulations"*. In this thesis, quantum-related institutions either enforcing these standards or promoting overall innovation within the industry are also added to

[33] https://www.ibm.com/quantum/network
[34] https://research.ibm.com/blog/100k-qubit-supercomputer
[35] https://quantumai.google/learn/map

this list. Combined, these form the five categories constituting the innovation-specific institutions building block, as seen in figure 3.20.

The initiatives regarding policies and regulations are exemplified for the Netherlands, as well as the two biggest European-wide standards initiatives, due to their relevance for the Dutch ecosystem. Further research is needed to both add greater detail to the mentioned initiatives and expand this list beyond the borders of the Netherlands.

The Netherlands has ambitious plans to become analogous to the 'Silicon Valley of Quantum'. Accordingly, the government created a National Quantum Technology Agenda in 2020 aimed to assist in the technological, societal, and ethical development of the industry. The National Agenda consists of three quantum programs regarding quantum computing and simulation, a national quantum-related network, and quantum sensing applications. Next to this, it covers four relevant 'lines of action' regarding scientific development and innovation, ecosystems, market creation and infrastructure, human capital, and lastly, the ethical, legal, and societal aspects [83]. These lines of action are the national guidelines towards official policies and regulations. Thus far, €615 million has been allocated to pursue the National Quantum Technology Agenda by the Dutch government.[36] The National Quantum Technology Agenda is managed by Quantum Delta NL.[37]

Due to the relative novelty of the quantum industry, there are no specific laws regarding quantum technologies in The Netherlands to date. However, Kop [84] suggests using current AI- and nanotechnology-related laws as foundations for a quantum-specific ethical, legal, and social issues framework.

The European Union launched the Quantum Flagship in 2018, a large research initiative consisting of €1 billion and a duration of 10 years in order to unify research institutions, academia, industry, and policymakers.[38] The goals of the European Quantum Flagship are twofold: *"to support and foster the creation and development of a competitive European quantum technologies industry"* and *"the consolidation and expansion of leadership and excellence in European quantum technology research"* [81].

One way the Quantum Flagship aims to accelerate development is by promoting standardization, one of the key factors identified in the *network formation and coordination* section as described in 3.6. Their path towards standardization is mapped in the *Standardization Roadmap on Quantum Technologies*.[39] This standardization roadmap is created to systematically address standardization efforts by analyzing which aspects of quantum technologies benefit the most from standardization and within which timeframe this should optimally occur. Furthermore, it is connected to universal worldwide standards-developing organizations, such as ETSI [40], ITU-T[41], ISO/IEC[42], IEEE[43], IRTF[44] and the European quantum consortium QuIC[45] [81].

The European Quantum Industry Consortium (QuIC)[46] is a European not-for-profit business association whose main goal is similar to that of the Quantum Flagship: to build a strong European ecosystem with both companies and research and technology organizations in the quantum technology domain. QuIC does so by developing IP strategies, cooperating with European institutions, fostering growth, establishing collaborative hubs, positioning quantum technology products and services as key enablers in the market, and coordinating strategic goals.

[36] https://open.overheid.nl/documenten/ronl-61f96d64-5471-48e7-aaeb-aad21a953d2c/pdf
[37] https://quantumdelta.nl/
[38] https://qt.eu/
[39] https://www.cencenelec.eu/areas-of-work/cen-cenelec-topics/quantum-technologes/
[40] https://www.etsi.org/
[41] https://www.itu.int/en/ITU-T/Pages/default.aspx
[42] https://www.iso.org/standard/27001
[43] https://www.ieee.org/
[44] https://irtf.org/
[45] https://www.euroquic.org/
[46] https://www.euroquic.org/

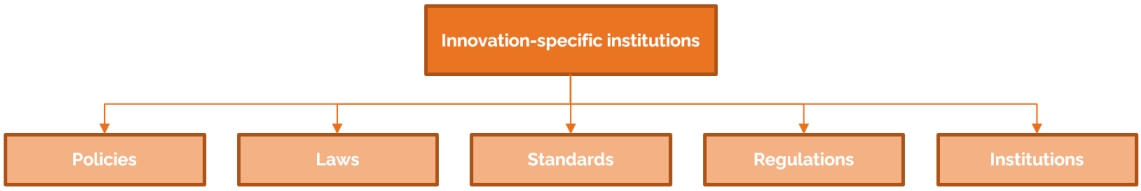


*Figure 3.20: The innovation-specific institutions can be subdivided into five categories: policies, laws, standards, regulations, and lastly, institutions.*

## 3.9 Generalizability of the model

The expansion of the Technological Innovation System framework is not solely applicable to the quantum processing unit industry. Some of the categories and KPIs described are universally applicable to most commercial products. This is the case for the entire *product profitability* building block because cost and price theories are product-agnostic.

The *production system* KPIs are likewise universal because any type of production process has a certain yield and total cycle time, generally referred to as the throughput of a process, and all processes require an input and output, expressed as raw materials in, and product quantity out.

Furthermore, the *network formation and coordination* and *innovation-specific institutions* contain categories broad enough to be universal. Most commercial products eventually require standardization. Cooperation of some form can be seen in any industry (monopolies excluded), and eventually, policies, laws, standards, regulations, and institutions form.

It is more difficult to determine the generalizability of the *customers* building block, as it will be applicable for some products but might need some alterations for others. For example, quantum processors are not expected to be as widespread as semiconductor processors. It is deemed highly unlikely that something such as a 'quantum personal computer' or a 'quantum smartphone' will exist. Therefore, the overall population is not included as a customer in this model. However, other products might have such end-users. Therefore, the applicability of this building block will have to be reassessed, but not necessarily altered.

The *product performance and quality* and *complementary products and services* both will need a full reassessment and alteration for each product evaluation. Even for adjacent industries, the KPIs are expected to be almost completely unrelated.

Nevertheless, the methods described in section 2.4 to narrow down the ultimate KPIs using various perspectives and opinions can be repeated to determine which KPIs are suitable for a different product.

# Chapter 4.
# Conclusion

## 4.1 Conclusion

The main objective of this study was twofold: first, to find a suitable framework for the forecasting of mass diffusion in nascent technologies and to apply it specifically to the emerging quantum industry, and second, to expand upon this framework in a manner that can be generalizable and applied to diverse industries. The following research question frames this overarching objective:

- *What are the bottlenecks that need to be addressed before mass diffusion can reasonably occur in the quantum processing unit (QPU) market, and what generalizable insights can be derived from this analysis that are applicable across all industries?*

In order to provide an answer to this main question, it was broken down into a number of subquestions that facilitate a more comprehensive understanding and contextualize the answer. The first set of questions was formulated to provide a theoretical foundation upon which the research question can be built. These questions were:

- *What is a quantum processing unit?*
- *What are the applications of a quantum processor?*
- *What are the current trends seen in the overall quantum computing market?*

A brief description of the basic physics behind quantum computing was explained in 1.1, which also highlights the potential applications of quantum molecule simulation, breaking cryptography, and the relatively unexplored optimization problems. Furthermore, a breakdown of the current trends unfolding in the quantum industry from the inventors', investors', intellectuals', and industry's perspectives are provided in appendix B to paint a better picture of what the industry looks like at present.

After the initial theoretical foundations for quantum computing have been explored, a model explaining the trajectory towards mass diffusion, applicable to nascent markets such as the quantum market, is required. To this end, the following subquestion was devised:

- *What are existing models to predict the development of nascent markets, and which is best suitable for the quantum industry?*

To answer this question, first, four different models capable of assisting in the elucidation of the pre-diffusion phase of the quantum industry market were explored, as well as a brief historical analysis of the development of the adjacent semiconductor industry. The first model, which was elaborated upon in section C.1, was the Hype Cycle model, popularized by Gartner, indicating the various phases of hype state-of-the-art innovations go through. This model was deemed unsuitable due to a lack of scientific evidence for the fundamentals of the theory. The theory can be expanded using more quantitative measures, but this expansion only provides

an answer in hindsight and thus proves relatively useless for future predictions. Therefore, neither the original Hype Cycle nor the expanded version will be used in this thesis.

The second explored model for nascent technologies was that of the Technology Readiness Levels in combination with other forms of Readiness levels as described in section C.2. This model for emerging technologies assumes a linear development and dependency of diffusion on the material technology alone. To combat these overgeneralizing assumptions, various other readiness levels, such as the Market Readiness Levels, were created to be used alongside the Technology Readiness Levels. However, these various other forms of readiness levels are relatively unresearched, thus remaining in the experimental phase. This experimentality, in combination with the overgeneralized assumptions, is the reason the Readiness levels are not further pursued in this thesis.

Thirdly, the more established model of (pre-)diffusion patterns was analyzed in section C.3. This approach was not pursued either due to the relatively early position of the quantum processor in the (pre-)diffusion phase, making any prediction based on this model too speculative in nature. Nevertheless, once the technology develops further, this approach is considered to be an interesting path for future scholars to use.

Thereafter, a brief historical analysis of the semiconductor industry highlighting the mechanisms behind Moore's law was outlined in section 2.1. Moore's law cannot be translated to the quantum realm one-to-one. However, the underlying theories behind Moore's law could potentially be applied to quantum computing. Nonetheless, the theory in itself only provides information for one aspect of the QPU development, and a physically correct analogy of Moore's law in quantum has not yet been found. Therefore, Moore's law is not used in the final model. Yet, once a correct physical analogy has been found, it is expected to incorporate smoothly into the expanded Technological Innovation System (TIS) framework detailed in this study.

Lastly, the suitable Technological Innovation System framework is explored in section 2.2. Various versions of this framework exist in the literature, depending on the perspective used. In this study, a company perspective is used. The company-based TIS framework consists of seven building blocks, which are all deemed equally necessary for mass diffusion to reasonably occur. However, the framework as described by Ortt and Kamp [50] lacks the desired depth expressed in the following two subquestions:

- *Which building blocks and accompanying key performance indicators can be identified as indispensable for the quantum processor market?*
- *What are the specific thresholds within these building blocks and key performance indicators that need to be reached in order for them to be considered sufficiently developed for mass diffusion to become feasible?*

To this end, the TIS model is extended to accommodate two additional layers of detail. These sublayers consist of generalizable categories and corresponding Key Performance Indicator (KPI)s. This both adds the desired level of depth and creates a significantly more quantitative rendition of the model.

Whilst analyzing the additional layers of the model, several dichotomies appear within the seven building blocks. Four of the building blocks can be described as being directly product-related. Moreover, the corresponding KPIs of these building blocks are generally quantitative in nature. The remaining three building blocks can be described as indirectly product-related. They are considered essential to the possibility of mass diffusion but are not vital to the operability of the product in question in itself. These building blocks are, contrary to the initial four building blocks, generally qualitative in nature. Finally, a distinction can be made between product-specific and product-agnostic KPIs. The product-specific KPIs will need to be reassessed each time the model is reapplied to a new product, being the performance and quality, the complementary products and services, and partially the customers. The other four building blocks are assumed to remain the same, regardless of the product.

Note that due to time constraints, only the first two building blocks of *product performance and quality* and *product profitability* are explicated in more detail. For these building blocks, two thresholds are provided, creating three different predicaments.

- Red indicates that the KPI is underdeveloped and currently severely hindering the odds of mass diffusion and thus seen as a bottleneck.
- Yellow indicates that the KPI is not fully developed yet, but not in a desired state either. The possibility of mass diffusion is slightly impeded.
- Green indicates the KPI is within the desired boundaries and thus does not provide any hindrance for reaching mass diffusion whatsoever.

For the remaining five building blocks, a suggestion for their corresponding categories and KPIs is provided, but further research to both confirm and assess the colors of these building blocks is required.

The first building block described in section 3.2 is also considered to be the most complex one, as it is one of two building blocks that need to be completely re-evaluated every time the model is applied to a new product, and because it is the most critical: without a functioning product, all other building blocks become obsolete. The definite categories and KPIs necessary to fully cover all indispensable metrics without overestimating their value were determined using various sources, such as an expert workshop, expert opinions, and available literature, as described in section 2.4. The definitive quantum processor-specific categories determined this way are: *scale*, *quality*, and *usefulness*.

The category of scale consists of one Key Performance Indicator: the (logical) qubit count. This KPI is considered vital because a bigger scale allows for more complex algorithms to be run and, thus, more groundbreaking applications to be tried. The red threshold for this KPI is anything that is classically simulatable. This boundary is calculated to be at 50 physical qubits. The KPI of *(logical) qubit count* is considered yellow for any amount of qubits within the NISQ era. It remains unclear when the NISQ era will end exactly, but estimates place it around $10^3$ - $10^4$ physical qubits. Lastly, the KPI is considered green once the Universal Fault-Tolerant Quantum Computing (UFTQC) era has started, which is estimated to be around $\pm 10^5$ qubits. The IBM roadmap positions the beginning of the UFTQC era around 2033[1]. At present, the qubit count is considered to be yellow.

The category of quality consists of two intrinsically linked KPIs: the *gate fidelity* and the *coherence time*. The *gate fidelity* or *gate error rate* is a measure of how accurately gates can be implemented on the quantum processor. A higher gate fidelity, or lower gate error rate, indicates less error/and or noise. The gate error rate is considered to be red below the error correction threshold, which is currently placed around $10^-2$. Except for some notable outliers, quantum processors of all architectures are considered to operate within this red area. Once the error correction has been convincingly surpassed, this KPI will switch to yellow. The gate error rate would be considered green once error rates around $10^{-6}$ - $10^{-9}$ have been achieved.

The second quality KPI of *coherence time* indicates the amount of time a qubit can reliably maintain its quantum state before being subjected to errors. The longer the coherence time, the more gates can be performed, thus the more useful the computation can ultimately become. A minimal threshold for the coherence time has been established at the order of $10^4$ - $10^5$ times the single gate execution time. This results in a yellow threshold of $10^{-7}$ - $10^-9$ seconds for superconducting- and spin-based qubits and $10^{-6}$ - $10^{-8}$ seconds for trapped ion-based qubits. Current QPUs operate well below this threshold and are thus considered to be red. The coherence time would be considered green as soon as times of $10^{-2}$ - $10^0$ seconds for superconducting- and spin-based qubits and $10^{-1}$ - $10^{-1}$ seconds for trapped ion-based qubits can be reached.

The final category of usefulness consists of two KPIs. First of all, there is the *connectivity* of the qubits. The connectivity describes the number of neighboring qubits one qubit is directly connected to. Gates are more easily applied to the processor if the amount of mutual connections is higher. Thus, more and more complex algorithms can be run, increasing the usefulness of the QPU. The connectivity can be subdivided into four distinctions. First, there is a 1D or 1D+ structure, which means an average connectivity of < 2. This is undesirable and hence

[1] https://research.ibm.com/blog/100k-qubit-supercomputer

considered to be red. The connectivity is considered to be yellow when the qubits are nearest neighbor or 2D connected, which entails an average connectivity of 3+. This is the current average connectivity for both superconducting- and spin-based qubits. Lastly, the connectivity is considered optimal or green for an all-to-all or 3D topology. This means the average qubit connectivity is 4+. This is the current average qubit connectivity for trapped ion-based architectures.

The last *product performance and quality* KPI is the quantum volume. This holistic KPI combines the circuit depth, which is an expression of the overall fidelity, and the circuit width, which expresses both the scale and the connectivity of the qubits simultaneously. The quantum volume is considered unsatisfactory or red when either the circuit depth or width is severely limiting to the overall quantum volume. Hence, only calculations that would be classically simulatable can be performed. Currently, the achieved quantum volumes are considered to be just below the yellow threshold, and thus this KPI is still red. The quantum volume is considered yellow for any calculation that is considered to be in the NISQ era, which requires both the fidelities and the scale to be moderately better. The green area is reached once both the width and depth have improved significantly, reaching the UFTQC era.

Overall, a building block is only as good as its worst category, which is, in turn, as good as its worst component. As three out of five KPIs and two out of three categories are considered red, the entire building block of performance and quality is considered red, as seen in figure 4.1.

