QUANTUM TECHNOLOGY AND
APPLICATION CONSORTIUM

QUTAC

Industry Quantum Computing Applications

QUTAC Application Group

Quantum Computing Application Working Group Contributors

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BMW

Munich RE

BASF We create chemistry

BOSCH

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Content

Abstract

Computational technologies drive progress in industry, science, government, and society. While these technologies form the foundation for intelligent systems and enable scientific and business innovation, they are also the limiting factor for progress. Quantum computing promises to overcome these limitations with better and faster solutions for optimization, simulation, and machine learning problems.

While the past several years were characterized by significant advances in quantum computing (e.g., Google's quantum supremacy experiment), the technology is still in its infancy, lacking commercially relevant scale and applications. Research and industrialization activities are currently driven by international technology companies (e.g., IBM, Google, Amazon Web Services, Microsoft, Honeywell, Alibaba), and start-ups (e.g., IonQ, Rigetti, D-Wave). As of now, industries are critically dependent on these partners for state-of-the-art work in the field of quantum computing.

Europe and Germany are in the process of successfully establishing research and funding programs with the objective to advance the technology's ecosystem and industrialization, thereby ensuring digital sovereignty, security, and competitiveness. Such an ecosystem comprises hardware/software solution providers, system integrators, and users from research institutions, start-ups (e.g., AQT, IQM) and industry.

Quantum computing is broadly applicable to business problems in optimization, machine learning, and simulation, impacting all industries. Therefore, it is instrumental for industry to seek an active role in this emergent ecosystem. The Quantum Technology and Application Consortium (QUTAC) vision is to establish and advance the quantum computing ecosystem, supporting the ambitious goals of the German government and various research programs. We share the belief that quantum computing provides a compelling opportunity to advance digital sovereignty and ensures competitive advantages across industries.

QUTAC's application working group is comprised of ten members representing different industries, in particular automotive manufacturing, chemical and pharmaceutical production, insurance, and technology. In this paper, we (together with AIRBUS as an external contributor) survey the current state of quantum computing in these sectors as well as the aerospace industry and identify the contributions of QUTAC to the ecosystem. We propose an application-centric approach for the industrialization of the technology based on proven business impact. By formalizing high-value use cases into well-described reference problems and benchmarks, we will guide technological progress and eventually commercialization.

QUTAC's engagement will ensure early markets for quantum computing technologies. Our members are committed to contributing applications, data, as well as technological and business knowledge to the emergent ecosystems. Our results will be beneficial to all ecosystem participants, including suppliers, system integrators, software developers, users, policymakers, funding program managers, and investors.

1. Introduction

With quantum computers surpassing leading super-computers in specific computational challenges [1, 2], and the availability of Noisy Intermediate-Scale Quantum (NISQ)-era quantum computing systems [3, 4, 5, 6] outside of laboratory environments, we have entered the industrialization stage of quantum computing (QC). Globally, national research programs and private investors are heavily funding quantum technologies (e.g., UK [7], US [8, 9, 10], China [11]). Investments are motivated by the need to ensure digital sovereignty and national security and sustain the industry's competitiveness.

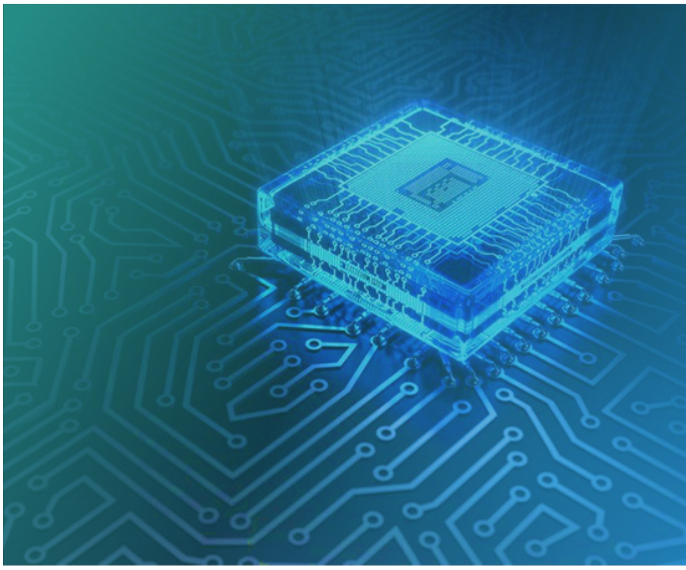
Industry Sector	Companies
Automotive Manufacturing	Volkswagen, BMW, Bosch
Chemical & Pharmaceutical	BASF, Boehringer Ingelheim, Merck
Insurance	Munich Re
Technology	Infineon, SAP, Siemens

Table 1: Industry Sectors and QUTAC members

Quantum ecosystems and markets are still in their infancy. As the technology matures, the market will grow. BCG estimates that the market size will surpass $450 billion annually in the next decade [12]. A crucial driver will be the technology's real-world use as part of business applications. Quantum computing promises to solve high-value, classically intractable computational problems in the domains of optimization, machine learning, and simulation across all industry sectors [13].

Europe needs a vibrant ecosystem to foster quantum computing development and compete on a global scale. With its internationally renowned research institutions engaged in foundational research [14] and strong industrial users [13], Germany is in an excellent position. However, industrialization in Europe has traditionally been hampered by the European paradox [15], referring to Europe's member states hosting world-leading scientific and technological research activities, but unable to convert these into global industrial and commercial leadership.

The European Union and its individual nations are establishing various programs to foster attractive ecosystems and markets for quantum technologies [16, 17, 18]. While these programs focus in particular on research and hardware technology industrialization (e.g., superconducting, ion-traps, photonic and solid-state qubits), they also emphasize the importance of holistic



ecosystems. These ecosystems are to align the entire value chain, including hardware and software solution providers, investors, and especially industry [16], which is essential for progressing high-value use cases that can advance commercialization.

Until now, industry commitment remained low, mainly because of associated high risks and delayed return on investment. The Quantum Application and Technology Consortium (QUTAC) addresses this issue. It brings together ten industrial companies from four sectors, in particular automotive manufacturing, chemical and pharmaceutical production, insurance, and technology. QUTAC's mission is to advance the German ecosystem, contributing an application-centric and business impact perspective to initiatives emerging from German and European policies. This paper presents QUTAC's application working group, surveying companies' quantum computing applications and challenges. Notably, we describe 23 quantum computing applications and their potential business impacts.

This paper is structured as follows: In section 2, we provide an overview of QUTAC. We continue with discussing a portfolio of use cases from the German industry in section 3, one of QUTAC's core assets that will guide further activities in the ecosystem. We discuss challenges for further industrialization in section 4. In section 5, we conclude with a call for action.

QUTAC's mission is to advance the German ecosystem, contributing an application and business perspective to emerging initiatives.

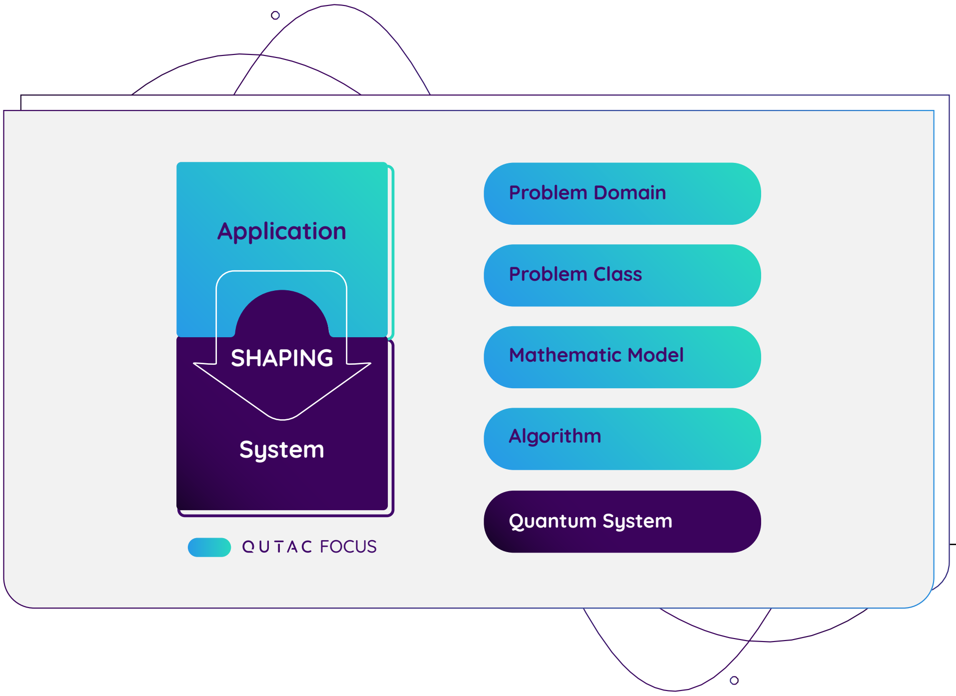


Figure 1: QUTAC Focus: QUTAC aims to shape the quantum computing ecosystem from the application perspective, balancing business impact and technological advances.

