Fraunhofer IPT

White Paper

Quantum Computing – A Technology Management Perspective

Contents

Management summary

Quantum computing surpasses the gain in performance of regular computational innovations by utilizing the principles of quantum physics. By shifting away from conventional computing technologies, quantum computing opens up new potentials in handling data-based tasks in industrial value creation.

Archetypical applications include optimization, simulation, artificial intelligence, and factorization. In all relevant application domains of industrial companies these archetypes have long-term potentials – from manufacturing to research and development to supply chain optimization. Nevertheless, the currently explored use cases of quantum computing do not yet generate significant business value for companies. They are only geared towards exploring problem characteristics that align well with the principles of quantum computing. Therefore, in the coming years development efforts will be required for value-generating application scenarios.

As a result, companies do not need to undertake immediate implementation efforts. Since building up know-how for quantum computing is far from trivial it is however crucial to understand the technology's characteristics, principles and potentials and to organize the groundwork upfront. To guide the technology journey of manufacturing companies, the present whitepaper aims to provide insights into the functional principles of quantum computing and to give a first outlook on currently explored use cases. The use case analysis indicates that typical optimization tasks in logistics and manufacturing are currently being explored, whereas simulation use cases are primarily being investigated for research and development purposes.

"Because quantum computing technology is so different from the information technology we use now, we have only a very limited ability to glimpse its future applications [...]."

Preskill (2018) [1]

Motivation: A shifting paradigm for computing

Conventional computing and opportunities from exponential data growth

Conventional computing based on transistors has long served as the backbone of computation, driving remarkable advancements across various domains. In the past few decades, their development has consistently aligned with Moore's law, doubling their computational power approximately every two years [2]. However, the progress of traditional computers could face physical restrictions imposed by transistor and semiconductor technology. This suggests that the exponential increase in computing power, to which we have become accustomed, may slow down at some point [3]. Beyond these potential hardware constraints, there are specific computational tasks that even high-performance computers (HPCs) struggle to tackle effectively [4]. These tasks comprise simulations, optimization procedures, and cryptographic challenges, all of which demand significant computational resources. Hence, researchers and engineers are turning to alternative technologies like quantum and neuromorphic computing to overcome limitations of conventional computing and advance computation into a new era [5].

In addition to the limitations of traditional computing technologies, industries are experiencing a significant and exponential increase in computing power demand. Figure 1 shows the increase of computing power demand from 1985 until today – especially since the emergence of generative AI, the demand for computing power has doubled every two months while according to Moore's law the number of transistors per integrated circuit and therefore computational speed is doubling only every two years [6].

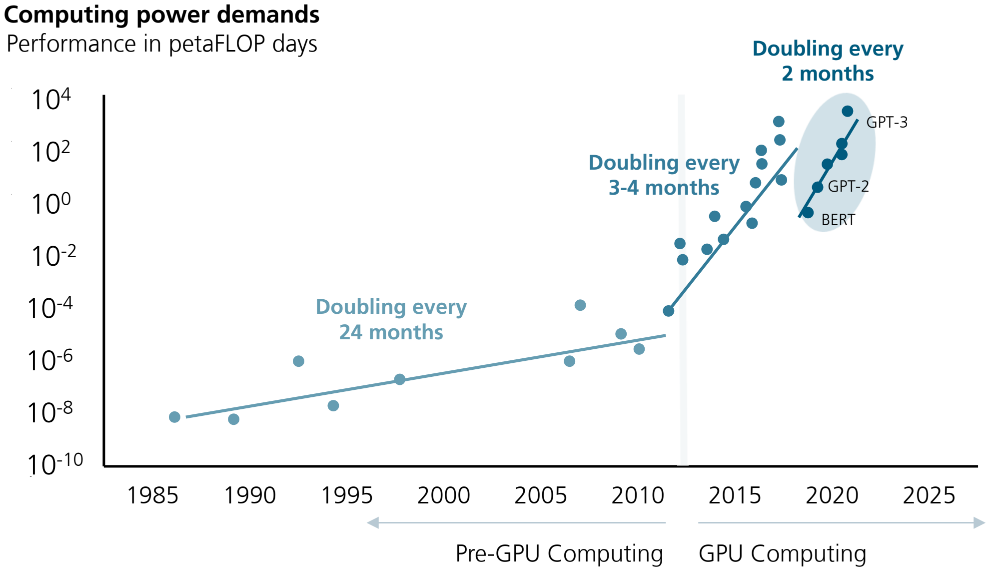

Figure 1: Demand for computational power according to the European Deep Tech Report [5]