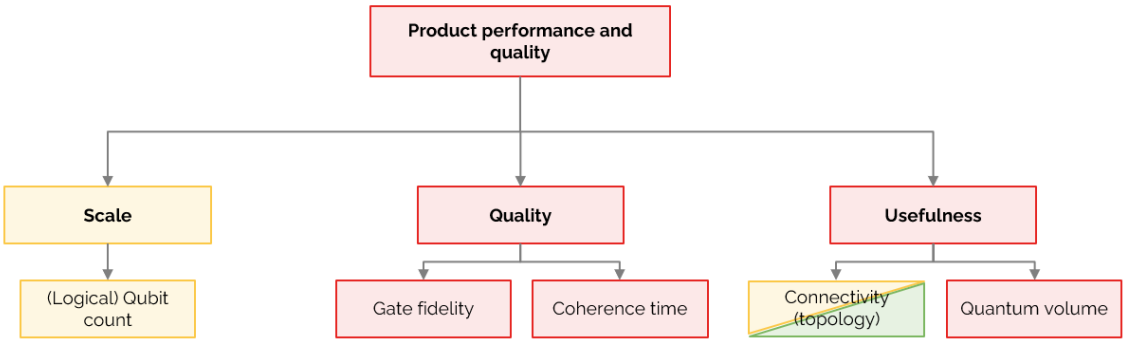


*Figure 4.1: The bottlenecks hampering the overall performance and quality of quantum processors currently are the quality, due to a low gate fidelity and coherence time, and the usefulness, as a result of a low quantum volume. Because the building block is only as good as its weakest component, the product performance and quality is considered red.*

The second building block is called *product price* in the original model. However, the possibility of mass diffusion is not dependent on the price of a product alone. At least equally important are the fixed and variable costs of producing the product. Therefore, an amendment is made. The building block is rebranded as *product profitability* to allow for the inclusion of both types of cost. Note that this does not necessarily imply that a profit has to be made, as a company can choose an arbitrarily low price for various reasons initially.

The renamed *product profitability* described in section 3.3 consists of two categories and three KPIs in total. The first category is the cost. Fixed costs are the first type of cost. These are one-time investments such as those in necessary infrastructure and machinery. The fixed costs are deemed red when neither academic nor commercial labs can afford to build a production facility of any sort. The yellow threshold is passed once some academic labs can afford a setup, but nothing of commercial scale can be built or produced. Lastly, the green threshold is passed once some specialized commercial parties can afford a production facility, which is currently already the case.

The variable costs are costs incurred per unit produced. The variable cost goes down substantially due to a phenomenon called the experience curve which states that the costs decline by a characteristic amount each time the accumulated experience is doubled. However, due to the small amount of QPUs produced and thus a meager amount of experience, the variable costs per processor are currently astronomical and thus considered red. A precise boundary to enter the yellow or green predicament could not be defined, but it is certain that

the accumulated experience has to double at least several times before the variable cost can be considered anywhere near desirable.

The second *product profitability*-related category is the revenue. The underlying KPI for the revenue is the product price. The quantity is also deemed relevant for the total revenue but is more suitable as a KPI for the *production system* building block.

Information regarding current prices of QPUs is highly sensitive and thus neither publicly provided nor available through expert interviews. Nevertheless, ultimately, the question remains where the price is 'reasonable enough' for large-scale diffusion. Given the knowledge that some products are already commercially available, the prices must be reasonable enough for some customers. Hence, the product price is considered yellow. To reach the green threshold, the supply curve must shift to the right significantly, allowing the price range to cater to a much larger public.

The building block *product profitability* is considered to be red due to the variable cost being intolerably high. However, once the variable cost is reduced as more experience is gained, the *product profitability* will immediately be upgraded to yellow, as the other two KPIs are already more favorable, as demonstrated in figure 4.2.

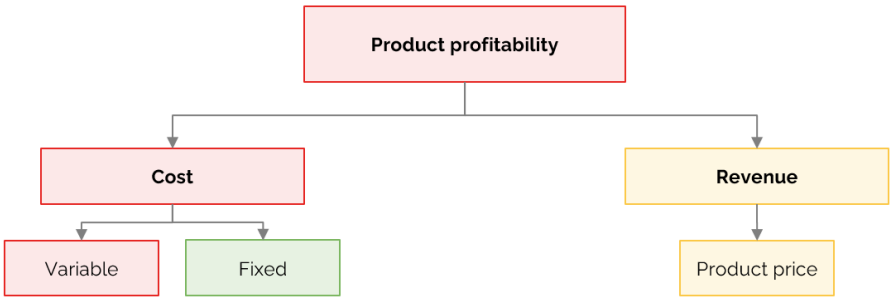


*Figure 4.2: The bottleneck hampering the overall product profitability of quantum processors is the variable cost. The fixed cost is considered fair and thus green, and the current price is considered tolerable, thus yellow.*

The third building block of the *production system* described in section 3.4 is suggested to have two categories, with two KPIs each. The process category encompasses the yield and total cycle time, and the raw materials and quantity represent the input and output, respectively.

For the quantum processor industry specifically, two probable scenarios for a mass production system are envisioned. Either companies will build their own manufacturing facilities from scratch, or current semiconductor facilities will be (partially) converted to become quantum processor compatible. The latter is improbable to happen as long as Moore's law stays alive and well, creating a redundant financial risk.

The fourth building block of *complementary products and services* described in section 3.5 is the second and last product-specific building block. In the case of quantum processors, it consists of two categories, quantum-enabling technologies, and quantum software, which each consist of three KPIs.

The quantum-enabling technologies are subdivided into qubit-specific hardware, control electronics, and wiring. The exact content of each of these quantum-enabling technologies is highly dependent on which qubit technology or technologies eventually become dominant. The quantum software is subdivided into algorithms, quantum language, and control software. These KPIs are slightly less architecture-dependent.

*Network formation and coordination* is the fifth building block described in section 3.6. It consists of two categories: standardization and cooperation. At present, there are two distinct approaches to developing a quantum computer. There are those advocating a full-stack approach, meaning all separate parts of the quantum computer are produced in-house, and there are those advocating an open-innovation approach, where each part is produced by a different, specialized player, requiring various forms of strategic alliances. For both approaches,

standardization will be a prerequisite, as a dominant design will have to emerge before mass diffusion can reasonably occur.

The next building block of *customers* can be considered from two perspectives, as described in section 3.7. In the short term, customers mainly consist of the R&D segment of both commercial and non-commercial players, with a few exceptions.

In the long term, it is significantly more difficult to accurately predict what the customer base of quantum processors will look like, as it is highly dependent on whether quantum cloud computing will become the main modality or if the development will be more similar to the semiconductor processing units, where each party making use of quantum computations owns their own quantum computer. Nevertheless, (large) corporations are expected to be a customer in one way or the other. Lastly, due to the potential military applications and safety hazards quantum calculations might bring, governments are expected to occupy a small yet notable portion of customers as well.

Lastly, there is the building block of *innovation-specific institutions* described in section 3.8. It consists of policies, laws, standards, regulations, and institutions. Within The Netherlands, the government has created a National Quantum Technology Agenda with a budget of €615 million, managed by the foundation Quantum Delta NL[2].

Furthermore, the European Union has launched a Quantum Flagship[3], a large research initiative consisting of €1 billion within ten years to both accelerate the development of quantum in Europe and by promoting standardization. Lastly, the European Quantum Industry Consortium (QuIC)[4] is another organ similar to the Quantum Flagship, assisting in collaboration within the EU. Next to these institutions and their corresponding policies and regulations, there are no specific quantum-related laws or standards within The Netherlands or the European Union so far.

The final version of the TIS framework for quantum processors from a company perspective consists of seven building blocks, 19 categories, and 18 KPIs as shown in figure 4.3
This study details the values and thresholds for 9 out of 18 KPIs. 5 out of 9 detailed KPIs, i.e. the *gate fidelity*, *coherence time*, *quantum volume*, *variable cost*, and the *qubit yield*, are currently considered to be bottlenecks, severely hampering the possibility of mass diffusion. The remaining KPIs and categories will need further investigation to determine whether more bottlenecks currently exist.

[2] https://quantumdelta.nl/
[3] https://qt.eu/
[4] https://www.euroquic.org/

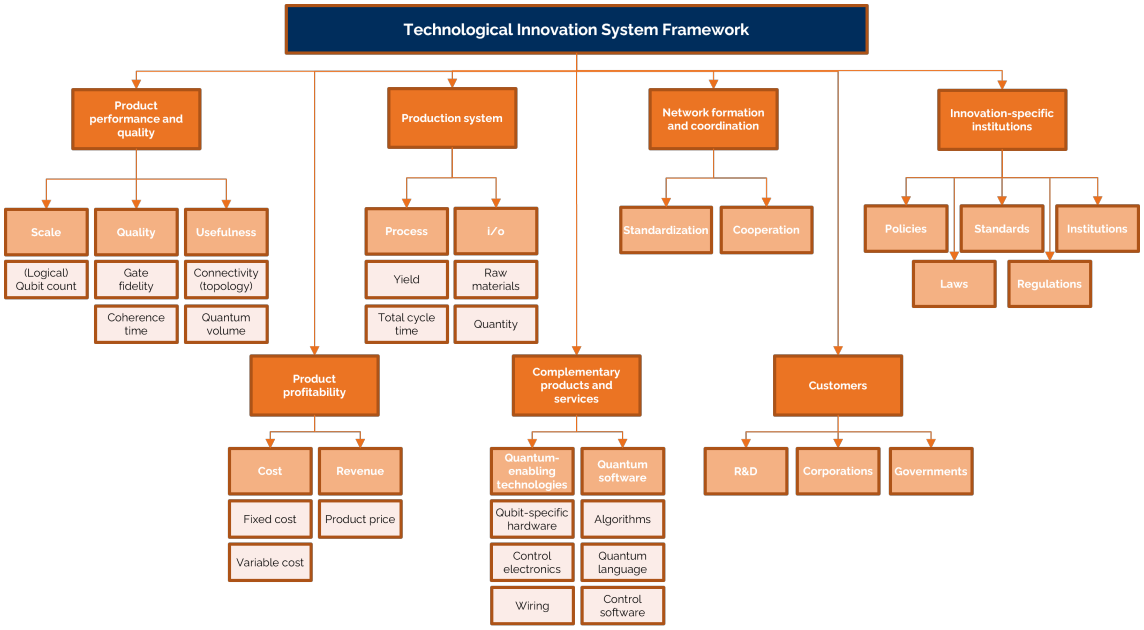


*Figure 4.3: The final version of the TIS model for quantum processors from a company perspective, including all seven building blocks, 19 categories, and 18 KPIs.*

Lastly, some lessons can be learned from this specific application that are more broadly applicable to other industries as well. Therefore, the last subquestion is posed as follows:

- *To what extent does the expansion of the TIS framework contribute to its prospective application in other industries?*

It is expected that four out of the seven building blocks can be universally applied to diverse industries. These building blocks are the *product profitability*, the *production system*, the *network formation and coordination*, and the *innovation-specific institutions*. The building block of *customers* might need some small adjustments depending on the product in question.

The remaining two building blocks of *product performance and quality* and *complementary products and services* are fully product dependent and will therefore have to be reevaluated for each product assessment. Even for closely related products, such as a quantum computer as a whole, the KPIs are expected to alter significantly.

To conclude, this study identified and structured the clouds of uncertainty that currently shroud the right development path to take for the quantum processor industry. Once the uncertainties quantified in various KPIs in this model are resolved, they will give way to reveal which way should be paved to achieve mass diffusion of quantum processors.

## 4.2 Discussion

Although a scientifically validated model was developed for the expected trajectory of the quantum processing market up to mass diffusion and simultaneous expansion of the existing Technological Innovation System (TIS) framework was undertaken, it is important to acknowledge certain limitations to this research as described in section 4.2.1. Moreover, this study paves the way for further in-depth research of the QPU market and the potential application of the expanded TIS framework across diverse industries as elaborated in section 4.2.2.

### 4.2.1 Limitations

Several forms of limitations can be identified for this study. First of all, the scope is limited to QPUs that already satisfy all five of the DiVincenzo criteria. However, the possibility exists that either a new qubit architecture or one of the existing qubit architectures that do not yet comply with all five DiVincenzo criteria is better suitable for the desired scale QPUs need to ultimately become useful. This is probable, as a similar architecture switch occurred in the semiconducting computer industry. Initially, the inferior vacuum tube technology was used to complete calculations. Only after the 'vacuum tube computer' scaled towards its physical limits the superior integrated circuit was discovered, quickly replacing the vacuum tube technology [38]. If a similar radical invention occurs within the quantum processor industry, the proposed model is not immediately invalidated. Despite efforts to create generalizable and unambiguous KPIs for the building block of *product performance and quality*, they may need to be reformulated depending on how rigorously different a potential new architecture is compared to the existing alternatives. Similarly, the *complementary products and services* and potentially the *customers* building blocks might need to be altered as well. Due to their product-agnostic nature, the other building blocks and their corresponding categories and KPIs should not be altered if the industry takes a radically different turn.

Furthermore, due to the constraints of the study timeline, not all building blocks could be contextualized in a comparable manner. Consequently, a prioritization approach had to be applied to determine which building blocks would be elaborated more comprehensively. Next to that, the differences created by the various qubit architectures could be explicated in more detail.

The *product performance and quality* building block was deemed most important for several reasons. First of all, this building block is completely industry-dependent and thus unique to the quantum realm. Secondly, the performance and quality of quantum processors are deemed critical as it currently proves to be the biggest hindrance to mass diffusion. Lastly, the commissioning party of this thesis, Orange Quantum Systems, highlighted this building block as having the highest importance.

The second and last more detailed building block is the *product profitability*. This building block was chosen because of its importance to the commercialization of the quantum industry and to reinforce the rationale behind the fundamental change from price to profitability in the TIS framework.

The choice for the *product performance and quality* and *product profitability* building blocks becomes even more clear through a parallel to the semiconductor industry. Throughout the years, the performance and quality, and price of semiconductor processors have remained the two most important aspects of the product by far. Moore's Law itself is built upon the importance of those two aspects to show that they are both intrinsically linked and the main indicator of the industry's performance overall. Therefore, similar importance for the performance and quality, and product profitability of processors in the quantum industry is probable, to say the least.

The remaining five building blocks are briefly elucidated in the results with preliminary suggestions for their respective categories and KPIs. Further research is required to both validate the suggested categories and apply them to the quantum processor use case.

Next to constraints to the timeline of the study, the resources available were likewise restricted in both availability and quantity. First of all, the amount of relevant available literature regarding the business aspects of quantum processors is severely limited. This is mainly due to the novelty of the industry and its underdeveloped commercial side. Because quantum processors are a nascent industry, any available information generally is considered to be highly sensitive information, and thus, companies are not keen on sharing it. This proved to be a limiting factor both in the information available in the literature and for any information experts were willing to share privately. Because of this information scarcity, a relatively high proportion of grey literature was consulted. This lack of peer-reviewed literature may lead to less trustworthy and/or more biased results.

Moreover, some topics demanded an expert opinion because the required information was non-existent in the literature. However, experts within the commercial quantum field are relatively scarce, resulting in a highly constrained sample size. This poses two problems. First, it increases the likelihood of the experts being identified in hindsight, despite anonymization efforts. This risk is inadmissible for any research and makes interviewees more hesitant to share potentially sensitive information. Furthermore, it increases the odds of bias being introduced into this research, as the interviewees come from a relatively like-minded group of experts, all of whom firmly believe the quantum computing industry will succeed. In future research, this bias could potentially be circumvented by both asking a bigger sample size of experts and asking physicists who do not work on the commercial side of quantum for their opinion.

### 4.2.2 Recommendations for further research

This study establishes a fundamental basis for future management scholars in two discernible ways. Primarily, it offers a starting point for those pursuing a more detailed prediction of the trajectory of the QPU market or adjacent quantum computing-related domains. It is recommended to use the building blocks and KPIs provided as a baseline for such predictions. Given the nascent nature of the industry, the model will have to be continuously aligned with the latest advancements in the field. Moreover, the provided model could be detailed further for each qubit architecture specifically. Additionally, an expansion of the five less detailed building blocks is required to establish the definite bottlenecks with greater certainty.