2. QUTAC: Quantum Application and Technology Consortium

QUTAC aims to raise quantum computing to the level of large-scale industrial applications while preparing our members for a new digital future. We bring together the expertise of Germany's industry to effectively advance quantum computing towards real-world applications, ensuring Germany's and Europe's digital sovereignty, national security, and competitiveness in a global economy.

QUTAC will move the emergent quantum computing ecosystem forward, supporting the ambitious goals of the German government. It comprises ten companies from four sectors (see Table 1) with the mission to contribute an industry perspective and focus on the development of the German and European quantum ecosystem. QUTAC focuses primarily on the applications of quantum computing. QUTAC members share the need to act due to the potentially disruptive impact of quantum computing on all aspects of their business and value chain. Additionally, quantum computing might allow some members to explore further opportunities in the quantum value chain, e.g., as a component or software provider.

Figure 1 illustrates the focus of QUTAC. The value chain of QUTAC members comprises complex optimization, machine learning, and simulation challenges that are likely to benefit from advances in quantum computing, providing significant business impact. Using a wide variety of problems with impact across diverse industries will provide guidance to software and hardware development.

QUTAC will participate and contribute to the emergent European quantum ecosystem collaborating closely with: (1) hardware solution providers, (2) component manufacturers, (3) software solution providers, (4) research institutions (public, private), (5) investors, and (6) end-users. Table 2 summarizes how QUTAC will provide value to all stakeholders. QUTAC's guiding principles are:

- Promote the establishment of an economically thriving, independent quantum computing ecosystem in Germany and Europe.

> QUTAC aims to raise quantum computing to the level of large-scale industrial applications while preparing our members for a new digital future.

Ecosystem stakeholder	QUTAC contribution
Hardware solution provider / component supplier	– Guidance on high-value use cases, reference problems and their business impact – Reference problems and benchmarks for assessing competitiveness of approach – Direct or indirect customer for future products
Software solution provider	– Assess the suitability of abstractions, frameworks, and services for industry problems – Guidance on end-to-end application workflows including both quantum und classical steps – Reference problems and benchmarks
Research institution and program (e.g., Hub, DLR, Fraunhofer)	– Guide application-centric research with reference problems and benchmarks – Collaborative research and industrialization – Joint ventures and spin-off opportunities
Investor	– Assess the viability of different approaches based on well-defined industry problems
Policy maker	– Industry perspective for current and future research programs – Assess the viability of different approaches based on well-defined industry problems – Reduce investment risks by early assessment of transfer opportunities – Develop a multi-perspective research landscape across all stakeholders – Explore new policies that increase ecosystem collaboration and time-to-market
QUTAC member	– De-risk through pre-competitive collaborative research – First-mover and competitive advantage for early access to technology – Explore potential business opportunities in the quantum ecosystem

*Table 2: **QUTAC Stakeholder Assessment:** QUTAC will make important contributions by providing an industry and application perspective to ecosystem stakeholders.*

The QUTAC application working group aims to identify high-impact business problems and drive the development of quantum-based, commercializable solutions.

- Raise awareness of the potential impact, and competitive advantage quantum technologies can provide across industries, motivating early investment and engagement.
- Understand, develop, and test cross-industry applications to identify commercially interesting solutions that can drive the quantum ecosystem forward.
- Contribute to the success of the government's ambitious quantum program by providing a perspective from the industry and application angle.

The QUTAC application working group aims to identify commercially attractive solutions for high-impact business problems. Members share the need to understand, develop, and evaluate cross-industrial applications on emerging quantum hardware. Such cross-industrial problems include a manifold set of optimizations, machine learning and simulation challenges in material science, engineering, production & logistics. The working group jointly identified 23 concrete use cases and common challenges that are the basis of this paper.

3. Industry Applications

While quantum computing will have a significant impact on various industries [12, 19], many questions and challenges remain: Which specific problems can be solved? Which of the NISQ quantum devices provide a quantum advantage? How can this advantage be translated into business impact? Here, we present an analysis of high-impact industry quantum applications. The analysis is based on several workshops, a structured survey, and interviews. The contributing companies have each shared up to three quantum computing use cases.

Members share the need to understand, develop, and evaluate cross-industrial applications on emerging quantum hardware.

We identified the following layers: problem domain, problem class, model, algorithm, and quantum system. To ensure consistency in cross-industry application discussions, we suggest the terminology defined in the following box.

catalytic nitrogen fixation of ammonia in the Haber-Bosch process uses up 1% of the world's energy production and

Definition:

Problem Domains: Problem areas of applied mathematics and computer science characterized by similar solution methods aiming to solve computational problems (e.g., Optimization, Simulation, Machine Learning, Cryptography).

Problem Class: A problem class is a set of applied problems that share a similar mathematical formulation and the computational complexity class. It can be characterized by the common mathematical and business problem formulation (e.g., Software testing posed as 3-satisfiability problem).

Model: A model is defined as a mathematical formulation describing a system capturing all practically relevant properties. Models are a simplified representation of reality supporting the understanding of its component's interactions and impact on resulting properties as well as predictions on future behavior (e.g., the train and driver recovery problem in a set partitioning problem formulation).

Algorithm: A quantum algorithm is a finite sequence of quantum computer-implementable instructions to perform computations. They are typically used to find a solution or an approximation of a class of mathematically defined problems.

Quantum System: A quantum computing system (short: quantum system) is a system for computation that makes direct use of quantum mechanical phenomena (e.g., superposition, entanglement) to perform operations on data.

3.1. Application Overview

General application challenges across the industrial sectors share common problem domains, in particular optimization, machine learning, and simulation. In the following, we highlight selected challenges from our value chains. We focus on four value chain parts: (1) material science, (2) engineering & design, (3) production & logistics, and (4) post-quantum security. Table 3 summarizes the collected use cases.

3.1.1 Material Science

Simulating and predicting the behavior of complex, quantum-mechanical systems is critical for new material design, such as new types of batteries or pharmaceutical drugs. McKinsey & Company predicts that quantum chemistry will be an early disruptive application of quantum computing [19]. Modeling polymers, solids, molecules at high precision without experimentally synthesizing materials in the lab enables identification of effective molecular structures that satisfy desirable properties such as high energy density or stiffness. Classic examples include drug discovery or the Haber-Bosch process: Industrial production of chemicals such as the is responsible for 1.4% of the carbon-dioxide output [20]. On a large scale, even relatively small improvements would cause a relevant absolute impact.

The global relevance of quantum computing in Material Science is also reflected in our working group. There are various QUTAC material science examples, including prediction of chemical reactivity in the chemical industry (BASF), molecular dynamics for drug discovery (Boehringer Ingelheim, Merck), and battery research (VW).

3.1.2 Engineering & Design

Engineering simulations are heavily used across the contributors of this paper, particularly in the manufacturing sector. Such simulations are crucial to decrease efforts for design and testing by reducing the necessity of physical prototypes and laboratories, e.g., wind tunnels in the automotive and aerospace domain. Current in-silico models are limited by the complexity and quality of supported models and the necessary compute time. Numerical simulations, particularly finite-element-method (FEM)-based, are crucial to simulate complex engineering processes such as aerodynamics, operating strength, structural dynamics, crash & safety, and production concerns [21]. For example, Bosch is investigating QC-based simulation approaches for electric drives. Further, AIRBUS is exploring the usage of quantum or hybrid quantum-classical approach for computational fluid dynamics to reduce the computation resources required to analyze the behavior of the airflow around the aircraft. Finally, research approaches, such as the usage of surrogate machine-learning-based models for numerical simulations (AIRBUS), are being investigated [23].

Another important problem domain is design optimization. An example is the design of aircraft wingboxes (AIRBUS) [24]. Solutions require various factors to be assessed simultaneously to ensure structural integrity is maintained. As a result, current processes to address the problem are inefficient and require significant computational resources with long design times. This problem is exacerbated by more advanced and computationally intensive generative design methods that are increasingly explored across industries.