Shifting the paradigm in computing technologies

The limitations of conventional computing technologies, combined with the tremendous increase in data generation and demand, create a promising niche for a new approach to data processing. This does not imply the obsolescence of conventional computing technologies. In fact, their relevance is still on the rise, and advancements in this field are ongoing. However, certain computational tasks will require fundamentally new ways for solving data-based tasks that go beyond the deterministic calculation of binary digits [7].

In the context of these fundamentally new ways for solving data-based tasks, the term "paradigm shift" refers to a transformative approach that fundamentally alters the way in which technologies address specific problems or execute tasks [8]. Quantum computing serves as an excellent example of such a technology, holding promise in addressing difficult data-based tasks. Many experts emphasize the disruptive potential quantum computing holds for solving data-based challenges [9].

Although quantum computers are currently limited in performance and lack practical value for businesses, their disruptive trajectory and the strong innovation dynamic in this field, should still put them on the companies' technology radars [10]. Therefore, various use cases are explored to create an understanding of how companies could utilize quantum computing in the future.

The following sections introduce prospective technology users to the basic principles of quantum computing. Afterwards, a closer look at the concept of quantum advantage is given, emphasizing its importance for the effective application of quantum computing. Finally, a variety of use cases currently under investigation is outlined, providing readers with an understanding of the types of problems that may be suitable for quantum computing in the future.

Fundamentals of quantum computing

Unlike classical computers, quantum computers use the laws of quantum physics and hereby establishing a new paradigm for computation. Quantum computers adhere to the strange and counterintuitive laws of quantum mechanics and introduce a new unit of information, the quantum bit (short: qubit). Qubits depend on quantum principles, such as superposition and entanglement, enabling them to carry out appropriate computational tasks in parallel and at an exceptional speed [11].

Figure 2 illustrates the principles of superposition and entanglement. Some physicists argue that these phenomena must be accepted and cannot be understood completely [12], [13]. Nevertheless, the following is an attempt to explain the principles based on the current state of knowledge.

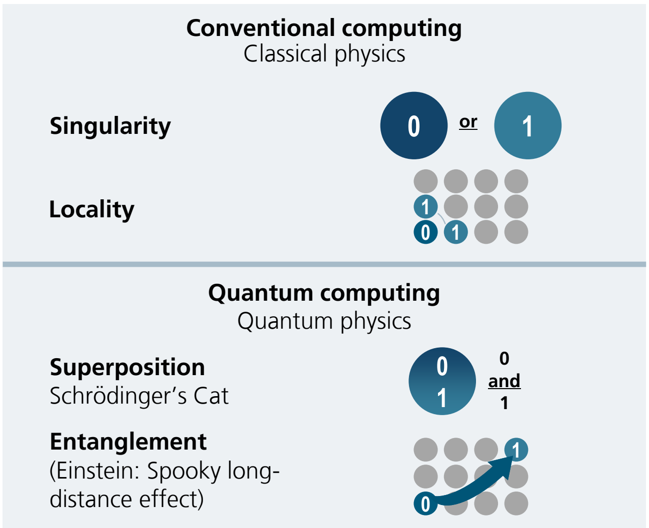

Figure 2: Principles of conventional and quantum computing [14]

Superposition – "Heads and tail"

The concept of superposition is not intuitive as it departs from our daily experience. Traditional bits have only two potential states – either a "zero" or a "one" – and are represented in hardware through electrical signals or their absence. By contrast, qubits exist in a spectrum of possible states between "zero" and "one", and they can be considered to simultaneously occupy both states until they are disturbed. When a qubit is disturbed, usually by a measurement process, its state collapses to either "zero" or "one" according to a certain probability distribution. Quantum computing embodies the manipulation of these probabilities. This fundamental probabilistic quality is intrinsic to quantum mechanics and is a critical element in seizing the quantum advantage [15].