Another compelling path for management scholars interested in the in-depth forecasting of the QPU trajectory to pursue is to identify the underlying interdependencies among the various building blocks and KPIs. Through such analysis, an interdependency graph of the overall model identifying how the KPIs influence each other could be constructed.

The second pathway paved by this study entails the augmentation of the TIS framework through the addition of two extra dimensions of categories and their corresponding KPIs. It is assumed that the suggested categories and KPIs from this study can be applied to any other industry, with the exception of those mentioned in the *product performance and quality* and *complementary products and services* and potentially the *customers* building blocks. However, future management scholars will have to substantiate the validity of this assumption.

Moreover, the proposed building block of *network formation and coordination* might be sufficiently captured in other building blocks. For example, the standardization efforts are undertaken by parties implementing standards as captured in the *innovation-specific institutions*, and cooperation is present implicitly in all other building blocks. Therefore, it could be seen as more of a 'checkbox' than a definitive KPI. However, future scholars will have to review whether this presumption holds when further elaborated.

Lastly, it would be interesting to further study the implications of a possible translation of Moore's law to the quantum realm. As a thorough understanding of the underlying physics of both semiconductor and quantum processors is required for this, it is recommended for scholars with either a physics background or a deeper curiosity towards the technological foundations for this theory.

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# Link to the MOT programme

Each of the study goals provided for a thesis written within the masters program of Management of technology offered by the Delft University of Technology has been achieved by this thesis. To demonstrate this, a short elaboration per thesis goal is provided:

- The final deliverable must contain analytical components.

An extensive analysis of the quantum processor market is provided through the appliance and extension of the existing Technological Innovation System (TIS) framework. This makes almost the entire thesis analytical in nature.

- The final deliverable is multidisciplinary in nature.
- The final deliverable focuses on a technical application or domain.

This entire thesis is multidisciplinary, as it applies management theories to physical problems, thereby unifying applied physics and the management of technology. The focus on quantum technology automatically fulfills the requirement of focus on a technical domain.

- The final deliverable shows the understanding of technology as a corporate resource.

The main goal of this report is to fit physical KPIs in a management framework, thereby using the deeply technical knowledge of engineers as a corporate resource and translating it into something more manageable and tangible.

- The final deliverable uses scientific methods and techniques as put forward in the Management of Technology curriculum

The various explored methods as mentioned in section C and 2.2 are all taught within the Management of Technology curriculum. Furthermore, the more holistic view as engineering principles from a managerial perspective as provided within this thesis, is an overall embodiment of the core of the curriculum, representing a perfect marriage of management and technology.

# Chapter A.
# The Company

## A.1 Company Description

Orange Quantum Systems (OQS) is a start-up that spun off from QuTech. Orange's mission is for its clients to get to "know your quantum chip." Orange Quantum Systems intends to do this with three lines of products [85]:

- Quantum Diagnostics Libraries
- Quantum Systems
- Quantum Care

**Quantum Diagnostics Libraries** is a product line of software libraries for advanced quantum device measurement and control. These software libraries can be run on the open-source data acquisition and processing platform Quantify. Within the library, several modules are currently offered [85]:

- Superconducting Qubit Tools (SCQT)
- Travelling Wave Parametric Amplifier (TWPA) Tools
- AutoDepGraph

The **Quantum Systems (QS)** product line offers full-stack systems that accelerate the characterization of quantum devices. These systems work seamlessly with the Quantum Diagnostics Libraries and Quantify. There are two types of systems currently available [85]:

- The *Research Systems* line offers turn-key systems for a flexible characterization of quantum devices. It currently contains the following off-the-shelf products [85]:
  - **Orange Box**: A lab computer with a pre-installed Docker Image of Quantify and a Quantum Control Software module
  - **Orange Rack**: A rack with all required room temperature measurement and control equipment to measure and control TWPA's and/or (up to 5 qubits) Transmon quantum devices. An Orange Rack contains an Orange Box with the Quantum Control Software modules installed.
  - **Orange Research System**: A full stack system to measure and control TWPA's and/or (up to 5 qubits) Transmon quantum devices. An Orange Research System contains an Orange Rack and third-party products like a dilution fridge, cryogenic wiring solutions, and a qubit sample.
- The *Industry systems* are under development because an industry-wide need for high-throughput quantum device characterization systems is shortly expected.

Lastly, to best integrate a Quantum System in a client setting, OQS also offers **Quantum Care (QC)**. QC is a service that allows clients to customize their Quantum System and Quantum Diagnostic Software or rely on training, regular maintenance, and next-day support [85].

## A.2 Company Strategy

There is a myriad of obstacles of various sizes which need to be overcome before quantum computing can become a widely adopted field. Two of these significant bottlenecks currently limiting the development of the field are the reliability with which quantum computing chips can be manufactured, preferably in a manufacturing line, and the characterization of the quantum chips. Characterization of the chips helps to understand both the exact specifications of the chips produced and how reliable the production method used actually is. These two bottlenecks are the driving forces behind Orange Quantum Systems' mission [85].

Currently, quantum chips are predominantly manufactured manually on small-scale wafers. This method is both unsustainable and unscalable. Furthermore, the current quantum chips are very unreliable due to the large probability of (human) errors in the manual process, which makes producing chips of consistently the same quality next to impossible. This bottleneck can be solved by creating a foundry-compatible fabrication process, which can benefit from the existing knowledge and industrial-scale fabrication facilities of the semiconductor industry. The foundry-compatible fabrication process would largely eliminate the error-prone human manufacturing process, vastly increasing the reliability and quality of the chips produced. Currently, attempts are being made at producing qubits using semiconductor manufacturing processes [74].

The second bottleneck, on the other hand, remains relatively uncharted territory. Orange Quantum Systems aims to resolve this by producing systems that enable reliable testing and measurement using diagnostic and benchmarking tools. These systems will stay essential far into the quantum supremacy era. The semiconductor industry has shown that these systems will eventually integrate into the more extensive set-up of manufacturing lines but always remain vital for the industry [40]. Therefore, Orange Quantum Systems fulfills a vital role in the value chain of the future quantum computer.

# Chapter B.
# Current industry trends

## B.1 Current Industry Trends

Clean up no longer useful pieces of text

This section provides a short overview of current trends in the industry. These trends are analysed, using four different perspectives:

- The **inventors' perspective**, which analyses recent developments and the current state of the art by reviewing patent documents worldwide;
- the **investors' perspective**, which analyses investments made by public and private investors;
- the **intellectuals' perspective**, which analyses top publishing countries and institutions, and lastly;
- the **industry's perspective**, which analyses trends in the rapidly evolving quantum ecosystem.

### B.1.1 Inventors' perspective: patent analysis

Figure B.1 shows the growth in the amount of patents granted by the patent offices of the European Union (EPO) and the United States (USPTO) between 2001 and 2021 [10]. Since 2014, a tremendous growth in the field can be seen, at a Compound Annual Growth Rate (CAGR) of 42%, which is significantly higher than the CAGR for quantum related technologies overall (CAGR = 18.64%) [11].

Of the patents granted between 2001 and 2021, the majority was granted by the USPTO (91.22%). In the overall quantum technology field, the patents are less concentrated in the USA, at 77.96% [10]. Notable is that the Chinese patent office surpassed the EPO in 2021 with 117 and 49 patents granted respectively [10].

The leading players based on the number of patents can be divided into several distinct categories [86, 11, 10]:

- well-known, established **IT giants** who also hold a significant share in the semiconductor market, such as IBM, Microsoft, Intel, and Google;
- **Asian conglomerates** who were historically positioned in telecom and electronic equipment such as Hitachi, Toshiba and Samsung Electronics;
- **defense and security organizations** such as Northrop Grumman, Raytheon and Lockheed Martin Corp.;
- the **academic sector** with renowned universities such as Harvard, Yale, MIT and the University of Delft;
- **government entities** such as the US Government, Japan Science and Tech and the government of Abu Dhabi;
- the **banking sector** such as Bank of America and Wells Fargo Bank

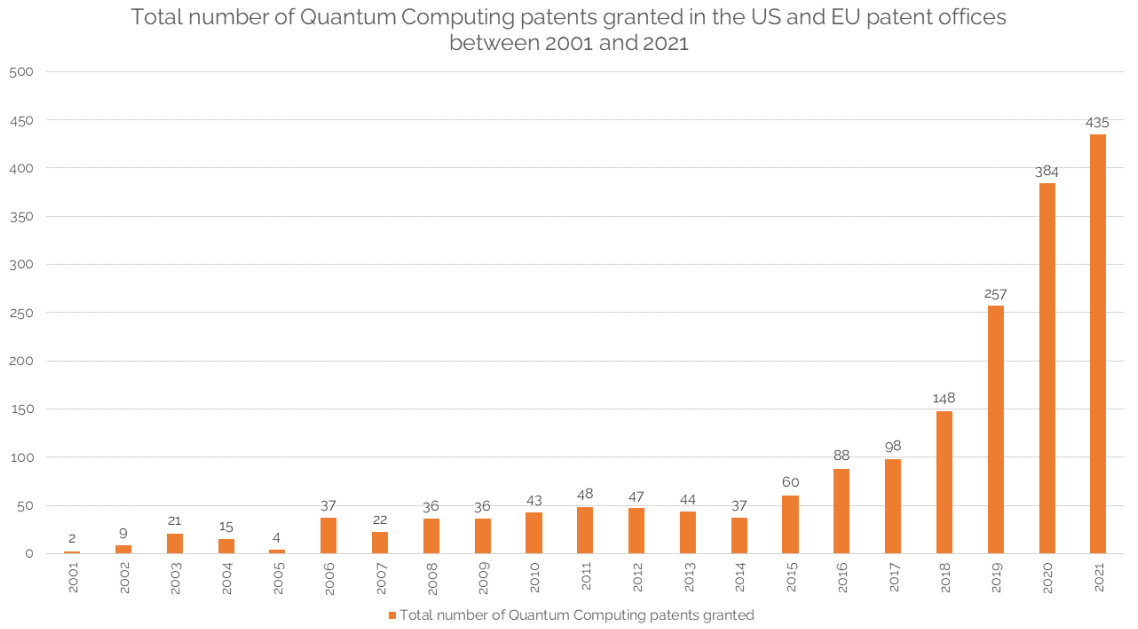


*Figure B.1: Total number of Quantum Computing patents granted in the US and EU patent offices between 2001 and 2021, based on Kop et al [10]*

- and lastly **specialized quantum SME's** such as D-wave, Rigetti, IonQ and SeeQC Inc.

Especially for the latter group, strong patent protection is critical [11]. This can be shown through two examples: the first example is D-Wave systems, who holds more quantum computing patents than almost all of the incumbent firms such as Google, Microsoft, and Intel (IBM is the only exception to this rule)[10]. The second example is Rigetti, a venture-backed firm founded in 2013, who already ranks 6th by amount of patents granted [10]. The reason for the high amount of patents is that new entrants need external investors, who in turn need proof of principle, generally requested in the form of a strong IP portfolio. Large-cap firms on the other hand, are able to invest in their research from their own extensive R&D budgets[11, 10].

There are two main identifiable patent strategies within the quantum computing market [11]:

1. **Employing a strong IP portfolio.** This strategy is generally more beneficial to new entrants, both as a source of competitive advantage and to raise capital during their incubation period.

   However, a substantial obstacle to this strategy is the expected time the quantum computing market will need to reach a size comparable to the classical computing market.

2. This potential dilemma can be diverted by using a different strategy: **trade secrets**. This strategy can be beneficial, especially for inventions whose expected commercial exploitation is after the patent lifetime, as trade secrets are short-spent. Using trade secrets instead of extensive patent protection is a widespread phenomenon in the IT sector.

Aboy et al. [11] argue that the expected business model for quantum computing will resemble this trade secret model. However, Kop et al. [10] point out that this strategy brings additional risk as competitors may apply for broad-scope patents, risking infringement and because secrecy hampers innovation in the pre-competitive quantum computing field. Both Kop et al. and Aboy et al. [11, 10] show that despite possible benefits of the trade secret strategy for incumbents, IBM still ranks first in the number of patents since 2021, thus potentially discrediting the incumbent trade secret model.

Contrary to the wide variety of companies owning quantum computing IP, the geographical distribution is very concentrated. The USA houses 51.4% of all quantum computing patents,

Europe takes second place (if the UK, Switzerland, and Russia are also counted as Europe) at 14.5%, followed by China (10.9%) and Canada (9.4%) [10]. This division changes significantly when zooming out to overall quantum technologies with China ranking first (52.1% and USA second at 24% [86].

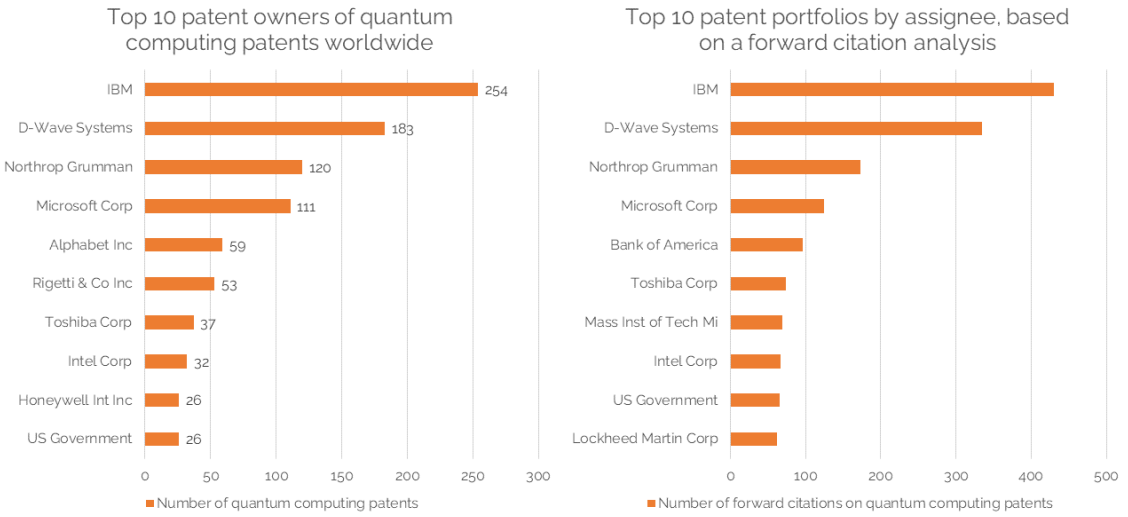


*Figure B.2: Top 10 patents owners of quantum computing patents worldwide (left) and top 10 patents owners on quantum computing worldwide based on forward citation analysis (right). Both graphs adapted from [11].*

Overall, the top 10 countries together own 93.7% of all quantum computing patent families, indicating localized hotspots [10, 86]. It should be noted here however, that Chinese patents are generally considered to be of lesser value due to different policies, as the same patent is often denied outside of China, due to lack of novelty. Despite this, the World Intellectual Property Organization stated that China has become the main patent applicant worldwide [86].

An important factor to keep in mind for companies filing for quantum computing patents now is that given that the duration of a granted patent is 20 years, all patents granted currently will be in the public domain by the time the market matures. Currently, already 9.23% of granted quantum computer patents have expired [11].

Additionally, 51.70% of patent applications since 2001 have become part of the public domain as they have not been granted [11].

Another relevant measurement unit for the inventors' perspective, is the forward citation analysis of patent portfolios. Forward citations measure the private value of a patent; they are considered a proxy for the potential social value of an invention, often used when there is no established market value yet. Both the top 10 patent owners worldwide based on amount of patents and based on forward citation analysis can be found in figure B.2. Remarkable is that the top four patent owners are the same based on amount of patents or amount of forward citations, however, based on forward citations, Alphabet corp, Rigetti & Co inc., and Honeywell Int. Inc. do not appear in the top 10, but instead make way for Bank of America, MIT and Lockheed Martin Corp. [11].