Problem Class	Applications
Traveling Salesman	Vehicle Routing (VW), Robot Production Planning (BMW), Fleet Management (BASF), Transportation Cover (Munich Re)
Knapsack	Demand Capacity Match (Infineon), Supply Chain Optimization (Infineon), Truck Loading (SAP), Lot Sizing (SAP)
Satisfiability (SAT)	Software Testing (Bosch), Vehicle Feature Testing (BMW)
Sequencing	Matrix Production (Siemens)

*Table 3: **Optimization Problem Classes:** Main problem classes that arose in use case description.*

3.1.3 Production & Logistics

Optimization and simulation problems are omnipresent in the production & logistics domain across all industries, i.e., manufacturing, chemical & pharmaceutical production, insurance and technology. Examples of common problems are routing, supply chain, production planning, and insurance risk assessment. Real-world problems often involve many variables and constraints to be respected. Classic algorithms, such as simulated annealing, can often only find local optima and provide a non-optimal solution. Quantum optimization approaches, such as quantum annealing, adiabatic or hybrid algorithms (such as the Quantum Approximate Optimization Algorithm (QAOA)) promise to solve problems with large parameter spaces, provide better quality solutions and faster solution times.

> Aircraft wingbox design solutions require various factors to be assessed simultaneously to ensure structural integrity is maintained.

Table 4 maps the use cases to problem classes in the optimization domain. Currently, there is an emphasis on three problem classes: traveling salesman for routing problems, knapsack for many supply chain optimization problems and constraint satisfiability problems (SAT). However, it must be noted that other important problem classes exist, e.g., graph coloring and partitioning, as well as adaptations of the problem class to quantum feasible models are under development. In [25] it was shown that many of these NP-hard optimization problems can be mapped to an Ising spin class formulation, making them amenable to quantum annealing and adiabatic algorithms.
The traveling salesman problem aims to identify the shortest path between a set of nodes, relevant on multiple scales for inbound, intra-plant and outbound logistics. The Knapsack problem is a packing problem aiming to determine the optimal collection of items in a collection minimizing the weight of all items and maximizing the value. It has many applications in supply chain management (e.g., truck loading, airplane loading [26], and lot sizing). Further, it is applicable to use cases in finance, e.g., selecting assets for an optimal portfolio. Satisfiability problems aim to identify possible solutions for a set of constraints, e.g., identifying a set of vehicles to produce given option codes and respecting constraints.

> Matrix production refers to the usage of flexible product-agnostic production cells that can be combined as needed.

Sequencing problems select an optimal sequence in which jobs should be executed considering the length of all jobs and available resources. A key objective of industry 4.0 is to increase the customizability and flexibility of production (batch size of 1). Matrix production refers to the usage of flexible product-agnostic production cells that can be combined as needed. However, the increased flexibility also increases demands for selecting the production sequence for a given production cell layout.
QUTAC members expect a medium business impact for most optimization problems. However, the number of optimization problems in our industries is enormous. Further, due to the industrial scale, a method that improves quality or time-to-solution by a few percentage points provides significant benefits.

Challenge	Problem Domain	Company	Use Case	Impact
Engineering & Design	Machine Learning	AIRBUS	QC for Surrogate Modeling of Partial Differential Equations	High
	Optimization	AIRBUS	Wingbox Design Optimization	High
		Bosch	Software Testing and Correctness Proving	Medium
	Simulation	Bosch	Design Optimizations for Electric Drives Using Numerical Simulation and Finite Element Methods	Medium
		Merck	Identification and control of Actionable Parameters for Disease Spread Control	Unknown
Material Science	Optimization	Boehringer Ingelheim	Optimized Imaging – Quantum-Inspired Imaging Techniques	Medium
	Simulation	BASF	Quantum Chemistry – Prediction of Chemical Reactivity in Molecular Quantum Chemistry	High
		Boehringer Ingelheim	Molecular Dynamics – Simulation of the Dynamics of Molecules	High
		Merck	Development of Materials and Drugs Using Quantum Simulations	Medium
		Munich Re	Battery Cover – Performance Guarantees for eVehicle Batteries	Medium
		Volkswagen	Chemistry Calculation for Battery Research	High
Production & Logistics	Machine Learning	Siemens	QaRL – Quantum Assisted Reinforcement Learning – Applicable to many Industrial Use Cases	Medium
	Optimization	BASF	Fleet Management – On-site Truck and Machine Deployment and Routing	Medium
		BMW	Robot Production Planning – Robot path Optimization for Production Robots (e.g., PVC sealing robot)	Medium
		BMW	Vehicle Feature Testing – Optimizing Test Vehicle Option Configuration	Medium
		Infineon	Demand Capacity Match in Supply Chain – Decide on a Production Plan given Predicted Customer Demand	Medium
		Infineon	Using Infineon Sensors and Actuators to Optimize Supply Chain Processes on the Customer Side	Medium
		Munich Re	Transportation Cover – Insurance of Time-Critical Freight	Medium
		SAP	Logistics – Truck Loading	Medium
		SAP	Supply Chain Planning – Improved and Accelerated Sizing of Orders (Lot Sizing)	High
		Siemens	QoMP – Quantum-Optimized Matrix Production – Realtime Shop Floor Optimization	Medium
		Volkswagen	Vehicle Routing Problem – Optimize Vehicle Utilization in a Transport Network	High
Post Quantum Security	Cryptography	Munich Re	IoT Cyber Cover – Insurance of Post Quantum Cryptography	Medium

Table 4: Initial Use Case Portfolio: A wide variety of optimization, simulation, and machine learning problems exist within the value chains across the German industry. While the near-term impact is low, several high-impact use cases have been identified.

3.2. Reference Use Cases

While various use cases for quantum computing have been proposed and explored [12, 19, 27], the findings only provide limited insights for hardware and software solution providers. Thus, hardware and algorithms advances are primarily driving the ecosystem and not applications. As a result, low-level benchmarks methods, e.g., randomized gate benchmarks [28] and metrics, such as quantum volume [29], are primarily used to evaluate the performance of a quantum system.

> Industry reference use cases allow the evaluation of application-level performance and provide the foundation for benchmarks that advance the industry

We propose establishing a complementary, application-centric evaluation process by using high-impact industry reference use cases for benchmark activities [30]. A reference use case comprises a description including an assessment of the business value, an analysis of the problem class, mathematical formulations, quantum and classic reference solution, verification routines, and evaluation metrics.

These reference use cases can be used for performance evaluation of entire QC stacks, allowing the assessment of application-relevant performance parameters. Figure 2 shows how industry reference use cases bridge application requirements and quantum solutions. The reference problems provide the foundation for benchmarks of different parts of the stack, e.g., for micro-benchmarks that characterize certain gate sequencing exhibited by a use case.

Use cases must satisfy the following defining requirements to be amenable as a reference problem:

- **Business impact:** defined as the impact of prospective quantum-induced improvements (e.g., due to improved model quality, better solutions, and shorter time-to-solutions) on processes, services or products (e.g., process efficiencies, enabled product and service innovation).
- **Generality:** describes the adaptability of the solution to adjacent problems in other business units, companies, and industries.
- **Access:** ensures that problems are openly visible, sufficiently abstracted, formalized, and understandable through definitions in unified terminology.
- **Technical feasibility:** determines that a concise formalization and evaluation of the use case on current and future technology can be conducted and well-defined metrics are established (e.g., required computer size, solution quality, maximal solvable problem size, time-to-solution).

The QUTAC application portfolio will serve as the basis for

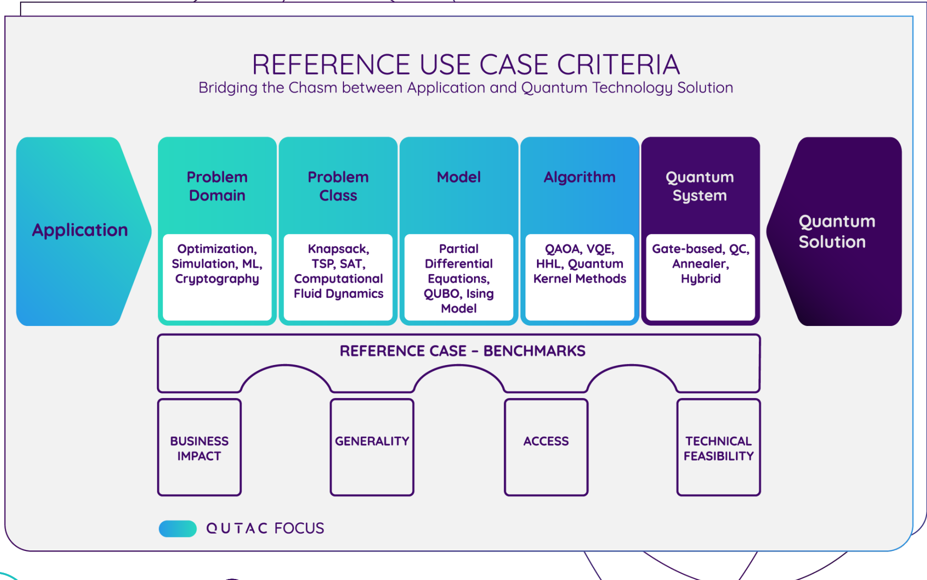


Figure 2: Reference Use Cases Criteria:. Reference use cases enable holistic benchmarking involving the entire stack, i.e., quantum system, algorithm.

selecting future reference use cases. Particularly, we aim to investigate use cases that (1) have a high business impact, (2) are constrained by classic methods for optimization, simulation, and machine learning, (3) have promising algorithmic candidates for quantum solutions.