Entanglement – "Spooky long distance effect"

When qubits are entangled, the state of one qubit is directly related to, or correlated with, the state of another qubit. Entanglement plays a crucial role in quantum computers' ability to process multiple possible outcomes simultaneously, effectively carrying out parallel computation [16]. Figure 3 illustrates a strongly simplified representation of the measurement process for a quantum register, which is a system comprising multiple qubits. In this instance the register consists of three entangled qubits.

The first row represents a quantum register that consists of the three entangled qubits. The second row depicts the measurement process on qubit b in the register. The remarkable

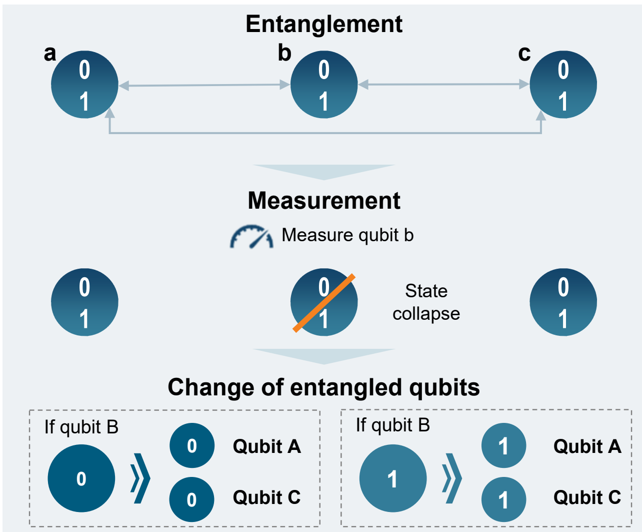

Figure 3: Simplified quantum register with entanglement of three qubits and their behavior during measurement [Own illustration]

consequence of entanglement is that the measurement of a single qubit triggers the collapse of the entire quantum register into one of two possible states. This is visually represented in the third row, displaying the two potential outcomes that result from the collapse of the quantum register following the measurement of qubit b. This phenomenon, unique to quantum mechanics, enables quantum computers to perform computations on a massive scale, exploring numerous possibilities simultaneously and potentially solving certain problems much faster than classical computers.

Low technological maturity and the goal for quantum advantage

Hardware manufacturers currently face the challenge of translating theoretical principles into practical hardware to exploit the potential of quantum computing. The key to this endeavor lies in realizing functional qubits with stable states and long coherence. Coherence, meaning the property that allows qubits to exist in a superposition of states, is crucial for quantum computations. However, maintaining coherence for extended periods is a major challenge in hardware development. Current hardware design approaches are sensitive to noise, which disrupts and degrades the coherence of qubits. As a result, the field of quantum computing currently has low technological maturity with no dominant design of quantum computers having emerged as the frontrunner so far. As a consequence, various manufacturers are pursuing different approaches concurrently to overcome coherence limitations and improve the overall performance of quantum systems [17].

IBM, one of the pioneers in quantum computing development, utilizes superconducting qubits, which have two energy levels corresponding to two states. These qubits are manipulated through the application of a microwave field [18]. IonQ, on the other hand, isolates single ionized atoms using electromagnetic forces to generate trapped ion qubits. The atoms are controlled using laser and cooling technologies [19], [20]. Arque Systems, an Aachen-based start-up, is pursuing a promising approach that relies on so-called spin qubits. This approach utilizes established semiconductor manufacturing techniques, offering high scaling potential [21]. In addition to the aforementioned approaches, there are numerous other possibilities for realizing quantum bits. However, as of 2023 and within the NISQ era, no quantum system has yet achieved a so-called practical quantum advantage [22].

The achievement of quantum advantage refers to the point at which a quantum computer can solve a problem faster or more efficiently than classical computers, marking a significant milestone in the development of practical quantum computing applications [23]. According to Google, a theoretical quantum advantage has already been achieved back in 2019. The underlying problem was, however, artificially formulated and designed to align with the inherent capabilities of the quantum computing systems [24]. Therefore, achieving a practical advantage, such as solving a problem that yields actual benefits, and an industry-relevant advantage are objectives that still remain distant. As a consequence, it also becomes clear that a refined understanding of quantum advantages is required for technology management in industry. Companies and users should therefore closely monitor potential breakthroughs towards a quantum advantage, while keeping in mind the distinct levels of a quantum advantage. Figure 4 shows a differentiated view of the term quantum advantage.