Overall the patent analysis exhibits a solid overall increase in patent activity worldwide but focused on specific geographical hotspots. Furthermore, a wide diversity of players is found amongst those with the highest number of patents, potentially indicating low entrance barriers. The presence of SME's amongst incumbents such as IBM and Google, among the top companies patent-wise, shows the uncertainty and unpredictability of the market but also may

provide potential for start-ups to outperform incumbents in the race to quantum advantage.

### B.1.2 Investors' perspective: investment analysis

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The overall trend in the market is estimated by McKinsey (2022) [12] in figure B.3.

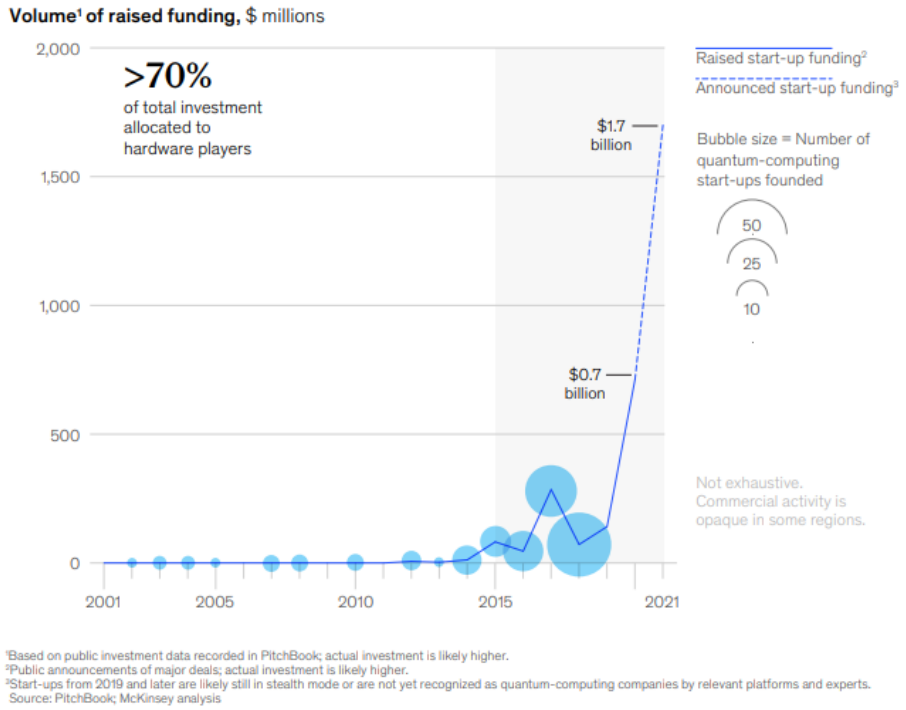


*Figure B.3: Market estimate as done by McKinsey [12]*

Although not all cash flows are publicly disclosed, private investment trends distilled from public information show that private investors are heavily funding quantum technology start-ups. In 2017 and 2018, companies received at least $450 million in private funding, quadrupling the $104 million invested in the previous two years [87]. This number accelerated even faster in the past two years, as the investment and funding of 2021 reached $1.4 billion, again doubling the $7 billion invested in 2020 [12].

The current level of Venture Capital (VC) investments in the quantum technology field are at par with those in AI firms before 2010, which eight years later grew over 20-fold to $9.3 billion [87]. However, if the investments in quantum follow a similar path to that of AI, investments will not multiply similarly immediately. After immense surges of interest in AI, investments ceased, and an 'AI winter' ensued. Some experts fear that the real quantum advantage is still decades away, and quantum technologies will thus fall into a similar pattern, referred to as a 'quantum winter' [87]. The more detailed financial data of Seskir et al. [88] does not dispute that a quantum winter is commencing, but it does not refute it either.

Between 2010 and 2020, $1.5 billion was invested in 80 different quantum technology start-ups [86]. 62.5% of these declared investments were in just 15 companies that specialize in quantum computing. These quantum computing investments can be broken down further into their underlying technology. 36% of investments went to start-ups using photonics-based qubits, 24% to superconducting qubits, and 22% to quantum annealers [86].

Over the last two years, three quantum computing startups, D-Wave, IonQ and Rigetti, have decided to go public early through a Special-Purpose Acquisition Company (SPAC), which provided them with significant extra funds (e.g. $261 million for Rigetti) to further expand their

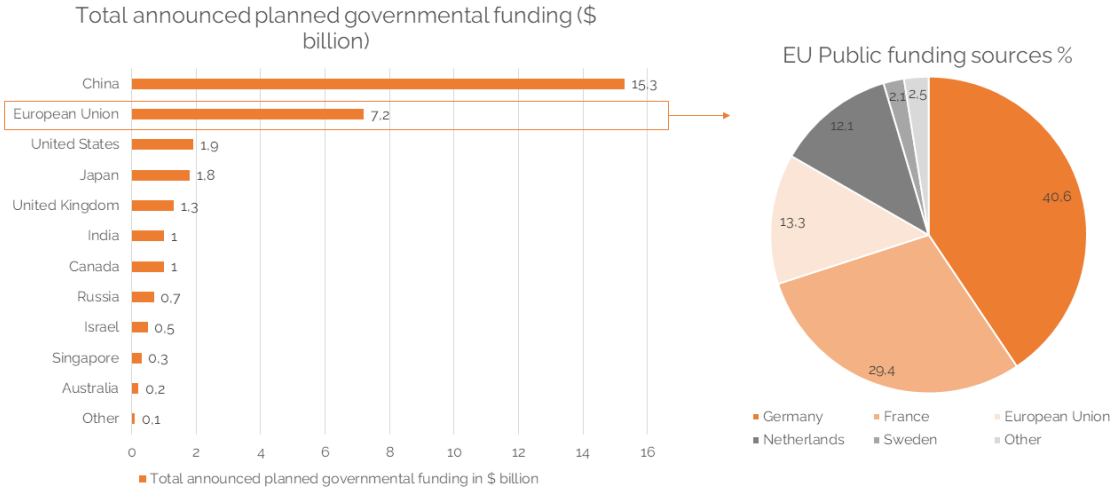


*Figure B.4: Total announced and planned governmental funding in billion dollars up untill june 2022. Adapted from [12].*

operations[1].

However, it remains to be seen whether this was the right strategic decision, because all three companies have been losing significantly on the stock exchange in the past year, with IonQ's shares dropping 60%, D-Wave's shares dropping 85%, and Rigetti's shares lowering 90% compared to their original listing prices [2].

Next to investments in companies developing quantum computers, potential users have also started incorporating quantum computing into their budgets. In 2018, already 1% of corporates actively budgeted for the potential use of quantum computing, and in 2023 20% of corporates are expected to do so [26].

### B.1.3 Intellectuals' perspective: bibliometric analysis

The total scholarly output in quantum computing between 2011 and 2020 as found by Wang et al, can be found in figure B.5 [13].

Between 2010 and 2020, the number of publications surrounding quantum computing research increased with an annual average of 10%, indicating a quickly increasing interest (Kurek, 2020). The top ten countries in which the publications were made dominate with a 98.9% share of publications, of which the USA and China are jointly responsible for over one-third [86, 89, 13].

Similar to the patent and investment patterns, the publications are also global but highly concentrated. Of the top twenty most productive institutions, five are located in the USA, four in China, and two in the United Kingdom [86]. A notable insight is that the USA is significantly less active in the quantum technology field than it is in other research fields, which does not stroke with their leading role in science. China, on the contrary, has a relative overcontribution in the quantum field, especially in quantum communication [89].

There is also a clear correlation between the top publishing countries and national funding initiatives: ten out of eleven countries have launched high-budget initiatives [89].

A notable precursor or catalyst to the formulation of national initiatives found by Seskir et al. [88] is the appearance of one or two start-ups in the quantum domain. After the national initia-

[1] https://www.wired.com/story/quantum-startups-stock-market-dreams-are-decohering/
[2] https://www.wired.com/story/quantum-startups-stock-market-dreams-are-decohering/

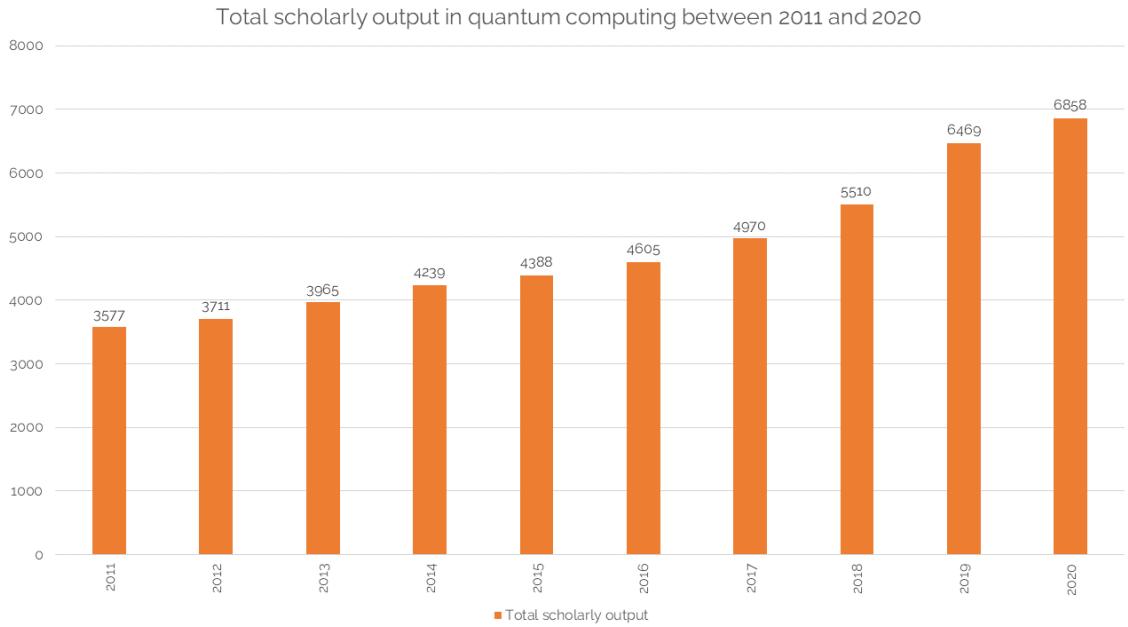


*Figure B.5: Total scholarly output in quantum computing between 2011 and 2020, adapted from [13]*

tives, start-up activity rises significantly. Following this pattern, over twenty countries are expected to launch a national initiative in the near future and have a subsequent entrepreneurial quantum boom [88].

There is however, an important side note to the bibliometric analysis: scientists often reframe research according to the latest 'hype' in the field, to continue funding. This might give a skewed image of the actual amount of new research regarding quantum computers. Furthermore, biases and other forms of incentives also might skew data, thus potentially downplaying the presented hype in quantum computing papers.

Next to the similar global but highly concentrated geographical patterns that were also found in patents and investments, no interesting new trends or research gaps have been identified from the scientific developments.

### B.1.4 Industry's perspective: trends in the rapidly evolving ecosystem

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The landscape of quantum start-ups has rapidly changed over the past few years. 92% of global quantum start-ups have been founded in the past ten years, of which 68% in the last five years [88]. Furthermore, the global but locally concentrated trend shown in the patents, investments, and publications is also evident from the industry's perspective. Over 50% of start-ups are located in the US, UK, and Canada [88]. A notable difference, however, is the lacking position of China. Despite having the highest number of publications, patents, and national investments, they rank sixth in the number of start-ups and lack any complementary technology or supporting start-ups [10, 86, 89, 88].

Another remarkable development is that the era of diversification in quantum start-ups may have ended. 2022 is the first year where mergers, partial acquisitions, and special purpose acquisition company (spac) deals have started to emerge [88]. On top of this, McKinsey [12] also found that the global rate at which start-ups are being founded has been slowing down for the past three years already. However, opposing this consolidation movement, 2022 also brought

new mechanisms in support of diversification, such as the European Innovation Council (EIC) support and a new open Pathfinder Challenge [88]. Since this development is so recent, more research and time are needed into whether the diversification trend will continue or the newly found consolidation movement will take over.

Unique for the quantum ecosystem, compared to other high-tech systems, is the disappearance of 'traditional' barriers such as public vs. private and research vs. commercial divisions. This could, on the one hand, accelerate the industrialization of quantum research. However, on the other hand, it also potentially exacerbates the risk of individual researchers or start-ups being bought out [86].

Another trend is the rise of platforms and networks for quantum development, which centralize the diversified supply of existing quantum computers. Examples of these overarching systems are the IBM Q Network, Microsoft Azur Quantum, and Amazon AWS Braket [86]. These networks stimulate and accelerate development. For example, the members of the IBM Q network can run their software using IBM's open-source programming language Qiskit [90]. Google has a similar setup where companies in their network can access their processors through Cirq, the open-source framework Google created [91].

The business model of Amazon's network is different from the open-source approach of IBM and Google. Amazon officially states that its ambition is not to create a quantum computer. Instead, they establish what Kurek [86] calls an 'uberization' of the quantum market. They enable small players to make their quantum hardware accessible on their AWS platform, much like Uber makes cars accessible via theirs. Whether this unique platform approach will be beneficial for start-ups in the medium- to long-term has not been researched [86].

Coccia [92] claims there are seven critical elements needed for a well-supported quantum computing ecosystem: research labs, human resources, R&D investments from both public and private companies, shared facilities and equipment, a steady supply chain oh high-tech instruments, standardization, and lastly the creation of niche markets between different sectors with stable demand. Coccia [92] suggests that any stakeholder attempting to accelerate the development of the ecosystem should focus on developing each of these seven pillars. However, the research does not adequately mention how this development should be achieved. Räsänen et al. [80] provide an alternative, significantly more actionable framework using seven pillars. These seven pillars are:

- create world-class quantum hubs;
- build manufacturing infrastructure such as clean rooms;
- act as an active purchaser of quantum computing solutions;
- build ecosystems around start-ups;
- support collaboration between start-ups and established companies;
- provide equity-style funding for scaling quantum computing companies;
- support IP standardization efforts.

Next to suggested frameworks for companies whose core business is in quantum technology, strategies for firms with a different core business who want to harness to use cases of quantum technology have also been identified by Jenkins et al. [93]. These approaches to quantum are:

- using it for traditional problem solving with superior performance;
- building capabilities for the future through pilot projects;
- exploring large problem spaces;
- looking to succeed in contexts with 'arms race' dynamics.

Because Bobier et al. [26] predicted that in 2023 20% of corporates will have budgeted for quantum technologies, the four strategies of Jenkins et al [93] are expected to become pronounced and widespread in the coming four years.

# Chapter C.
# Unused methodologies

## C.1 Hype cycle model

The 'hype cycle model', first introduced by Gartner Inc., explains the general path a technology takes over time in terms of expectations or visibility of the value of this technology in relation to the time [94]. The model was formed by merging two equations [14]:

- the *hype level curve*, which is a human-centered equation describing expectations and
- the *technology S-curve* which depicts the maturity of a technology.

The model states that for an upcoming technology, the hype reaches a peak, followed by disappointment, followed by a recovery of expectations, be it to a lower level than the original peak. This is visualized in figure C.1.