QUTAC's target is to identify at least one reference use case per problem domain. Table 4 gives first indications for suitable reference problems, e.g., traveling salesman problems are relevant in all industries (Vehicle Routing (VW), Robot Production Planning (BMW), Fleet Management (BASF), Transportation Cover (Munich Re)).

Initial QUTAC use case one-pagers will be extended to formalized use case descriptions (including data generators, reference implementation and verification routines). We will provide these as open-source contributions to the community, encouraging an active engagement on these problems. We postulate that cross-industry benchmarks of reference cases will guide hardware & software providers towards industry use cases.

3.3. Discussion

Quantum computing will impact many parts of the value chains across all industries. Figure 3 illustrates value chain

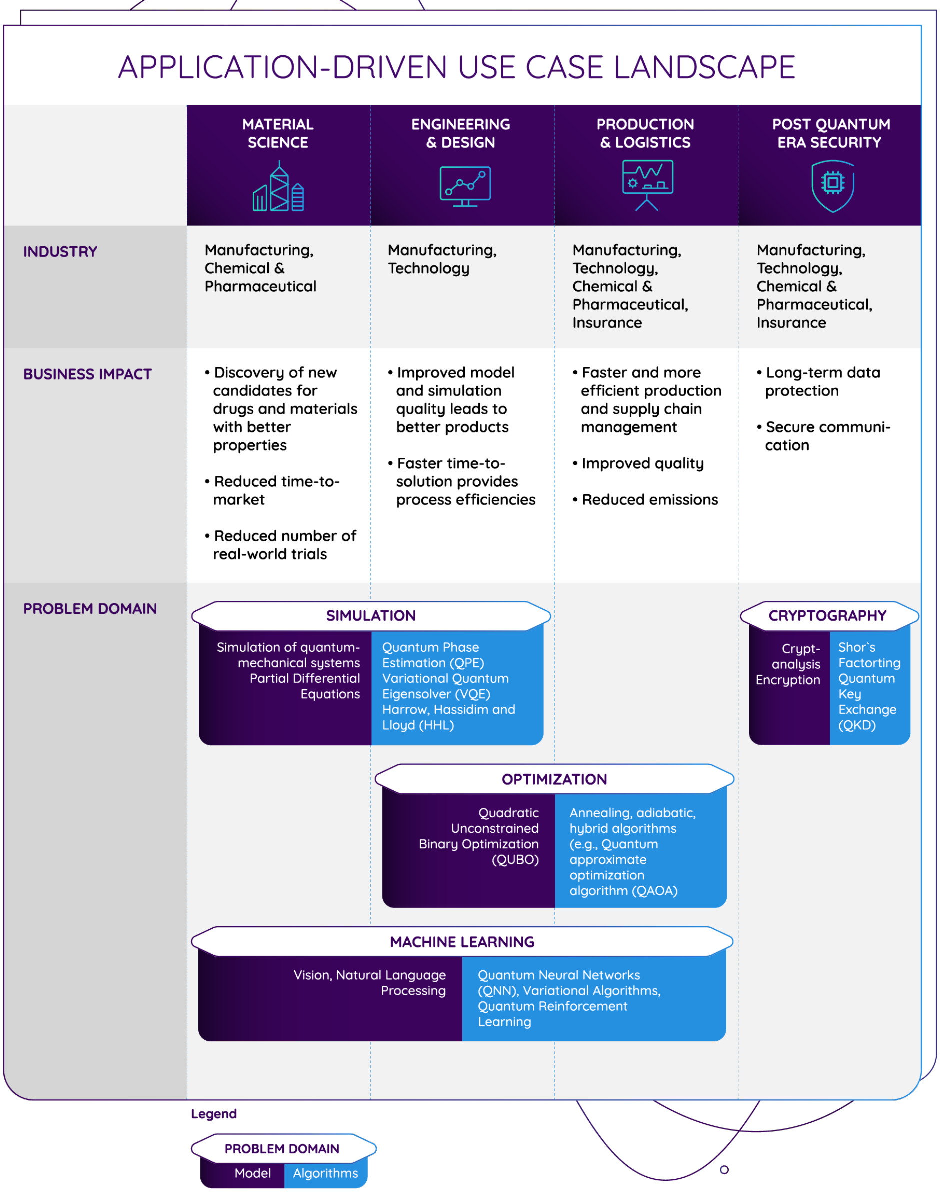


Figure 3: Application-Driven Use Case Landscape with Business Impact and Problem Domain: *Quantum computing promises benefits across different value chains, in particular material science, engineering & design and production & logistics. The most important problem domain is optimization with >50% of all use cases. The majority of the optimization use cases address the production & logistics challenge. On average, the business impact is given as medium and the time to maturity as high.*

parts and common problem domains amenable for quantum solutions. The most common problem domain is optimization with >50% of all use cases. The majority of the optimization use cases is in the production & logistics challenge. On average, the business impact is given as medium and the time to maturity as high.

The time-to-maturity for the simulation of quantum-mechanical systems is assessed as medium. Quantum-mechanical simulations are quantum-native problems and make up more than 20% of all use cases across multiple industry sectors, particularly, chemical and pharmaceutical production and manufacturing. Their potential business impact is assessed as high, as they might enable the acceleration of material discovery for drug discovery and enable new products, particularly batteries. There are only two simulation use cases for engineering process support (e.g., electric drives for Bosch and computational fluid dynamics (CFD) for AIRBUS). The time-to-maturity of these use cases is estimated to be high.

Artificial intelligence and machine learning are being widely adopted across industry sectors [31]. QUTAC use cases are surrogate modeling for CFD simulations obtained from fellow author AIRBUS, and reinforcement learning (Siemens). However, AI is broadly applicable to almost all products and parts of the value chain. For example, BMW lists more than 400 AI use cases in its portfolio. That means that advances in Quantum AI will benefit many use cases [32].

4. Challenges

While impressive quantum supremacy results have been achieved on a technical level [1, 2], various challenges remain concerning transferring these results into large-scale industrial applications of quantum computing. In this section, we discuss the result of the QUTAC survey and interviews. Figure 4 illustrates the main challenges in the three focus areas: (1) industry use cases, (2) collaboration, and (3) market incubation.

4.1. Industry Use Cases

There is no proof of value for QC applications yet. The main reason is the early stage of the technology in need of fundamental research breakthroughs to allow for a scale at which business impact is tangible (see section 3). The contributing application experts identified the following challenges:

– **Business Impact:** The contributing companies identified various use cases with medium to high impact through quantum computing. However, often a precise and proven business impact cannot be provided, as this business impact critically depends on both technical (e.g., number qubits) and business details (e.g. the value associated with certain model types). The lack of proven and coherent method for estimating business impact hinders long-term investments both by use case owner and ecosystem partners.

- **Benchmark:** The QC market and ecosystem are highly diverse and dynamic. Existing benchmarks primarily emphasize low-level hardware performance (e.g., gate fidelities and coherence times) and do not accurately reflect application-level performance. Due to a lack of community-driven, application-centered benchmarks, users cannot easily infer the performance they can expect from proposed solutions. By enabling comparisons between quantum solutions, benchmarks can drive improvements on all layers of the QC stack. For example, the ImageNet [33] benchmark led to breakthroughs in artificial intelligence and drove the creation of specialized hardware. Application benchmarks further help to establish a converged application and hardware roadmap.

- **Business Integration:** Transferring quantum technology solutions to business impact is complex, and in addition to a deep understanding of quantum technology, requires domain and integration expertise. For example, like data-driven use cases, QC solutions rely heavily on available data and models. Results of the quantum solution must then be translated into business outcome, e.g., by integrating them into operational systems or business decisions. In addition to quantum hardware and algorithms, business applications need holistic considerations.