The proposed three-step scale for quantum advantage (see fig. 4) also reflects, that the first achievements of a practical quantum advantage will likely be limited to niche problems and therefore may not have broad relevance for every industrial company. Quantum computers will only find their way into widespread use when an industry-relevant quantum advantage is achieved.

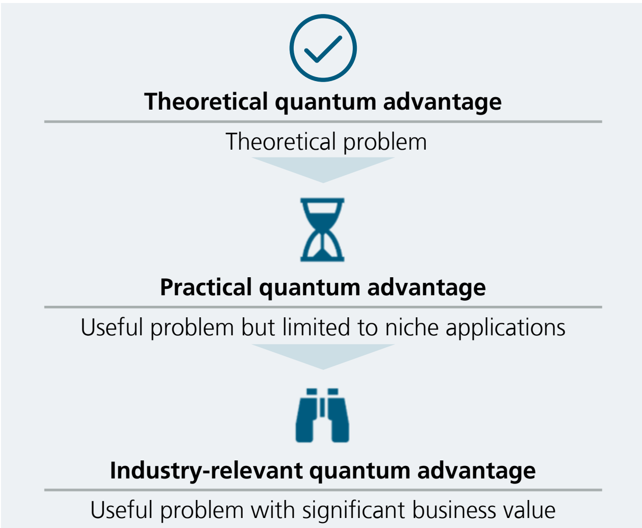

Figure 4: Levels of quantum advantage [Own illustration]

Applications: Exploring potential areas for a practical quantum advantage

The suitability of data-based problems for a quantum advantage does not extend to every conceivable task. A key requirement is that the characteristics of a problem match well with the capabilities of a quantum computer to achieve a practical advantage. The exact characteristics that determine the suitability for quantum benefits are still the focus of intense research efforts. In this context, the use cases that are currently being explored by companies and research institutions serve as a first indication of possible industrial application potentials.

Quantum computing use cases are typically categorized into four primary archetypes: optimization, simulation, artificial intelligence, and factorization [25]. Optimization problems involve finding the best solution among a range of feasible options while considering specific constraints. Classical computers encounter significant hurdles when faced with optimization problems because the number of potential solutions increases exponentially as problem sizes expand. Quantum computers have the potential to efficiently tackle optimization challenges by discovering solutions within shorter times or identifying superior solutions [26].

Modeling and simulating quantum mechanical systems accurately is challenging for conventional computing due to the complex behavior of quantum objects, which is attributed to quantum phenomena such as superposition and entanglement. Given that quantum computers are composed of quantum objects they are naturally suited to carry out the simulations of quantum systems [27].

With regard to artificial intelligence, algorithms refine their capabilities by utilizing training data. Therefore, improvements in training quality and the utilization of larger datasets contribute significantly to enhancing their overall performance. Quantum computing could potentially manage larger sets of data in a shorter time. By replacing classical training processes with quantum algorithms, the quality of training could be improved, thus enhancing AI capabilities [28].

Finally, prime factorization involves breaking down a number into the product of smaller numbers and continuing the process until each number is reduced to a prime number. When faced with a large number resulting from the multiplication of two prime numbers, classical computers find it practically infeasible to compute the constituent prime numbers within a useful timeframe. This is significant because many cryptographic protocols rely on the complexity involved in determining the prime factorization of large numbers. Hence, quantum computers have the ability to use Shor's algorithm, which greatly reduces the time needed to decompose a number into its prime factors [29].

To provide users with a better understanding of potential use cases, this section presents examples from the three archetypes optimization, simulation and AI, aligned with the typical functions of a company in the areas of manufacturing, research and development, and logistics. The archetype factorization is not considered, as it is mainly relevant for the very specific use cases of decrypt passwords.

Manufacturing

The growing diversity in product configurations presents challenges for manufacturing processes and job scheduling. Optimizing assembly lines becomes more complex due to variations in processing times at each station. Further, a comprehensive digitization of the planning process is difficult due to the high level of complexity. Also, simulations of machining processes offer benefits but are computationally expensive. Therefore, quantum computing shows promise in overcoming current computational limitations [30]-[33].