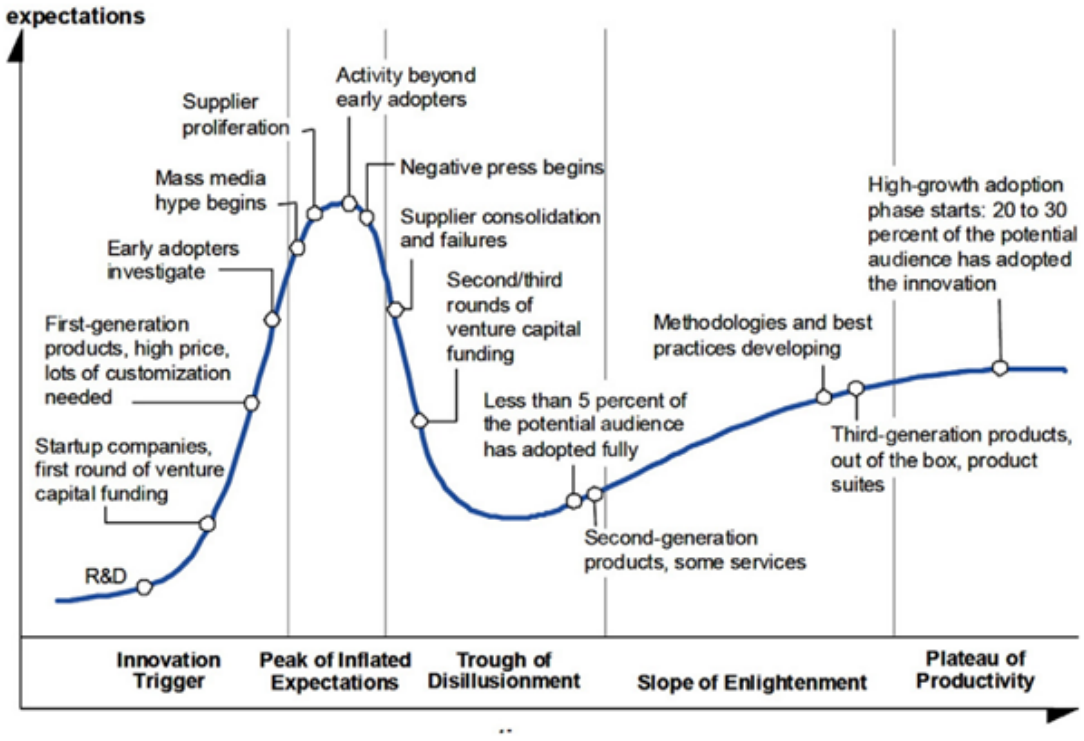



*Figure C.1: The Hype Cycle model by [14].*

The technology model hereby follows the First Law of Technology, which states that humans *"invariably overestimate the short-term impact of a truly transformational discovery, while underestimating its longer-term effects"* [14, 95]. So far, the hype cycle model has gained relatively limited interest within academic circles, especially in comparison with its substantial use

by practitioners and in business contexts, creating an interesting position for this model in the market.

Since the introduction of the hype cycle by Gartner in the '90s, literature exploring the hype cycle has expanded significantly. Still, criticism of the reliability of the hype cycle on various grounds also arose [14, 95]. These criticisms do not entirely discredit the original model but instead propose additions to make it more scientifically accurate and less dependent on the hind-side bias. Both [14] and [95] show incongruences in the reports of Gartner.

Dedehayir and Steinert [14] propose that the hype cycle model is precious if extended with other existing frameworks, such as the diffusion of innovations framework proposed by Rogers [96, 97], which is further elaborated upon in section C.3, and the influence of industry, product and technology lifecycles as proposed by Routley et al. [98].

Building on the foundations laid by Rogers' innovation framework, Dedehayir and Steinert [14] proposes a threefold addition to Gartner's hype cycle model, to make it more scientifically accurate, namely 'innovation,' the 'media' and the 'social system' with respect to the fourth element of 'time.' Table C.1 shows an overview of these additions. They do not entirely refute the model, as they recognize the importance of including the notion of hype in scientific literature forecasting the adoption of innovations.

The first element of '**innovation**' is partly congruent with the aforementioned innovators' perspective, as described in section B.1.1. It is argued that hype is likely to manifest in technological growth curves produced from increasing technological performance levels, which in turn can be quantified in patent activity. Several scholars have proven that patterns similar to that of the hype cycle can be found in patent activity [99, 100, 101, 102]. However, innovation activity in the form of a patent analysis alone is only useful for more matured technologies. Therefore a second metric of event history analysis, which can be gathered from professional and mainstream sources, is proposed [14, 103].

The second element of '**media**' is partly congruent with the aforementioned intellectuals' perspective, as described in section B.1.3. Hype in media can manifests itself in the overall article count over time, which can be divided into 'professional media' or technical news sources and journals and 'mainstream media' [14].

The third element of '**social system**' is partly congruent with the aforementioned industry's perspective, as described in section B.1.4. Here, hype manifests itself in the amount of adopters or sales of a given innovation over time. However, the amount of adopters is generally a metric only used in hindsight. Therefore, as an additional metric, the number of search queries over time is used as an ex ante indicator of adoption behavior [14].

*Table C.1: Proposed additions for studying the hype cycle in existing life cycle models. Adapted from [14].*

| | Quantitative approach | Dependent variable | Data source |
|---|---|---|---|
| Innovation | Patent activity<br>Event history analysis | Patent counts<br>Event counts | Patent offices<br>Engineering journals or newspapers |
| Media | Bibliometric and content analysis<br>Bibliometric and content analysis | Article count<br>Article count | Technical journals<br>Mainstream newspapers |
| Social system | Diffusion pattern<br>Search traffic | Number of adoptions<br>Number of search queries | Market research databases<br>Search engines (e.g. Google trends) |

These three additional elements to include hype in technology adoption models, give Gartner's hype cycle a more quantitative nature and thus take away the cloud of uncertainty shrouding the model. Furthermore, all six dependent variables mentioned can be found through desk research or in existing literature regarding Quantum Computing and can thus be seen as a relatively realistic measure for a forecast of the technology.

Two papers already made an attempt to apply the hype cycle to quantum computing, although the paper of Smith remains to vague to be useful for further research [104, 105]. Kondo et al. [105] quantified the proposed alterations to the hype cycle model as made by Dedeyir

and Steinert [14] further by applying graph network analysis and applied them to the case of Quantum Computing. Of each of the three proposed additional elements, innovation, media and social system, they analysed one of the quantitative approaches, namely the patent activity, a bibliometric and content analysis of technical journals and search traffic by the number of search queries [105].

The increasing trend in the amount of papers published on Quantum Computers as found by Kondo et al. [105] is similar to the trend described in section B.1.3, although the amount of publications considered is significantly less, most likely due to a more strict search query [105, 86, 13, 89].

The slightly irregularly increasing trend found in the amount of patent publications on Quantum Computers as found by Kondo et al. [105] is rather different from the trend identified by Kop et al. [10]. Whereas Kop et al. [10] identify a notable steep growth starting from 2015, Kondo et al. [105] identify this growth from 2010 until 2015, and identify a plateau starting in 2015 instead. The reason for this difference in trends, is uncertain.

A clear correlation between epoch-making events between 2010 and 2023 and the activity in search queries regarding quantum computers can be seen in the Google Trend analysis, as shown in figure C.2. The notable peaks in interest represent important events in the quantum computing industry [105]:

- the first sale of a Quantum Computer (May, 2011),
- Google and NASA's usefulness recognition of Quantum Computing (May, 2013),
- Google and NASA's certification of Quantum Computing's superiority (December, 2015) and
- Google's Quantum supremacy paper (October, 2019).

Note that a notable shortcoming of the Google Trends analytics is, that it does not account for synonyms or other ways of writing. For example, 'quantum computing' and 'quantum computer' are not considered to be the same search query, as it only looks for 100% matches to the requested search query.

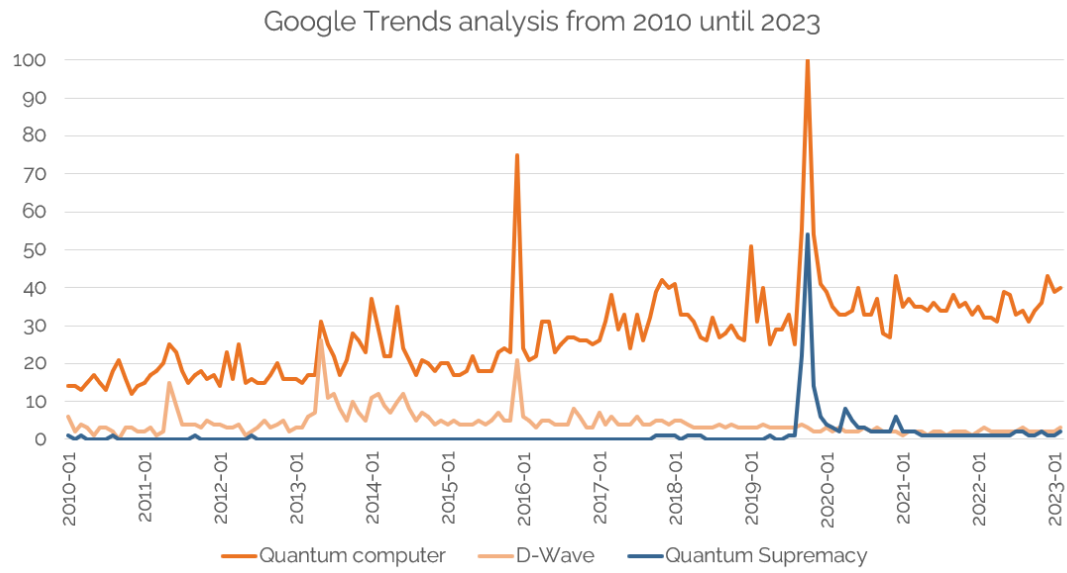



*Figure C.2: Result of the Google Trends survey on interest in Quantum Computing between 2010 and 2023 made using Google Trends.*

To conclude, Gartner's Hype Cycle by itself is not deemed relevant for this research, as it lacks scientific proof and a concrete basis. The quantitative additions proposed by Dedehayir and Steinert [14] and partly executed by Kondo et al. [105] provide a clear basis to build upon, which makes up for the flaws in Gartner's original model.

Nevertheless these quantitative additions only provide a better understanding of the current market, not for future accounts. Whatever useful information about the future it might provide, is solely based on extrapolation, which is both extremely unreliable and rather unscientific.

## C.2 Technology Readiness Level in combination with the Market Readiness Level

The concept of *Technology Readiness Levels (TRL)* was created by NASA almost 30 years ago and has since become a renowned and widely used assessment method in almost every sector [106]. However, technologies do not develop in a linear manner, nor does diffusion depend solely on material technology alone. They also depend on the market in which they can potentially be sold, so later on the *Market Readiness Levels (MRL)* were also created [107].

After this, a myriad of other readiness levels was born, such as *Regulatory Readiness Level (RRL), Acceptance Readiness Level (ARL), Organizational Readiness Level (ORL), Customer Readiness Level (CRL), Funding Readiness Level (FRL), Team Readiness Level (TMRL), IP Readiness Level (IPRL)* and undoubtedly many others that fit their specific contexts [108, 107, 109].

However, despite the fact that considering the development of an emerging technology will undoubtedly profit from considering many angles, only the TRL and MRL have proven their value thoroughly in the literature. All other experimental readiness levels are currently mentioned by their respective inventors and maybe one other scholar, thus remaining just that: experimental. Therefore, I think this methodological view provides nothing more than an interesting point of view due to its easily quantifiable nature, and I will thus not further pursue this method.

## C.3 Diffusion of Innovations

The foundation for the diffusion of innovations was laid by Rogers in the early 80s [96]. Rogers defined the original famous S-curve model for the diffusion of innovations, which indicates the rate of adoption of a technology over time. Diffusion is defines as '*the process by which an innovation is communicated through certain channels over time among the members of a social system*' [96]. Note that, as Rogers [96] also indicated, the terms *innovation* and *technology* are interchangeable in this specific context.

However, later research proved that this 'perfect S-curve' logically does not always apply. The S-curve can demonstrate either a much more erratic pattern [97, 110] or behave even more differently and consist of multiple initial introductions which do not lead to mass diffusion, but instead create a pre-diffusion or adaptation phase [15, 96].

Since the quantum computer in its current form is not yet ready for mass diffusion, as also proven in the text below, it can be concluded that quantum computing is currently in this pre-diffusion stage. Therefore, this section will focus on research regarding the pre-diffusion phase.

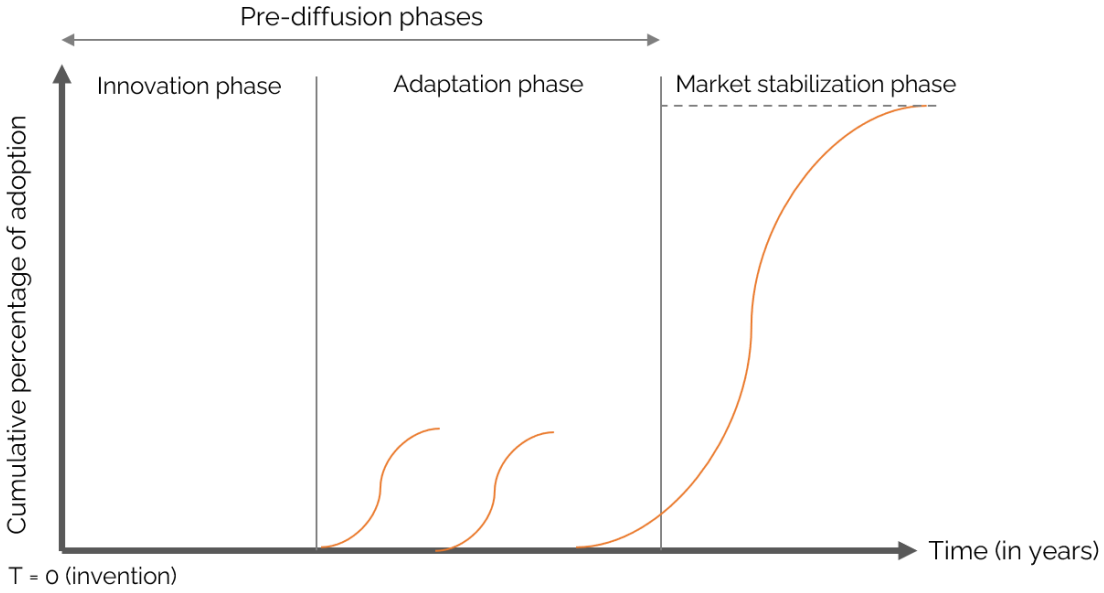



*Figure C.3: The pattern of development and diffusion of high-tech products, including the pre-diffusion phases, based on [15]*

The pre-diffusion phase is defined as the time between the invention of a technology and large scale production and diffusion of said technology [15]. The pre-diffusion phase consists of three important milestones:

- Milestone 1: **invention**. The invention is defined as *'the first time that the technical principle of this category is demonstrated and mastered'* [15]. The first published record of a quantum computer was already made in 1981 by the renowned physicist Richard Feynmann [17]. However, since the definition also requires 'a demonstration and mastery', one could argue that the invention counts as either the first demonstrated working quantum computer in 1998 [111] or the first quantum computer that demonstrated quantum advantage in 2019 [22]. This forty year time difference illustrates the importance of choosing the definition of this milestone, as also substantiated by Ortt [15].
- Milestone 2: **Introduction**. The introduction is defined as *the date at which the product is available for sales or can be transferred to users'* [15]. Using this definition, the introduction date can also be disputed. There are several companies who lay claim to the 'first

commercial model'. There is D-wave, who introduced their first 128-qubit model in 2011[1]. However, this is model uses quantum annealing, making its claim to being a 'full-fledged' quantum computer disputed. Choosing the more strict definition of a commercial quantum computer, the first model would be IonQ's trapped ion model, released in december 2018[2]. However, one could also argue that the introduction of the quantum computer has not yet begun, as quantum supremacy or useful quantum computation has not yet been reached.

- Milestone 3: **Large-scale production and diffusion**. The definition of large-scale production and diffusion is subdivided into three elements [15]:
  - A standard product that can either be reproduced multiple times or that can be combined in many different ways, but based on the same standard platform.
  - A production unit with dedicated production lines (either for industrial production or a standard product).
  - Diffusion of the product.

  This is the milestone which distinguishes products that are still in the pre-diffusion phase and those which have started the actual diffusion phase and also the proof that quantum computing is still in the pre-diffusion phase. One could argue that some form of diffusion of the product has begun, however, the first two elements of this milestone have not been reached yet.

  There is no standard product, currently there are various deviating ways of producing qubits, such as spin qubits, superconducting qubits, neutral atoms, NV centers and photonic qubits. It remains unclear which type of qubit will ultimately prove 'the best' for reaching the quantum supremacy era. Furthermore, there is also no standardized way to produce qubits on a large scale or using production lines yet, which is mainly due to the complex nature of the chips, which means the second element is not complete either.