4.2. Collaboration

To guide ecosystem activities towards industrialization and commercialized, market-ready products, an environment conducive to innovation is key. Until now, ecosystem development has been held back by traditional, rigid collaboration models in a complex stakeholder landscape, particularly between industry and research institutions. A highly intertwined technology stack and multidimensional governmental funding mechanisms create a complicated ecosystem of institutions and initiatives with many inter-dependencies and overhead. The current state makes partner contracting/sourcing a complex and lengthy process.

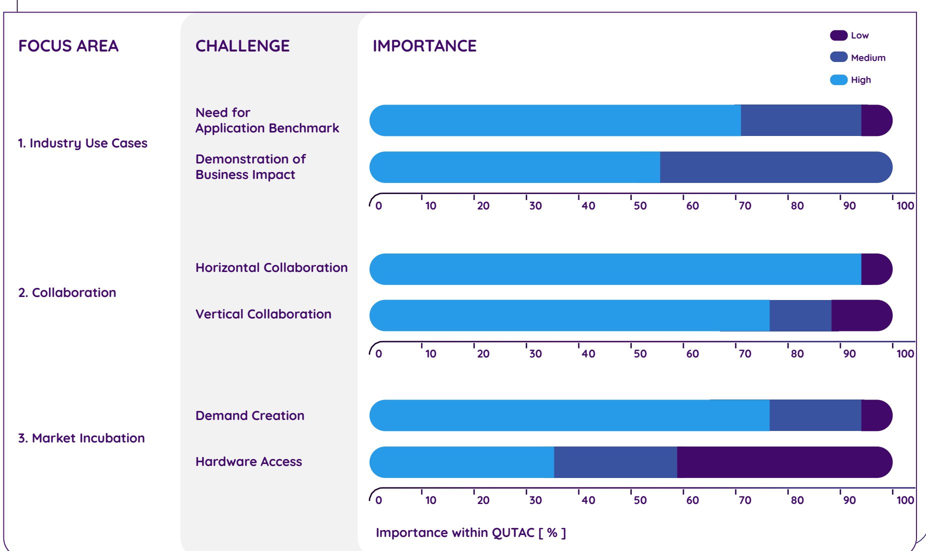


Figure 4: Importance of quantum computing challenges in three focus areas in the German industry (answered by 17 experts from 11 companies across 5 industry sectors). Realization of expected long-term business impact derived from use case portfolio.

Funding: Agencies around the globe have been funding basic research in QC for decades (e.g., US [9, 10]). In Europe, more than 20 projects are funded as part of the Quantum Technologies Flagship [18]. Germany significantly extended its quantum program, supporting both foundational research and industrialization of hardware and software [16, 17, 34] with a budget of two billion Euros over five years. Quantum hubs will focus on different specific qubit technologies (e.g., ion traps or superconducting qubits). Application research is supported by a competence network. Further, state-level initiatives in Germany have emerged, including Munich Quantum Valley [35] and Lower Saxony Quantum Valley [36].

The resulting funding landscape is complex, fragmented and exhibits partially competing and overlapping objectives. As a result, the establishment of large-scale industrialization projects will be challenging. Thus, we expect a high number of small initiatives, bearing the risk

Survey respondents noted effective cross-industry collaboration to advance quantum computing as one of the highest-ranked challenges.

of redundancy and lack of focus. In this environment, avoiding the decoupling of application-centric industrialization and foundational research is instrumental to advance the technology at this early maturity level.

Horizontal collaboration: Survey respondents noted effective cross-industry collaboration to advance quantum computing as one of the highest-ranked challenges. Cross-industry collaboration is a crucial enabler for (1) creating a shared industry voice towards the ecosystem, (2) establishing high-impact applications that accelerate industrialization, (3) jointly facilitating activities with the emerging ecosystem, and (4) de-risking long-term investments.

Several consortia on international level have been founded to address these challenges, e.g., QED-C [37] and QuIC [38]. Germany is missing a consortium to advocate for industry needs in growing German QC programs. Additionally, a framework for addressing collaboration challenges is needed, including (1) the lack of a unified terminology and standards (e.g. for use cases, benchmarks and access protocols), (2) the difficulty of sharing proprietary data and information, and (3) the lack of effective strategies to balance openness and corporate interests.

Vertical collaboration: Collaboration of industry and quantum solution providers is crucial to coherently advance applications and hardware by optimizing integration across the entire stack (hardware/software co-design). This requires the integration of industrial domain knowledge with hardware, software, and algorithmic knowledge. Setting up vertical collaborations, especially with international partners, can be challenging and requires careful consideration of IP protection, data security and privacy.

4.3. Market Incubation

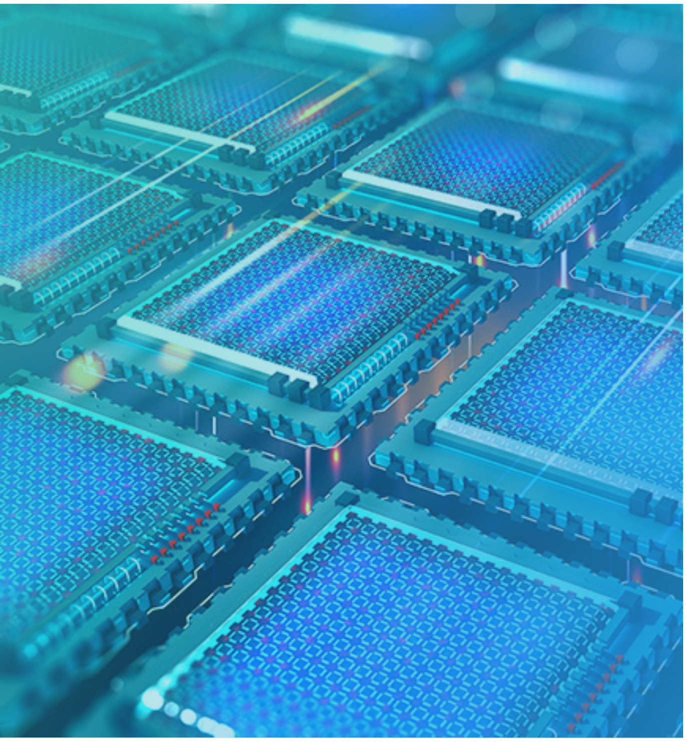
While governments, research institutions and cloud providers began to procure quantum devices, the commercial market is still in its infancy. Industrial applications with proven business impact are instrumental

in establishing such markets, creating a virtuous cycle of demand and supply [39]. The contributing experts emphasize three challenges:

Hardware Access: Access to different quantum systems is now possible through cloud service providers [3, 5]. However, the availability, scale, and costs limit research and industrialization activities. In many cases, careful consideration of international and data protection law and vendor-specific contracts are required. Further, access is often limited, preventing low-level experiments. High-end, state-of-the-art hardware is often unavailable. As technology advances, we expect this situation to exacerbate. Another challenge is limited access to research testbeds emerging from public projects.

Demand Creation: A virtuous cycle of demand and supply is crucial to establish a new market. Additional to government-driven markets, industrial applications can serve as an important market to initiate such a cycle. Applications on NISQ devices useful for industry can drive demand. Market creation is a well-known challenge of deep-tech ecosystems [12], but it is particularly pronounced in quantum computing due its long-term nature.

Collaboration of industry and quantum solution providers is crucial to jointly advance applications and hardware.



Talent & Education: QC requires both highly specialized and interdisciplinary skills that bridge different research fields, including engineering, industrialization, and business. Developing talent with knowledge in theoretical and applied computer science (e.g., complexity theory, operations research) and quantum computing (e.g., basics of QC operation and control, error mitigation, quantum algorithms, quantum software development kits, assessment of application relevant hardware features) in combination with business acumen (e.g., identifying customer needs, knowledge in production and operations processes, their business and technical limitations) is seen as critical. With first applications reaching commercial viability, this situation will exacerbate.

5. Call for Action

To advance quantum computing towards the level of industrial-scale applications, we need to act now. As we observed in other fields, e.g., artificial intelligence, early investments are essential to ensure a competitive advantage in a fast-paced digital economy. QUTAC members identified three fields of action in the focus areas: industry use cases, collaboration, and market incubation, and two enablers: talent & education and standards (Figure 5).

QC requires both highly specialized and interdisciplinary skills that bridge fundamental research, engineering, computer science, industrialization, business and society.