Figure 5 presents a summary of various use cases that have been explored through an extensive literature reserach in the context of quantum computing and manufacturing. It includes optimization tasks such as paint shop scheduling, robot trajectory planning, flexible job shop scheduling, and factory layout planning. Areas for future applications also include simulation tasks like manufacturing process simulation, focusing on minimizing simulation time. Additionally, there are artificial intelligence tasks such as surface quality supervision and predictive maintenance of electric vehicle components, both aiming to minimize surface quality irregularities and component failures. The analysis demonstrates that a considerable number of the examined use cases involve well-established issues in the field of manufacturing. It remains to be established whether these cases are of sufficient value to justify the use of quantum computers.

Optimization

Robot Trajectory Planning:
Determining the most efficient workload distribution and optimal sequencing of robotic tasks within larger production lines *[30]*

Factory Layout Planning:
Layout planning for functional units (e.g. machines) to minimize distance and material handling costs *[31]*

Manufacturing Order Optimization:
Continuous and process-parallel optimizing of machine allocation and process sequences *[32], [33]*

Simulation

Manufacturing Process Modelling:
Modeling and simulating of manufacturing processes using numerical methods such as the finite element method (FEM) *[34]*

Artificial Intelligence

Predictive Maintenance:
Predicting failure of components based on sensor data for e.g., critical vehicle components *[35]*

Surface Quality Supervision:
Supervising surface quality in manufacturing processes using computer vision *[36]*

Figure 5: Application potentials in manufacturing (Extract) [Own illustration]

Research and development

Quantum computers are well-suited for simulating natural systems, making them valuable in research and development. Their potential in this area is immense, as many research questions revolve around understanding the behavior of materials and individual molecules. Quantum computers offer unparalleled opportunities to explore and analyze the complexities of nature at a fundamental level, thanks to their ability to handle complex quantum states and interactions. This creates new possibilities for scientific discovery and innovation in fields such as materials science, chemistry, and biology.

In addition to simulation use cases, quantum computing also has potential in optimization and artificial intelligence, as shown in Figure 6. These include tasks such as the design and infrastructure optimization, which deal with the optimal allocation of objects in a given solution space, or the training of AI models being used for R&D purposes.

The analysis indicates that, compared to manufacturing, the value potential of use cases in research and development can be higher. Specifically, using quantum computers for developing new drugs or discovering unknown materials offers tremendous potential. Therefore, companies in these industries should closely monitor technological advancements.

Optimization

Automotive Vehicle Composition:
Optimizing the placement of automotive vehicle components to minimize cost and fulfill regulations *[37], [38]*

Energy System Infrastructure:
Identifying energy facility locations that optimize costs and satisfy energy demands *[39]*

Simulation

Risk & Impact Management:
Simulating scenarios to quantify risks and impact of measures, within medical, IT and financial contexts *[40]-[42]*

Vehicle & Aircraft Design :
Improving the design of aircrafts and vehicles through the simulation of fluid dynamics and material behavior *[43]-[45]*

Chemistry:
Modelling chemical reactivity to develop drugs or improve battery design principles *[46]-[48]*

Artificial Intelligence

Disease Detection:
Increasing the accuracy of machine learning algorithms to better predict and classify diseases *[49]*

Vehicle & Aircraft Design:
Improving the design of aircrafts or vehicles by improving aerodynamical simulations through artificial intelligence *[50]*

Fraud Detection:
Using a quantum machine learning approach to detect fraudulent online activities *[51]*

Figure 6: Application potentials in R&D (Extract) [Own illustration]

Logistics

The logistics industry faces the challenge of adapting to a dynamic environment characterized by advancing technology, changing consumer preferences, and a growing emphasis on sustainability and efficiency. Therefore, the implementation of new technology, the utilization of data, as well as the optimization of transportation routes are necessary. The thereby resulting rise in complexity requires an increase in calculation speed and computational power. Quantum computing's capability to process a vast number of variables can prove advantageous in addressing optimization problems frequently encountered in logistics. Figure 7 shows an extract of application potentials in logistics.