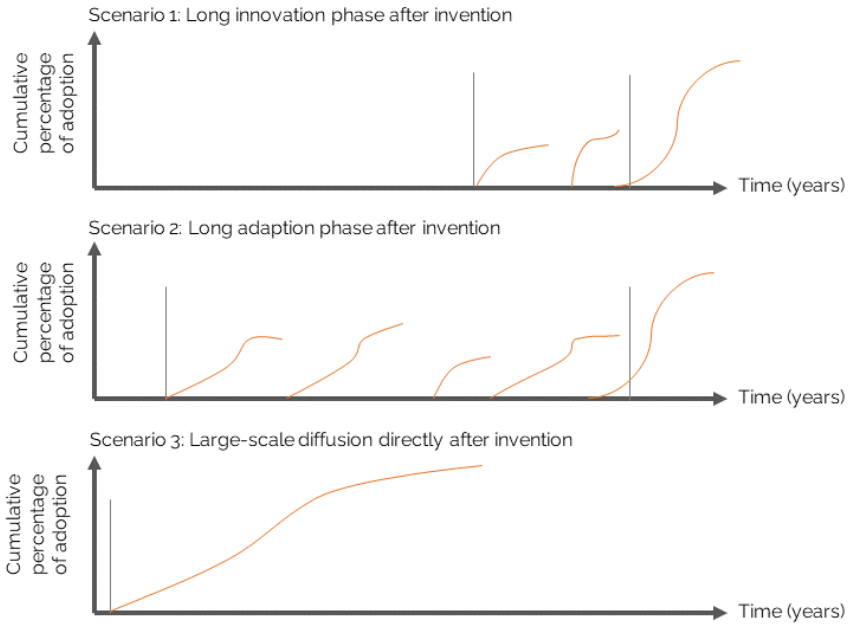



*Figure C.4: Three scenarios other than the 'average' scenario after the invention of a breakthrough technology, as found in a case study by [15].*

The pre-diffusion phase itself can be further divided into two subsequent periods: the time between invention and introduction is called the innovation phase and the time between introduction and large-scale production and diffusion is called the adaptation phase [15]. A visual

[1] https://fortune.com/2021/10/05/quantum-computer-d-wave-google-ibm-gate-model/
[2] https://physicsworld.com/a/ion-based-commercial-quantum-computer-is-a-first/

representation of the pre-diffusion phases and the subsequent large-scale diffusion is shown in figure C.3.
Ortt examined fifty different cases of new high-tech products and determined that the average duration of the innovation and adaptation phases is 10.0 and 6.7 years respectively [15]. This detailed case study also revealed that the 'average' pattern of (pre-)diffusion as shown in figure C.3 can behave rather differently in specific cases. These 'anomalies' can in turn be divided into three distinct scenarios [15]:

- A long innovation phase.
- A long adaptation phase.
- Almost no innovation or adaptation phase, but rather immediate large-scale diffusion after the moment of invention.

Despite the scientific evidence for this model, there is one major drawback related to these three identified anomalies. The model works perfectly in hindsight or when the technology is starting to enter the market stabilization phase, but as long as the technology remains in either the innovation or adaptation phase, it is incredibly difficult to tell when pre-diffusion ends. This signifies that this method lacks the forecasting ability needed for this research, at this moment.

Therefore, it is highly recommend for future scholars to pursue this theory once the technology has advanced further, but for the current nascent stage quantum computer chips are in, it cannot yet be considered scientifically relevant.

# Chapter D.
# Workshop Results

# Exercise #1

- Everyone received sticky notes
- The assignment:
  - I would like you to write down as many **Key Performance Indicators (KPIs)** as you can think of, which would be necessary to determine either the **performance** or the **quality** of a **quantum computing chip**
  - Please **do not talk** to each other regarding your ideas
  - You get **ten minutes** to think of as many potential KPIs as possible
  - Note: please try to write down your ideas in a readable manner

1

# A summary of my thesis so far

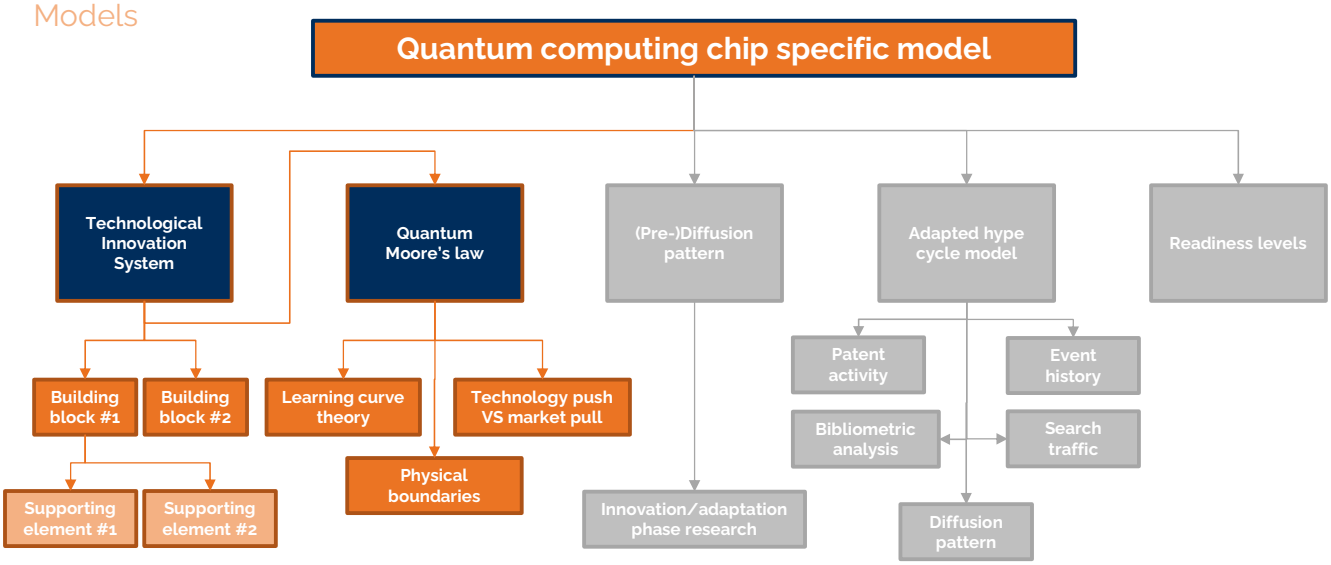
## Decision table

| | 1. Industry Trends | 2. Hype cycle model adaptation | 3. TRL + MRL | 4. Moore's law | 5a. Diffusion of Innovations | 5b. Technological Innovation System Framework |
|---|---|---|---|---|---|---|
| **Literature available?** | | *Some* | | Yes | Yes | Unsure |
| **Ability to model #quantum chips** | | No | | Yes | Too early | Maybe |
| **Ability to model market growth** | | Not scientific enough | | Yes | Too early | Maybe |
| **Scientific proof** | | No | | Partially | Yes | Unsure |
| **Connection to other methods** | | Diffusion of innovations and trends | | Diffusion of innovations | Hype cycle and moores law | Diffusion of innovations |
| **Use for further research?** | Not necessary for now | No | No | Yes | No | Yes |

2

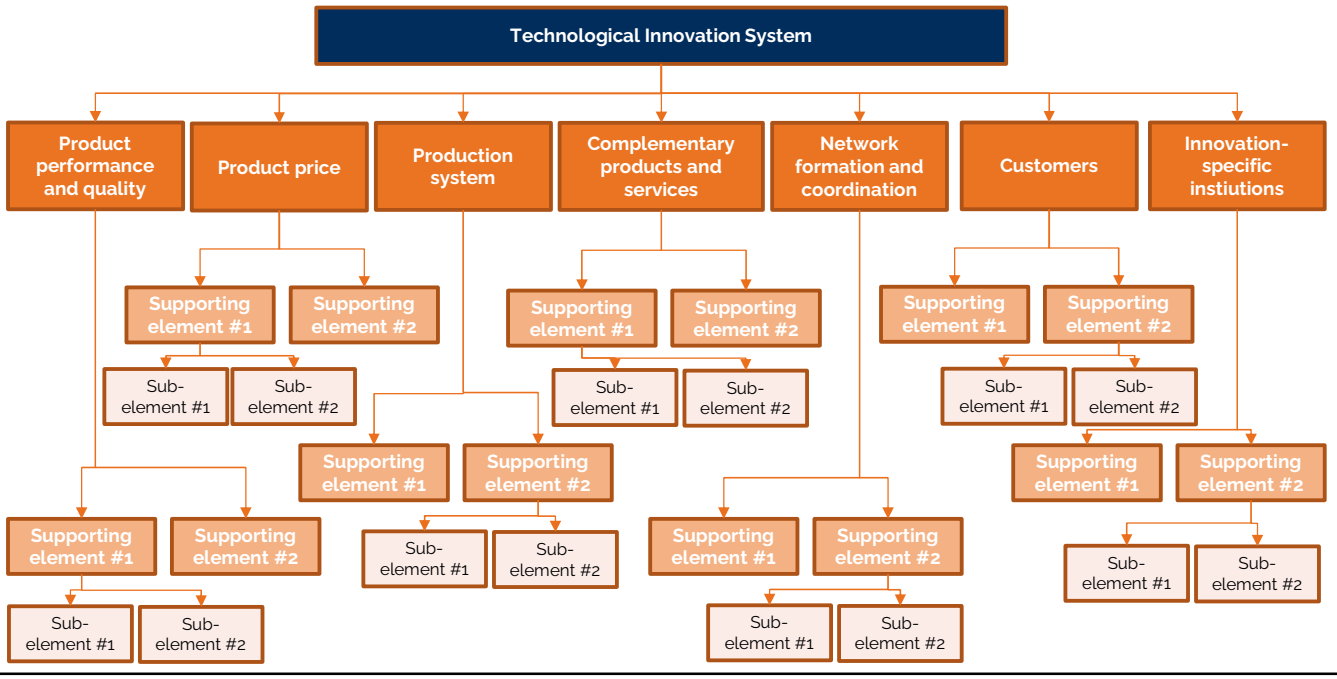
## The underlying models of the methods, and the method I will use

Models




3

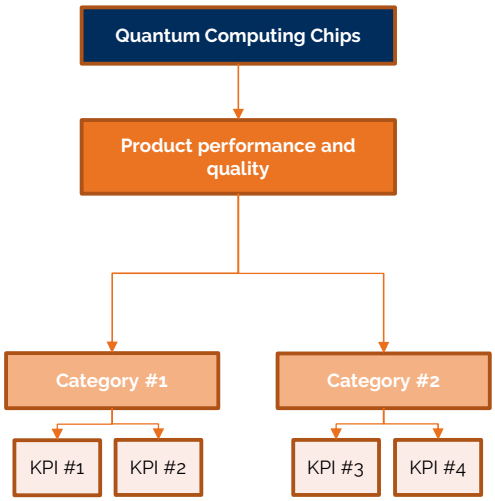
## High-over example of the TIS Framework and its several layers




4

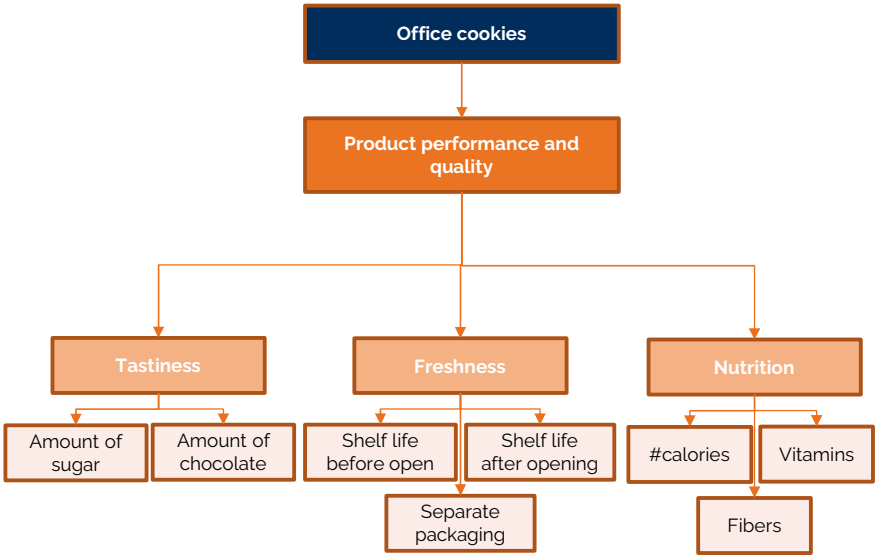
# Exercise #2

- Everyone pair up in groups of **two people**
- Make sure you hold on to your sticky notes from exercise #1
- The assignment:
  - **Take the time** to look at each other's sticky notes, ask for explanation where necessary
  - Together, try to create a model using the sticky notes, which is able to determine the overall **performance and quality** of a **quantum computing chip**
    - To do so, add an additional layer of **categories** to the sticky notes and use these to create **Mutually Exclusive, Collective Exhaustive** groups. This means there is **no** considerable overlap, but together **everything** is covered.
    - If deemed **necessary**, additional **new** sticky notes can be added to complete your model