- **A1 Industry Use Cases:** To establish useful QC application on near-term devices, the industry must: (1) prioritize, develop and communicate industry reference problems and transform them to community benchmarks to steer quantum solutions towards commercial usability, (2) focus on end-to-end applications including the integration in business processes to demonstrate business impact, and (3) communicate demonstrations of quantum impact.
- **A2 Collaboration:** European and German funding streams must be aligned to avoid redundancy. Demands and guidance for industry partners must be clearly communicated. Industry users must engage proactively in the consortia, with well-defined value propositions and contributions. Furthermore, international collaborations and cooperation beyond Germany are vital (e.g. through QuIC [38]).
- **A3 Market Incubation:** Commercially useful quantum applications are vital to create new demands for quantum technologies, initiating the virtuous cycle of demand and supply. Industrialization of quantum computers to industry scale must be the long-term target, enabling profitable business models for all value chain participants, including start-ups, components suppliers, etc.

The following enablers contribute to all action items in the three focus areas and are prerequisites for their success:

- **E1 Talent & Education:** As technology matures, the demand for quantum computing will grow. Both industry and academia must develop critical skills at the intersection of physics, engineering, computer science, and business [40], addressing undergraduate, graduate, post-graduate students, and professionals. A particular focus must be interdisciplinary skills that bridge these fields and combining low-level quantum knowledge with industry domain expertise.
- **E2 Standards:** Entry-barriers must be lowered by development of appropriate high-level interfaces and standards (e.g., terminologies, APIs for accessing infrastructure). Standards are also instrumental for minimizing vendor lock-in.

To advance quantum computing towards the level of industrial-scale applications, we need to act now.

Figure 5:
Action per Focus Area: *We suggest three action areas (Industry Use Cases, Collaboration, and Market Incubation) to accelerate commercialization of quantum computing technology.*
Enablers: Talent, education and standards are crucial enablers for successful realization.

The QUTAC application working group aims to advance the industrial-scale applications of QC (A1). This paper presents an initial set of cross-industry applications of quantum computing, which will provide the foundation for establishing industry reference problems. Based on these reference use cases, we will establish benchmarks which we hope will spark horizontal and vertical collaboration (A2). We actively evaluate engagement models with QuIC and other industry consortia (A2). By collaborating on community standards, e.g., a glossary, access interfaces, high-level business abstraction, we will lower the entry barriers (E2).

We work towards strengthening exchange with German and European funding agencies (A2). We specifically envision collaborative lighthouse projects that increase collaboration across the ecosystems and channel it towards high-value industrial challenges (A1, A2). By providing domain expertise, we contribute critical knowledge while benefiting from the advancements in quantum solutions. At the same time, this will generate demand for industrial quantum solutions - solving the deadlock between users and platform providers.

We postulate that QUTAC's engagement and industrial perspective will enable early markets for quantum computing technologies (A3). Partners are committed to contributing applications, data, technological and business knowledge to the emergent ecosystem (A2). Our results will be beneficial to all ecosystem participants, e.g., suppliers, system integrators, software developers, users, policymakers, funding program managers, and investors. We believe in the long-term business impact of quantum computing. We do not expect immediate value, but are convinced that it is now the time to obtain and share experience with different technologies and advance our business infrastructure to accelerate the adoption of quantum-based methods.

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Appendix A – Use cases

(Harvey Balls scale defined in Appendix B)

AIRBUS	QC for Surrogate Modeling of Partial Differential Equations		
Industry	Aerospace	Function	Design Modeling
Problem Domain	Machine Learning	User	Internal Engineers
Business Challenge	Computational fluid dynamics (CFD) is used to model the performance of aircraft designs. Recently, machine learning techniques have been applied to solve PDEs: simultaneous treatment of space & time. Optimizing the NN training time with quantum is to be considered.		
Value Proposition	Faster modeling of aircrafts, in small or large parts. The exploration of a larger optimization space to yield novel and more efficient designs.		
QC Solution Approach:	Modeling Burgers' equation for a 1D fluid flow with given boundary conditions with a quantum-enhanced neural network. Both an inviscid and viscous flow are considered.		
Problem Class	Fluid Dynamics	Model	PDEs
Algorithm	QML	Hardware	Gate-QC + HPC
QC limitations:	QC for neural networks and PDEs is a new, but growing subfield of QC. This project proposal is intended to explore its potential for fluid flow modeling.		
Time to Maturity	◑	Potential Impact	●

AIRBUS	Wingbox Design Optimization		
Industry	Aerospace	Function	Multidisciplinary design
Problem Domain	Optimization	User	Internal Engineers
Business Challenge	Multidisciplinary design optimization consists in the simultaneous optimization of multiple, interdependent parameters. The challenge remains outstanding.		
Value Proposition	The exploration of a much broader design space, leading to potentially novel and more efficient designs.		
QC Solution Approach:	Quantum-based optimization of parameters across three disciplines – airframe loads, mass modeling and structural analysis.		
Problem Class	SAT	Model	Inversion
Algorithm	HHL, TBD	Hardware	Gate-QC + HPC, QA
QC limitations:	The finite-size of NISQ era QC limits the size of the problem under consideration. The challenge is thus both on leverage large amounts of QC capabilities and optimally hybridizing it with classical HPC.		
Time to Maturity	●	Potential Impact	●

BASF We create chemistry	Quantum Chemistry – Prediction of Chemical Reactivity in Molecular Quantum Chemistry		
Industry	Chemicals	Function	R&D
Problem Domain	Simulation (Chemistry)	User	Quantum Chemists
Business Challenge	Currently, exact or near-exact simulation of chemical reactivity and molecular properties is not practical with classical computers.		
Value Proposition	Highly accurate predictions for large molecular systems will be in reach for the first time without the trade-offs in accuracy needed with classical computers.		
QC Solution Approach:	Solutions of the molecular Hamiltonian / Schroedinger equation need to be found.		
Problem Class	Electronic Structure Simulation	Model	Hamiltonian
Algorithm	VQE	Hardware	Gate-QC
QC limitations:	Highly accurate solutions require too many qubits and too high gate depth which is not feasible on current hardware. Though some improvement on NISQ hardware is possible, the systems are small compared to the realistic systems.		
Time to Maturity	◑	Potential Impact	●

BASF We create chemistry	Fleet Management – On-site Truck and Machine Deployment and Routing		
Industry	Manufacturing	Function	Logistics
Problem Domain	Optimization	User	Production Logistics
Business Challenge	Determining the optimal route for trucks and machines within a production facility is non-trivial and expensive.		
Value Proposition	Optimization of routing will increase efficiency for site operations, minimize downtime, increase reliability of planning, and reduce operational costs.		
QC Solution Approach:	A solution of a traveling-salesman-type problem needs to be found.		
Problem Class	TSP/SAT	Model	QUBO
Algorithm	QA, QAOA	Hardware	QA, Gate-QC
QC limitations:	Considering real-world problems often leads to increased complexity or overhead for QC, e.g., constraints and data processing limitations.		
Time to Maturity	◑	Potential Impact	◑

Boehringer Ingelheim	Molecular Dynamics – Simulation of the Dynamics of Molecules		
Industry	Pharma	Function	R&D
Problem Domain	Simulation	User	Comp. Chem. Researchers
Business Challenge	Accurate time-averaged properties of drug molecules in the drug discovery cycle.		
Value Proposition	Improving prediction accuracy facilitates drug design efforts and reduces the number of wet-lab and animal experiments. This leads to shorter drug development cycles.		
QC Solution Approach:	Use a quantum computer as an accurate electronic structure solver to drive the molecular dynamics simulations.		
Problem Class	Ab initio molecular dynamics (AIMD)	Model	Fermions
Algorithm	VQE, QPE	Hardware	Gate-QC
QC limitations:	No algorithm available. Drug-sized molecules and proteins require deep circuits, coherence times too short -> need error correction -> hardware development.		
Time to Maturity	●	Potential Impact	●

Boehringer Ingelheim	Optimized Imaging – Quantum-Inspired Imaging Techniques		
Industry	Pharma	Function	Development
Problem Domain	Optimization	User	Analytical Scientists
Business Challenge	Imaging techniques are an important piece of information to identify structures and distribution of molecules in tissues.		
Value Proposition	More accurate identification of structures and distributions. Supports target identification campaigns by high resolution imaging of diseased tissue as well as spectroscopic functions in analytics.		
QC Solution Approach:	Optimization of imaging techniques using information-theory principles inspired by quantum algorithms for improved pattern recognition through hyperparameter search.		
Problem Class	Tbd	Model	Ising
Algorithm	QAOA	Hardware	Gate-QC
QC limitations:	Performance guarantees of QAOA. Missing error mitigation schemes for QAOA. Hardware too small for interesting problem sizes. Missing theoretical foundation for heuristic approaches e.g. barren plateau.		
Time to Maturity	○	Potential Impact	◐