The computation of vehicle transport routes can optimize supply chains, ensuring cost-effective and prompt deliveries to customers and warehouses. Additionally, aircraft and truck loading can be improved by harnessing the computational effectiveness of quantum computing to optimize cargo placement, maximizing both safety and efficiency. In the field of traffic control, quantum algorithms have the potential to dynamically adjust routes in real-time, reducing congestion and travel time. These algorithms can consider variables such as weather conditions and real-time demand fluctuations, making them useful for managing transport robots in warehouse environments or for urban vehicular traffic management. In warehouse management, simulating different customer demand scenarios can improve the accuracy of predicting optimal order quantities at various time intervals. This approach balances inventory space costs, ordering expenses, and potential lost sales, resulting in profit maximization while reducing overproduction and ecological burden.

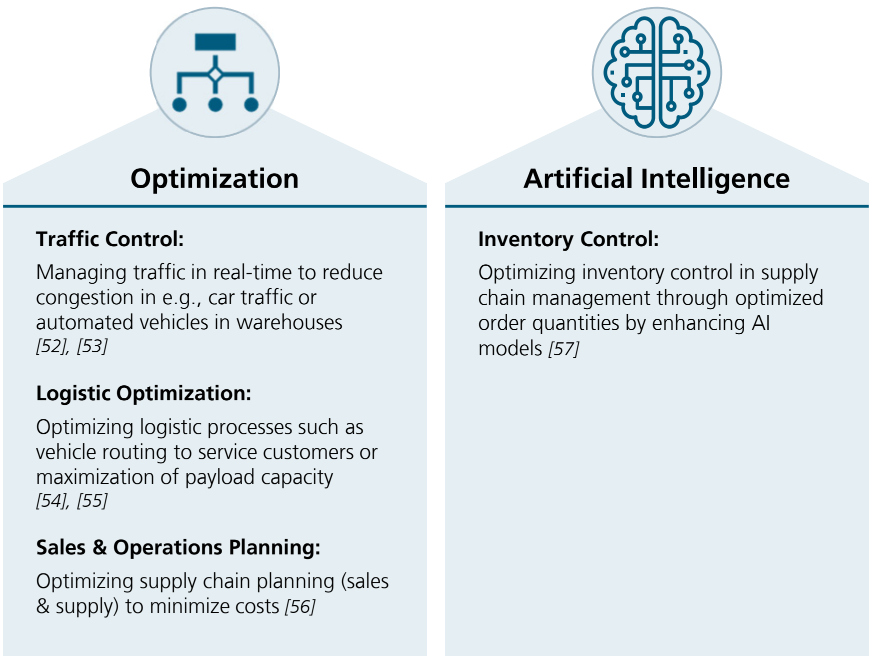

Figure 7: Application potentials in logistics (Extract) [Own illustration]

Outlook and courses for action

Quantum computing enables new potentials in handling data-based tasks by shifting away from the established paradigm of conventional computing technologies. It surpasses regular technological innovation by exploiting a different set of physics. Therefore, companies and research institutions should prepare for the future impact of quantum computing, even though a practical quantum advantage may not be achieved in the short term.

With regard to managing the paradigm-shifting technology of quantum computing, technology management offers three practical tools (see fig. 6). A promising strategy for companies is to identify and evaluate use cases for which quantum computing can offer significant advantages over conventional computing. By exploring and understanding these applications, companies can establish the necessary foundation and begin developing their quantum knowledge and competencies. Therefore, it is crucial to monitor the progress and development of quantum computing technology closely. Staying informed about advancements, breakthroughs, and trends is important in the rapidly evolving field of quantum computing. By monitoring the path of quantum advantage, companies should adjust their strategies and investments dynamically to leverage the potential benefits of quantum computing once it becomes practical.

For companies having identified potential use cases that could disrupt or boost their business model and have started to undertake early implementation actions in a field, technology roadmapping helps to plan and prioritize implementation activities. Building expertise in quantum computing is a challenging task due to the scientific depth of the topic. To effectively navigate this complex journey, companies should create a roadmap that outlines the necessary steps, resources, and timelines for building up quantum expertise.

Technology Scouting: Identification and evaluation of possible use cases
"Which future applications are disruptive for my business and operating model?"

Technology Monitoring: Systematic monitoring of QC developments
"When will a quantum advantage be achieved for the identified use cases?"

Technology Roadmapping: Planning of implementation activities
"Which steps need to be taken to apply quantum computing in my company?"

Figure 6: Technology management toolbox [Own illustration]

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DOI: 10.24406/publica-3327