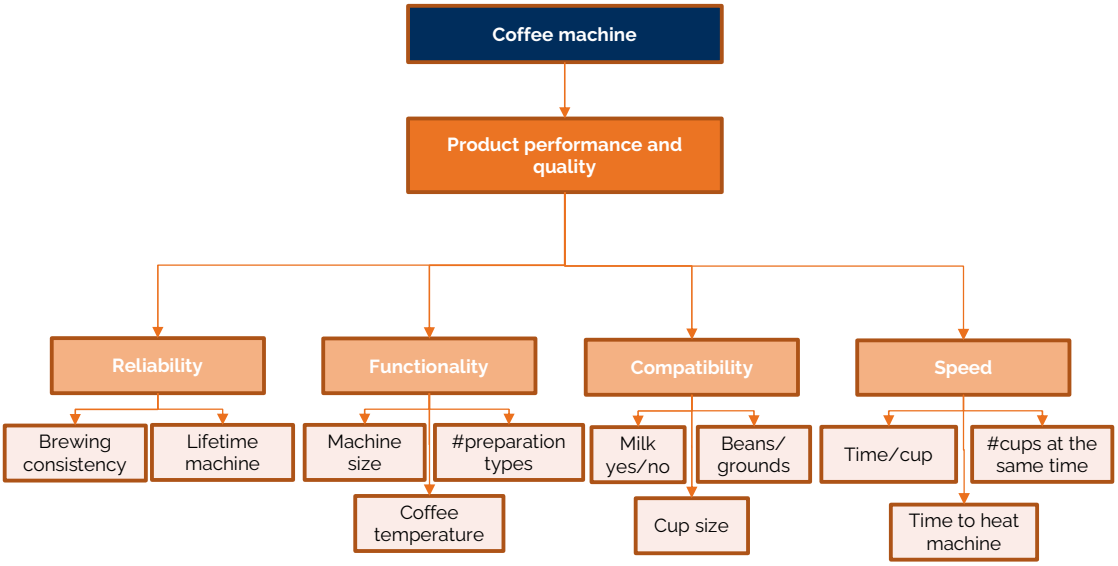

5

# Example




6

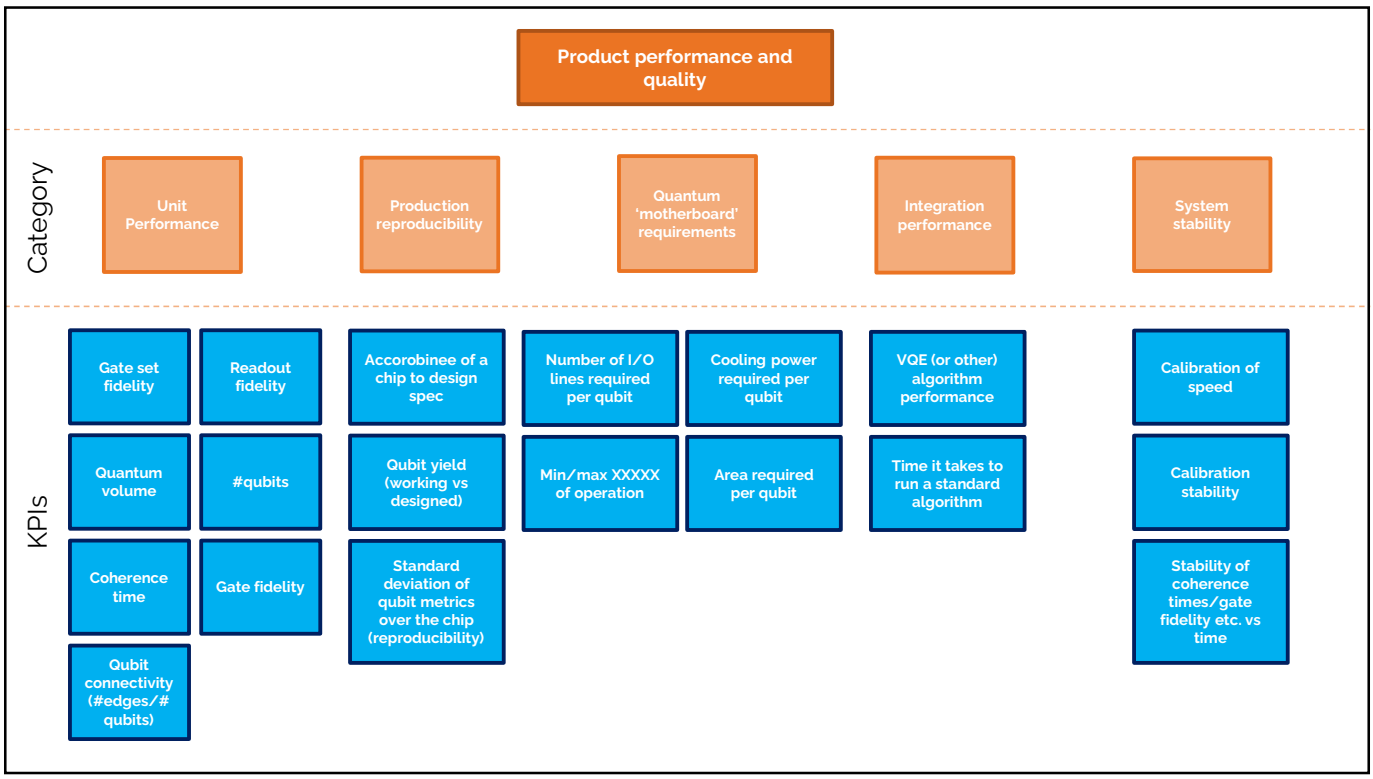
## Example



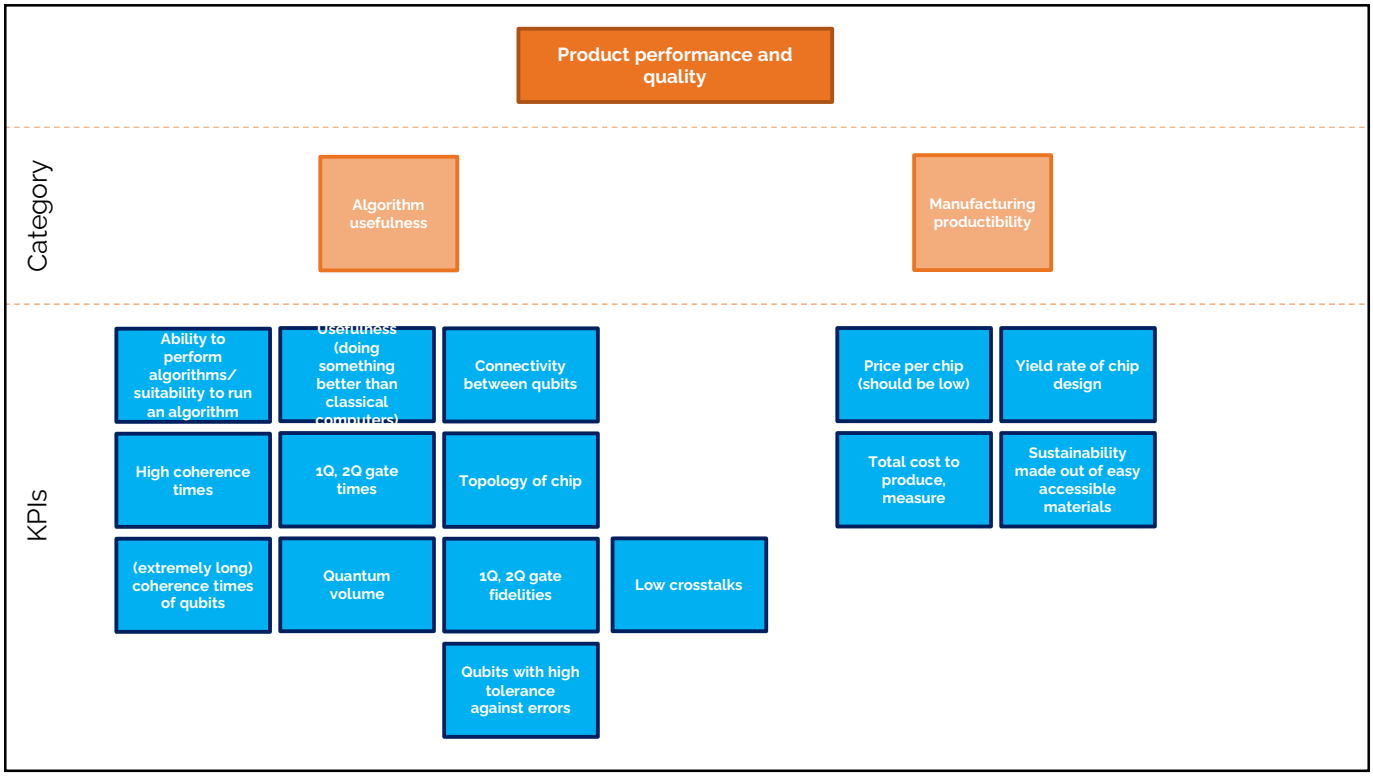

7

## Results of the workshop on 'Product performance and quality'

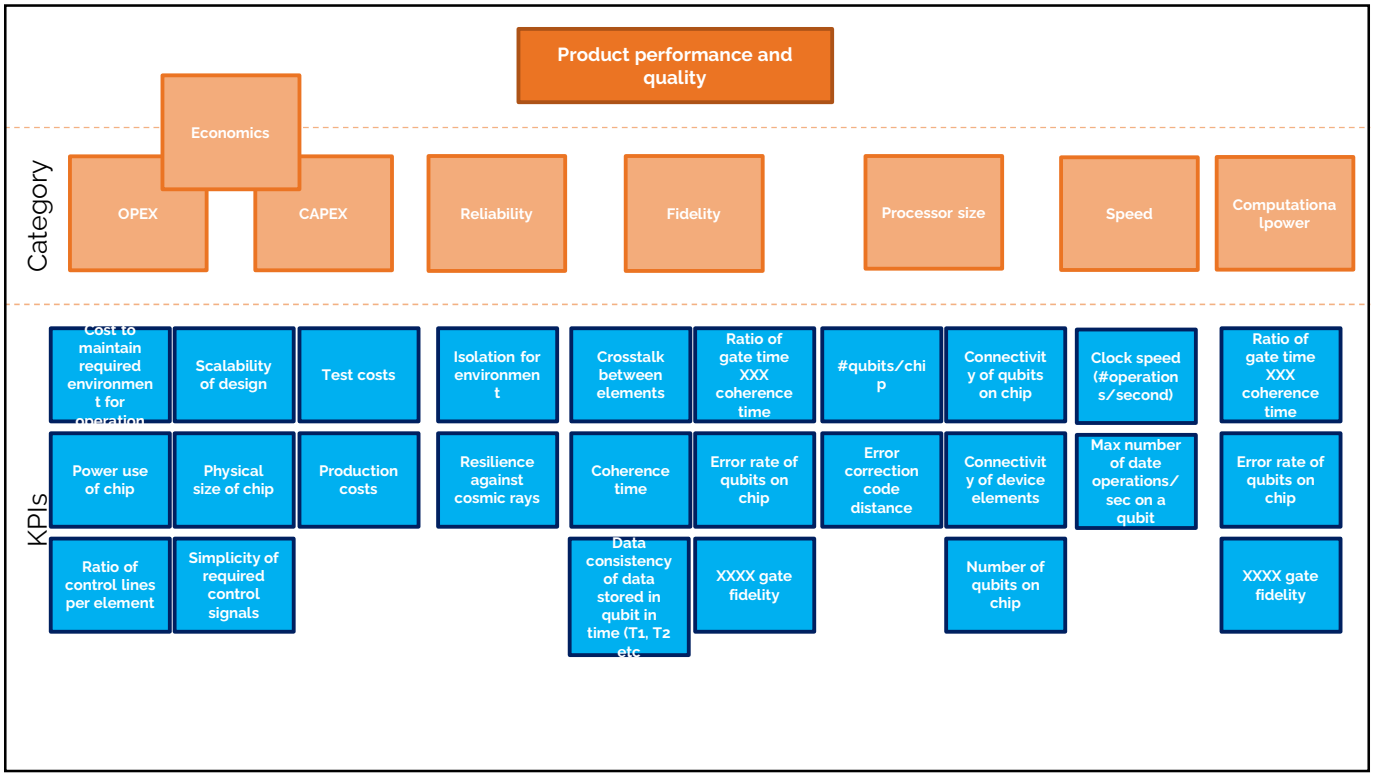
8


Product performance and quality
Category
Unit Performance
Production reproducibility
Quantum 'motherboard' requirements
Integration performance
System stability
KPIs
Gate set fidelity
Readout fidelity
Quantum volume
#qubits
Coherence time
Gate fidelity
Qubit connectivity (#edges/# qubits)
Accorobinee of a chip to design spec
Qubit yield (working vs designed)
Standard deviation of qubit metrics over the chip (reproducibility)
Number of I/O lines required per qubit
Min/max XXXXX of operation
Cooling power required per qubit
Area required per qubit
VQE (or other) algorithm performance
Time it takes to run a standard algorithm
Calibration of speed
Calibration stability
Stability of coherence times/gate fidelity etc. vs time

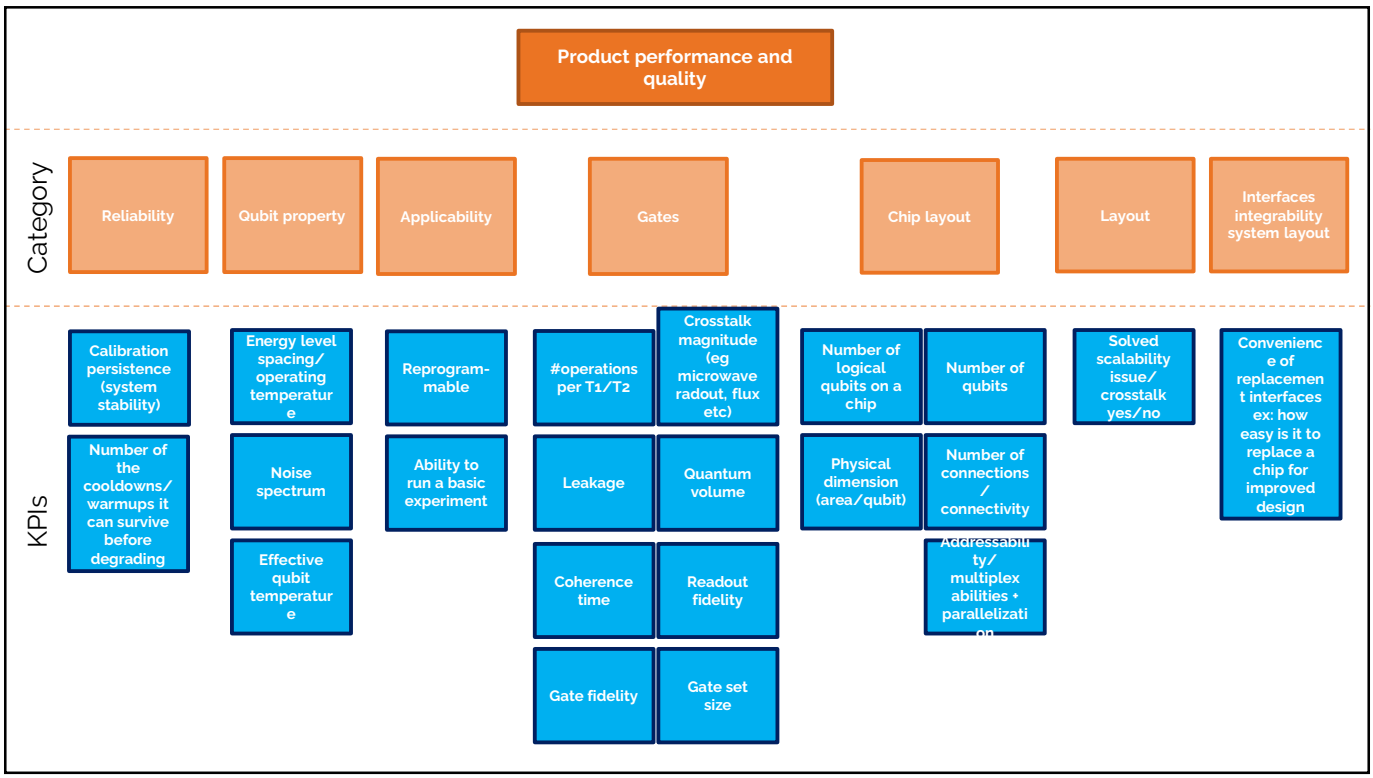
9


Product performance and quality
Category
Algorithm usefulness
Manufacturing productibility
KPIs
Ability to perform algorithms/ suitability to run an algorithm
Usefulness (doing something better than classical computers)
Connectivity between qubits
High coherence times
1Q, 2Q gate times
Topology of chip
(extremely long) coherence times of qubits
Quantum volume
1Q, 2Q gate fidelities
Low crosstalks
Qubits with high tolerance against errors
Price per chip (should be low)
Yield rate of chip design
Total cost to produce, measure
Sustainability made out of easy accessible materials