BOSCH	Design Optimization for Electric Drives		
Industry	Products	Function	Engineering
Problem Domain	Simulation (plus optimization)	User	Engineer
Business Challenge	Optimizing the design of electric drives with the goal of keeping central properties like reliability etc. with lower material consumption.		
Value Proposition	Faster solution of the many-parameter optimization problem. Possibility to make a larger design space accessible.		
QC Solution Approach:	Optimization high-dimensional parameter space plus determination of value of optimization function (cost function) via simulation (finite-element method).		
Problem Class	FEM	Model	PDEs
Algorithm	HHL, QAOA	Hardware	Gate-QC
QC limitations:	Many more qubits needed as currently available. Error correction needed.		
Time to Maturity	●	Potential Impact	◑

BOSCH	Software Testing and Correctness Proving		
Industry	SW development	Function	Engineering
Problem Domain	Optimization	User	SW developer
Business Challenge	Software testing involves searching in a high-dimensional search space, which is very costly in time and money.		
Value Proposition	QC solution would be faster and would bring the possibility to use even larger search spaces.		
QC Solution Approach:	Testing software and proving its correctness can be mapped to a constraint-satisfaction problem.		
Problem Class	SAT	Model	SAT
Algorithm	Quantum SAT, QAOA	Hardware	Gate-based
QC limitations:	Many more qubits needed as currently available. Error correction needed.		
Time to Maturity	●	Potential Impact	◑

BMW	Vehicle Feature Testing – Test Vehicle and Test Feature Assignment		
Industry	Products	Function	Product Testing
Problem Domain	Optimization	User	Product Test Designer
Business Challenge	Test-vehicles are designed to test new feature combinations. Reducing the number of vehicle designs by efficiently assigning tested features needs.		
Value Proposition	Production cost – reducing the number of designs and test vehicles produced enables five-digit savings per vehicle.		
QC Solution Approach:	The problem is mathematically modelled with in conjunctive normal form as a satisfaction problem.		
Problem Class	SAT	Model	QUBO
Algorithm	QA, QAOA	Hardware	Annealer, Gate-QC
QC limitations:	Higher order satisfaction constraints require hardware inefficient overhead of number of qubits.		
Time to Maturity	◐	Potential Impact	◐

BMW	Robot Production Planning - PVC Sealing Job Shop Scheduling		
Industry	Products	Function	Product Planning
Problem Domain	Optimization	User	Production Planner
Business Challenge	PVC foam for corrosion protection Is applied by multiple robots with multiple tools. Collision free and fast coverage of all seams is only solved approximatively today.		
Value Proposition	Production efficiency - Shortening the process by one sealing can result in hundreds of additionally produced vehicles.		
QC Solution Approach:	The problem is mathematically modelled with a quadratic constrained binary problem with set cover constraints and was reformulated into a Quadratic Unconstrained Binary Optimization Problem (QUBO).		
Problem Class	TSP/SAT	Model	QUBO
Algorithm	QA, QAOA	Hardware	Gate-QC
QC limitations:	Add additional constraints to address complexity of practical problem (e.g., multiple robots) Iterative approaches require low classical-qc hardware latency / hybrid integration.		
Time to Maturity	◐	Potential Impact	◐

infineon	Demand Capacity Match in Supply Chain – Decide on a Production Plan given Predicted Customer Demand		
Industry	Semiconductor	Function	Internal Supply Chain Planning
Problem Domain	Optimization	User	Silicon-Foundry & subcon
Business Challenge	Given predicted customer demand and capacities, come up with a daily ATP (Available to Promise) taking into account 1 million orders which are (re)confirmed daily. At the moment, this is solved by decomposed solvers and heuristics.		
Value Proposition	Better ATP via a) capacity utilization (less CO2) and b) better usage of flexibility, thus better order confirmation (to customer wish date and commit date) yields a) better cost position and b) more turnover for better overall EBIT and share price increase.		
QC Solution Approach:	We model this situation as (a variant of) a knapsack/allocation problem.		
Problem Class	Knapsack	Model	QUBO
Algorithm	QA, simulated annealing	Hardware	Annealer, Simulation
QC limitations:	Difficulties with mathematically formalizing the supply chain process.		
Time to Maturity	◐	Potential Impact	◐

infineon	Using Infineon Sensors and Actuators to Optimize Supply Chain Processes on the Customer Side		
Industry	Semiconductor	Function	Usage of IoT
Problem Domain	Optimization	User	Infineon customer and customer of customer
Business Challenge	Sensor data enable us to perform many tasks more efficiently. Exploiting these data requires solving NP problems such as TSP which occurs e.g. in the problem of finding an optimal route for glass waste collection.		
Value Proposition	Customer satisfaction with providing systems and solutions on top of products.		
QC Solution Approach:	Depending on the concrete circumstances, the problem can be modelled as a TSP / capacitated vehicle routing.		
Problem Class	TSP	Model	QUBO
Algorithm	QA, QAOA	Hardware	Annealer, Gate-QC
QC limitations:	Dynamically updating routes because of continuous sensor data flow.		
Time to Maturity	◐	Potential Impact	◐

MERCK	Calculation of Material Properties and Reactivity		
Industry	Materials (Chem / Pharma)	Function	Material Development / Drug Discovery
Problem Domain	Simulation	User	R&D, QA, Mat. dev.
Business Challenge	Development of materials is supported by simulations and a tradeoff between precision and efficiency. For full calculations with high precision current infrastructure does not scale.		
Value Proposition	Many Material properties, physical parameters and chemical parameters.		
QC Solution Approach:	Embedding of quantum chemical calculations in the overall process of material testing (perform QC on a QC) ranging from molecular dynamics (low accuracy, high scale and throughput) to DFT (medium precission, scale and throughput) and full CI.		
Problem Class	Electronic structure simulation	Model	MD, DFT
Algorithm	VQE, …	Hardware	Gate-QC
QC limitations:	Mainly NISQ size is a problem to do meaningful calculations. Many properties are not ONLY Quantum chemistry problems. Overall Workflow has only small QC component.		
Time to Maturity	●	Potential Impact	◑

MERCK	Identification and Control of Actionable Parameters for Disease Spread Control		
Industry	Multi / Healthcare	Function	Multi
Problem Domain	Simulation	User	government, supplier and logistics
Business Challenge	Disease spread control has a multitude of dependent parameters which change in real time and require to adjust the "optimal" treatment with limited resources (logistics, multi factor)".		
Value Proposition	Different "sustainability KPIs" – Allow timely adjustment of targeted interactions with minimal impact on the rest of population and environment.		
QC Solution Approach:	Potentially via QUBO or other constraint satisfaction optimization (not binary) – alternatively differential equations if that makes sense from a QC-speedup perspective. Potentially a hybrid approach to identify the relevant networks and parameter dependencies.		
Problem Class	Potentially SAT	Model	Tbd, maybe QUBO
Algorithm	Maybe QA, QAOA	Hardware	Annealer, Gate-QC
QC limitations:	Unclear formulation, potential hardware limitations for data load, algorithm limitations/ assumptions – condition number, sparsity, barren plateaus, noise…). Further limitation: availability of relevant data (sensors etc.).		
Time to Maturity	◑	Potential Impact	○

Munich RE	IoT Cyber Cover – Insurance of Post Quantum Cryptography		
Industry	IoT	Function	Security of IoT Devices
Problem Domain	Cryptography	User	IoT (device) manufacturers
Business Challenge	IoT devices have to safely communicate, but are susceptible to future attacks from quantum computers. Insurers may provide device-specific cyber cover against encryption vulnerabilities.		
Value Proposition	Quantum-secure encryption techniques reduce the probability of 'hold and decrypt' attacks from quantum computers on IoT devices and prevent (long-term) accumulation risks.		
QC Solution Approach:	Quantum-secure cryptography provides future-proofing for IoT devices based on quantum key distribution (QKD) or post quantum algorithms, this allows hardening of existing encryption algorithms against attacks from (more powerful) quantum computers in the future.		
Problem Class	Post Quantum Encryption	Model	-
Algorithm	QKD	Hardware	-
QC limitations:	No dependency on availability of quantum hardware in encryption. 'Hold and decrypt' attacks are already a prevalent threat which can be addressed today.		
Time to Maturity	○	Potential Impact	◑