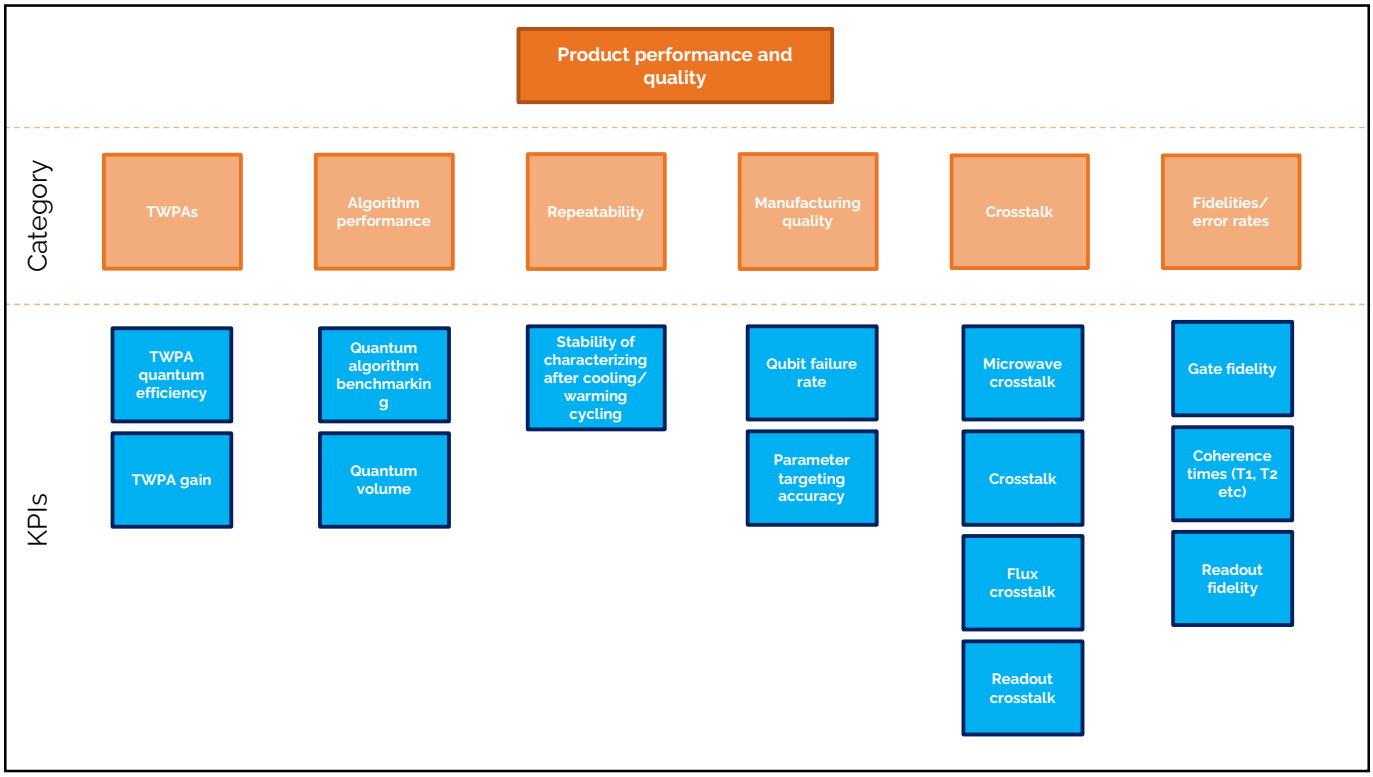
10


Product performance and quality
Category
Economics
OPEX
CAPEX
Reliability
Fidelity
Processor size
Speed
Computationa lpower
KPIs
Cost to maintain required environmen t for operation
Scalability of design
Test costs
Isolation for environmen t
Crosstalk between elements
Ratio of gate time XXX coherence time
#qubits/chi p
Connectivit y of qubits on chip
Clock speed (#operation s/second)
Ratio of gate time XXX coherence time
Power use of chip
Physical size of chip
Production costs
Resilience against cosmic rays
Coherence time
Error rate of qubits on chip
Error correction code distance
Connectivit y of device elements
Max number of date operations/ sec on a qubit
Error rate of qubits on chip
Ratio of control lines per element
Simplicity of required control signals
Data consistency of data stored in qubit in time (T1, T2 etc
XXXX gate fidelity
Number of qubits on chip
XXXX gate fidelity

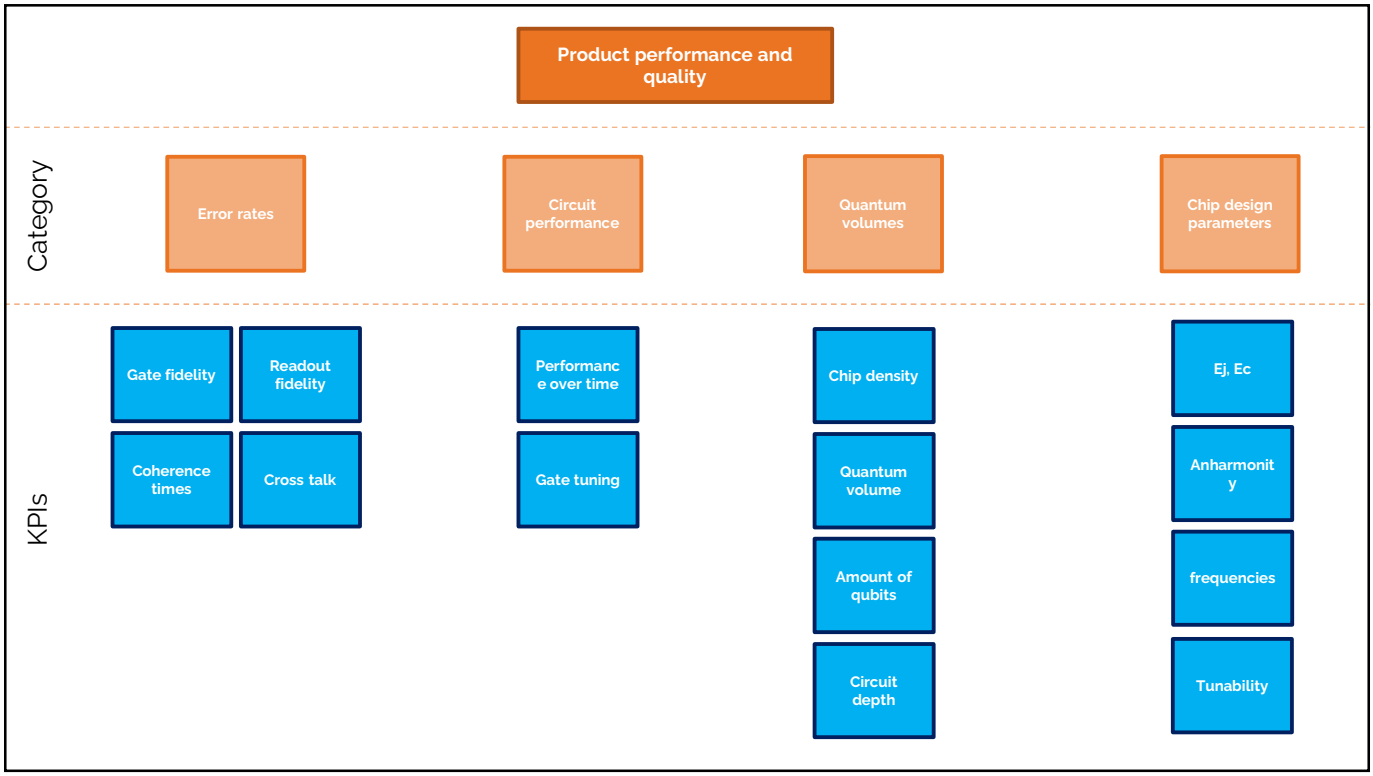
11


Product performance and quality
Category
Reliability
Qubit property
Applicability
Gates
Chip layout
Layout
Interfaces integrability system layout
KPIs
Calibration persistence (system stability)
Number of the cooldowns/ warmups it can survive before degrading
Energy level spacing/ operating temperatur e
Noise spectrum
Effective qubit temperatur e
Reprogram- mable
Ability to run a basic experiment
#operations per T1/T2
Crosstalk magnitude (eg microwave radout, flux etc)
Leakage
Quantum volume
Coherence time
Readout fidelity
Gate fidelity
Gate set size
Number of logical qubits on a chip
Number of qubits
Physical dimension (area/qubit)
Number of connections / connectivity
Addressabili ty/ multiplex abilities + parallelizati on
Solved scalability issue/ crosstalk yes/no
Convenienc e of replacemen t interfaces ex: how easy is it to replace a chip for improved design

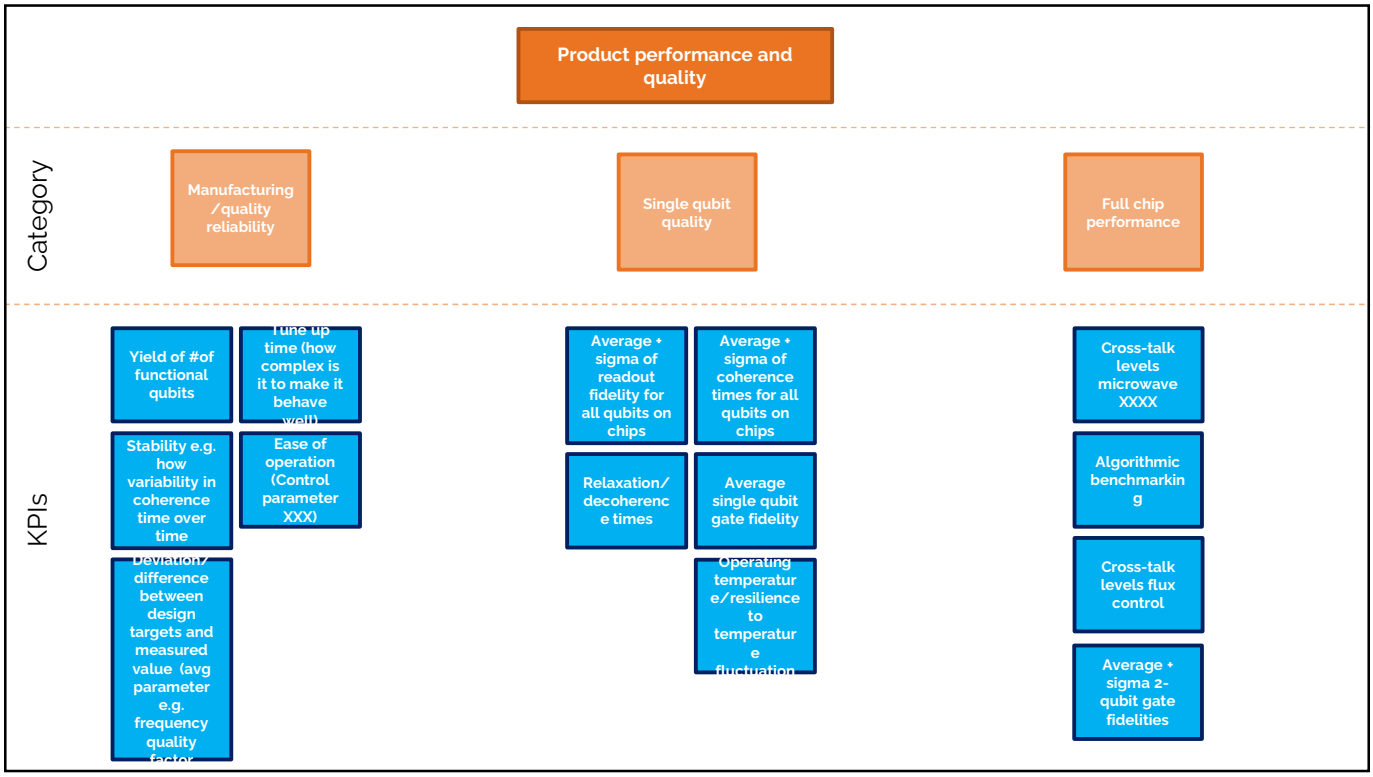
12


Product performance and quality
Category
TWPAs
Algorithm performance
Repeatability
Manufacturing quality
Crosstalk
Fidelities/ error rates
KPIs
TWPA quantum efficiency
TWPA gain
Quantum algorithm benchmarking
Quantum volume
Stability of characterizing after cooling/ warming cycling
Qubit failure rate
Parameter targeting accuracy
Microwave crosstalk
Crosstalk
Flux crosstalk
Readout crosstalk
Gate fidelity
Coherence times (T1, T2 etc)
Readout fidelity

13


Product performance and quality
Category
Error rates
Circuit performance
Quantum volumes
Chip design parameters
KPIs
Gate fidelity
Readout fidelity
Coherence times
Cross talk
Performance over time
Gate tuning
Chip density
Quantum volume
Amount of qubits
Circuit depth
Ej, Ec
Anharmonicity
frequencies
Tunability

14


Product performance and quality
Category
Manufacturing /quality reliability
Single qubit quality
Full chip performance
KPIs
Yield of #of functional qubits
Tune up time (how complex is it to make it behave well)
Stability e.g. how variability in coherence time over time
Ease of operation (Control parameter XXX)
Deviation/ difference between design targets and measured value (avg parameter e.g. frequency quality factor
Average + sigma of readout fidelity for all qubits on chips
Average + sigma of coherence times for all qubits on chips
Relaxation/ decoherence times
Average single qubit gate fidelity
Operating temperature/resilience to temperature fluctuation
Cross-talk levels microwave XXXX
Algorithmic benchmarking
Cross-talk levels flux control
Average + sigma 2-qubit gate fidelities

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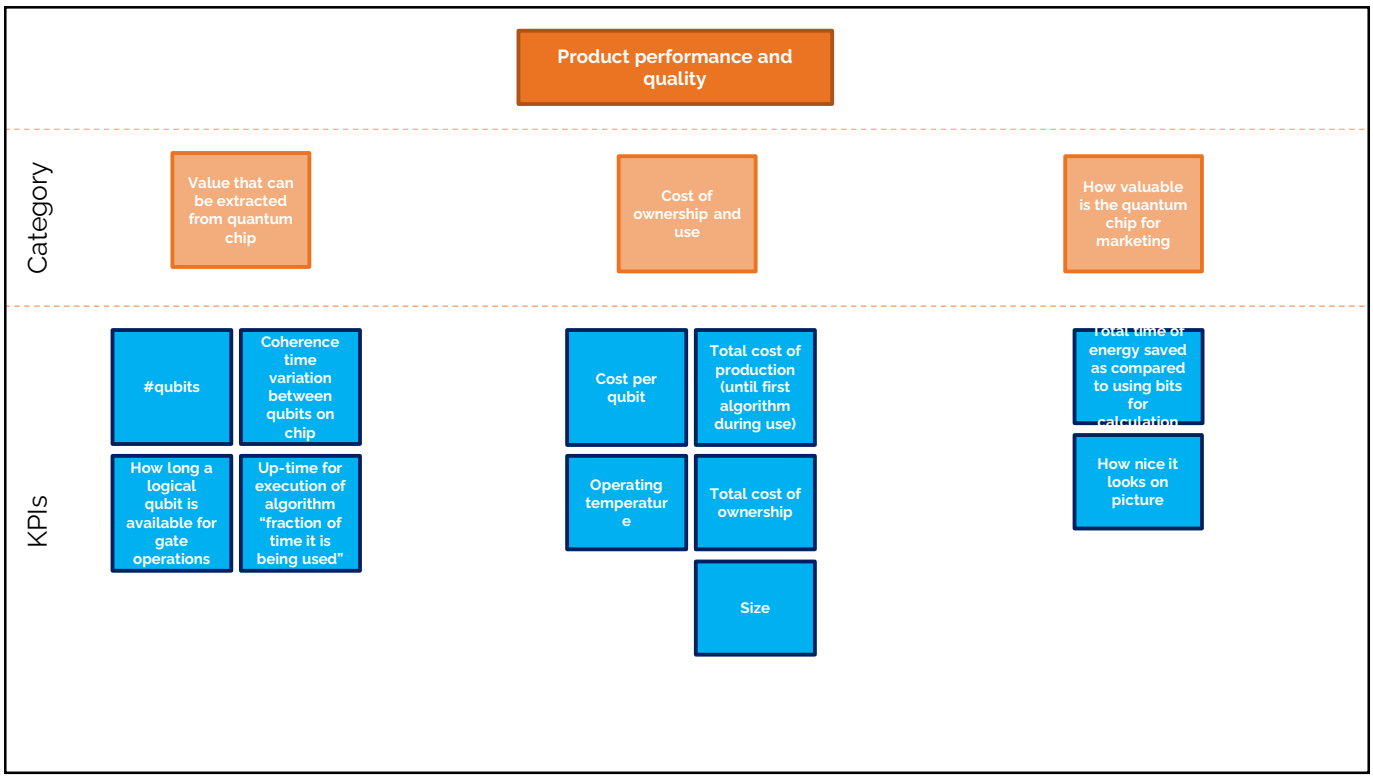
Product performance and quality
Category
Value that can be extracted from quantum chip
Cost of ownership and use
How valuable is the quantum chip for marketing
KPIs
#qubits
Coherence time variation between qubits on chip
How long a logical qubit is available for gate operations
Up-time for execution of algorithm "fraction of time it is being used"
Cost per qubit
Total cost of production (until first algorithm during use)
Operating temperature
Total cost of ownership
Size
Total time or energy saved as compared to using bits for calculation
How nice it looks on picture

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# Chapter E.
# Interviewee list

- Interviewee A. Dr. ir., quantum expert for a quantum startup.
- Interviewee B. ir., quantum engineer for a quantum startup.
- Interviewee C. ir., quantum engineer for a quantum startup.
- Interviewee D. ir., quantum business expert.