Munich RE	Transportation Cover – Insurance of Time-Critical Freight		
Industry	Transportation	Function	Route Optimization
Problem Domain	Optimization	User	Cargo / freight companies
Business Challenge	Cargo companies depend on optimal routes when delivering time-critical freight and intend to reduce carbon footprint. Insurers can offer (ad hoc) performance guarantees & quantum-based services.		
Value Proposition	Quantum computing enables real-time optimization of routes and therefore increases transportation efficiency and sustainability. Real-time risk assessment facilitates adhoc / on-demand insurance products.		
QC Solution Approach:	Quantum optimization techniques enable solving highly complex routing problems in situations with continuously changing inputs in near-real time. Main benefit are faster solutions, but improvements may also be possible.		
Problem Class	TSP	Model	QUBO
Algorithm	QA, QAOA	Hardware	Annealing, Gate-QC
QC limitations:	Smaller use cases are already possible in near future. Large speed-ups and real-time applications are expected on the mid-run with increasing no. of qubits.		
Time to Maturity	○	Potential Impact	◑

Munich RE	Battery Cover – Performance Guarantees for eVehicle Batteries		
Industry	Automotive	Function	Batteries for eVehicles
Problem Domain	Simulation	User	Battery producers / OEMs
Business Challenge	eVehicle batteries degrade over time limiting battery life and vehicle range. Insurance requires reliable risk models for providing battery warranties / performance guarantees.		
Value Proposition	Quantum computers are well suited to direct simulation of complex chemical reactions and molecular structures critical to batteries, e.g., lithium-sulfur batteries.		
QC Solution Approach:	Quantum based simulation of degradation helps battery OEMs better optimize their batteries and test more efficient materials and components where classical computing has clear limitations.		
Problem Class	Electronic Structure Simulation	Model	-
Algorithm	VQE	Hardware	HPC
QC limitations:	Quantum advantage comes with improvement of the state of qubits and increased quantum volume. Approximate timeframe till quantum advantage: 5 years.		
Time to Maturity	◐	Potential Impact	◐

SAP	Logistics – Truck Loading		
Industry	Logistic	Function	Truck Load Building
Problem Domain	Optimization	User	Logistics planner
Business Challenge	To utilize trucks in the best manner, it is required to build the pallets in such a way that the load is balanced and can utilize the complete space.		
Value Proposition	An optimized assignment of goods to pallets for a certain truck can increase the overall truck utilization. It will reduce costs, traffic jams and climate emissions. Such a combine approach can improve today's uncoupled planning steps.		
QC Solution Approach:	The binary decision which product is placed on which pallet on which position can be modeled as QUBO. It is possible to express preferences, which product should be loaded together and can consider the restrictions of a certain position in the truck.		
Problem Class	tbd	Model	QUBO
Algorithm	QA, QAOA	Hardware	Annealer, Gate-QC
QC limitations:	A possible pre-grouping before calling the QC can reduce the size go the QUBO with only minimal effect on the quality.		
Time to Maturity	◑	Potential Impact	◑

SAP	Supply Chain Planning – Accelerated Lot Sizing		
Industry	All	Function	Supply Chain Planning
Problem Domain	Optimization	User	Supply Chain Planner
Business Challenge	Current Supply Chains can be approximated by linear programming. Transforming these linear results into lot sizes is complex and slow.		
Value Proposition	Faster roundtrips of automatic supply planning will increase service-level and resource utilization while reducing the impact of disruptions.		
QC Solution Approach:	Add additional constraints to address complexity of practical problem (e.g., multiple robots). Iterative approaches require low classical-qc hardware latency / hybrid integration.		
Problem Class	tbd	Model	QUBO
Algorithm	QA, QAOA	Hardware	Annealer, Gate-QC
QC limitations:	There are a lot of linear bunds to consider which make the problem large. Therefore, good decomposition techniques are required to break down complete supply chains in solvable pieces.		
Time to Maturity	●	Potential Impact	●

SIEMENS	QoMP – Quantum-Optimized Matrix Production – Realtime Shop Floor Optimization		
Industry	Manufacturing	Function	Industrial Automation
Problem Domain	Optimization	User	Production Planner
Business Challenge	Highly customized error-tolerant lot size one production.		
Value Proposition	Robustness against perturbation, flexibility of production planning, efficiency of machine usage.		
QC Solution Approach:	The problem is mathematically modelled as a constraint-free mathematical optimization problem.		
Problem Class	Tbd (Quadratic program)	Model	QUBO
Algorithm	QA, QAOA	Hardware	Dwave, IBM
QC limitations:	Restricted number of qubits; Limited on-chip connectivity; Limited quantum volume.		
Time to Maturity	○ (empty)	Potential Impact	◐ (half)

SIEMENS	QaRL – Quantum Assisted Reinforcement Learning – Applicable to many Industrial Use Cases		
Industry	Cross Industry	Function	Data Analytics
Problem Domain	Machine Learning	User	Data Scientists
Business Challenge	Improved real-time decision making.		
Value Proposition	Data analytics speed-up.		
QC Solution Approach:	Reinforcement learning algorithms are augmented by quantum primitives (projective simulation, quantum random walks or using parametrized VQC as value function approximators).		
Problem Class	Tbd (Quadratic program)	Model	QUBO
Algorithm	VQE, QAOA	Hardware	Dwave, IBM
QC limitations:	Restricted number of qubits. Limited on-chip connectivity. Limited quantum volume.		
Time to Maturity	◐ (half)	Potential Impact	◐ (half)

VOLKSWAGEN AKTIENGESELLSCHAFT	Vehicle Routing Problem – Optimize Vehicle Utilization in Transport Network		
Industry	Production/Logistics	Function	Operation Optimization
Problem Domain	Optimization	User	Production, modern mobility end-user
Business Challenge	Vehicle routing problem for mobility services (autonomous driving) or production (routing of material delivery drones at multiple production lines).		
Value Proposition	Increased efficiency for Ride-pooling. Increased efficiency for Logistics. Increased efficiency for Production.		
QC Solution Approach:	Problem is formulated in PBO form with Constraints and solved with either RQAOA or LHZ QAOA.		
Problem Class	Tbd (NP-Hard)	Model	PBO
Algorithm	RQAOA / LHZ QAOA	Hardware	Gate-QC
QC limitations:	Stabilizer Implementation; Limited Coherence time.		
Time to Maturity		Potential Impact	

VOLKSWAGEN AKTIENGESELLSCHAFT	Chemistry Calculation – Speed Up Density Functional Theory		
Industry	Automotive/Chemistry/Pharma	Function	Product Development
Problem Domain	Simulation	User	B2B, R&D department
Business Challenge	Battery Simulation (e.g., prediction of charge and discharge cycle) Determining cumulative material parameters needed for simulations.		
Value Proposition	Faster Development Cycle for Battery. Lower Costs for Battery Development. Applicability well beyond Battery simulation in Chemistry/Pharma industry.		
QC Solution Approach:	Exponential speedup for density functional theory with single body Schroedinger equation simulation via gray code.		
Problem Class	Electronic Structure Simulation	Model	Hamiltonian
Algorithm	QPE	Hardware	Gate-QC
QC limitations:	No quantum error correction yet.		
Time to Maturity		Potential Impact	

Appendix B – Definitions

Potential Impact Scale

- Low – incremental – impact by prospective QC induced improvements and relevance for business processes, services or products (e.g., by cost reductions, increased market share, etc.) is incremental (sub- to few-percent-range) and likely cannot be generalized across business.
- Medium – at scale – impact by prospective QC induced improvements and relevance for business processes, services or products (e.g., by cost reductions, increased market share, etc.) is significant (two digits percentage) and could be generalized across business (e.g., extended to other products, processes, services).
- High – disruptive – impact by prospective QC induced improvements and relevance for business processes, services or products (e.g., by cost reductions, increased market share, etc.) is disruptive (order of magnitude relative improvement) and could be generalized across business, even enable creating new products, services, processes and markets.

Time to Maturity Scale

- Short: <5 years – access on necessary hardware and software exists and use cases are formulated in sufficient detail. Implementations and first proof-of-concepts have been implemented and scale with the available software & hardware performance such that a at least incremental improvement is expected in the next 5 years.
- Medium: 5-10 years – access on early prototypes of hardware is possible such that use cases can be formulated and very small-scale implementations created. These steps work as basis to extend user and software-/hardware-providers know-how on challenges and new approaches to innovation and incubation of QC and related technology but first business relevant implementations with minor improvements are not expected before 5 years.
- Long: >10 years – there is no access to early prototypes and use cases can be formulated based on reasonable assumptions of future hardware developments. Substantial R&D on user, software- and hardware provider side are needed, and first business relevant implementations are not expected before 10 years.