Proceedings of the 57th Hawaii International Conference on System Sciences | 2024

Towards Requirements Engineering for Quantum Computing Applications in Manufacturing

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Abstract

Quantum computing (QC) shows the potential to trigger a paradigm shift for numerous industries. As an emerging technology, methodological support for designing and developing QC-based applications is lacking. This paper presents the results of a case study applying consortium research in order to perform a requirements engineering process for two QC-based applications in the manufacturing industry. The results show the differences between requirements engineering for QC applications and conventional software applications. The major findings point to the need for QC knowledge and best practices for a successful requirements engineering process and elaborate on the main differences between QC application- and software application requirements.

Keywords: Requirements Engineering, Quantum Computing Applications, Simulations in Manufacturing

1. Introduction

Quantum Computing (QC) represents one of the most disruptive technologies of our time (Hazan et al., 2020). Exploiting the principles of quantum mechanics, quantum computers can solve very complex problems significantly faster compared to conventional computers (Rietsche et al., 2022). The expected "quantum advantage," i.e., the fact that quantum computers can perform computations that are not possible with conventional computers in general or in a reasonable amount of time, demonstrates the massive changes that can be expected from QC (Bova et al., 2023). Still, researchers started to investigate "practical quantum advantage", representing the point where quantum devices will solve problems of practical interest rather than artificial problems through QC applications (Daley et al., 2022). Especially in artificial intelligence (AI), optimization and simulation, QC is expected to provide unmatched advantages (Rietsche et al., 2022). Despite potential benefits for various industries such as finance, manufacturing, logistics, or energy, real-world QC applications are still in their infancy, scalability is not possible yet, and business value generation or capturing utility is unclear in large parts (Amir et al., 2022; Bova et al., 2023; Chipidza et al., 2023). Bova et al. (2023) argue that the relative benefits of QC depend on how the advantages of faster computations compare to the higher costs of scaling up. In addition, QC applications often depend on the development of quantum hardware and the necessity to adapt applications to algorithmic, architectural and hardware limitations (Byrd and Ding, 2023). Similar to AI applications, QC applications are not like conventional software applications (Janzen et al., 2022). Applications based on QC do not meet the "closed world assumptions" of deterministic software systems. Deterministic means that given a particular input, a system or algorithm will always produce the same output. Due to the nature of qubits, enabling superposition, quantum systems, software, and applications are probabilistic. Furthermore, QC applications target specific problem spaces. They promise high-resolution and faster results, especially when solving large linear equation systems. For classical software systems, software engineering development lifecycles are in use to support the design and implementation of such systems. For QC, no quantum software development lifecycles were defined yet (Ali et al., 2022). This leads to lacking methodological support for requirements engineering, architecture and design, development, testing, debugging, and maintenance (Ali et al., 2022).

URI: https://hdl.handle.net/10125/107301
978-0-9981331-7-1

Especially requirements engineering (RE) for QC applications represents an uncharted area where more research is needed (Ali et al., 2022).

Aim of this work is to investigate the requirements engineering process for real-world QC applications in order to specify deviations from the classical software requirements engineering process and resulting requirements. We present the results of a case study where consortium research was applied (Österle and Otto, 2010). Building on existing RE approaches, we performed a RE process within a QC research project, resulting in two QC-based real-world applications in the manufacturing context. Thereby, the area of interest lay in the context of simulations in the manufacturing processes of milling and laser cutting.

The remainder of this paper is structured as follows: We present related work on RE, basics on quantum computing and on simulations in manufacturing. Next, we describe our methodology and present the results of the RE process. Finally, we discuss our results and elaborate on the differences in the QC RE process and QC-specific requirements compared to conventional software RE, before we conclude the paper.

2. Related Work

2.1. Requirements Engineering

According to Glass' Law, "Requirement deficiencies are the prime source of project failures". Boehm's first Law says, "Errors are most frequent during the requirements and design activities and are the more expensive the later they are removed". Through requirements engineering (RE), functional and non-functional requirements are derived that capture the behavior of intended software systems (Garlan, 2000; Nuseibeh and Easterbrook, 2000; Robertson and Robertson, 2012). Functional requirements define specific behavior or functions of a system, while non-functional requirements specify the operation capabilities and constraints and attempt to improve the functionality of a system. With RE, a system or software architecture is specified, implemented, and tested. RE comprises requirements elicitation, analysis, system modeling, requirements specification, requirements validation, and management (Sommerville, 2011). RE methods cover different aspects and techniques to derive requirements, e.g., conceptual modeling (Nuseibeh and Easterbrook, 2000). Most start by defining the goals of the intended system to be developed (Dardenne et al., 1993; Horkoff and Yu, 2016; Sutcliffe et al., 2007). Furthermore, RE models include groundwork, e.g. risks and feasibility are analyzed, or feasibility studies are conducted (Nuseibeh and Easterbrook, 2000; Sommerville, 2011). They specify the existing business context by analyzing tasks, issues, resources, and stakeholders (Horkoff and Yu, 2016; Robertson and Robertson, 2012; Sutcliffe et al., 2007). Thereon, several methods analyze and derive business events (Robertson and Robertson, 2012; Sutcliffe et al., 2007), which form the basis for business use cases, i.e., as-is situations. According service use cases (to-be situations) are defined to solve business problems defined in business use cases through system development (Robertson and Robertson, 2012). Afterward, functional and non-functional requirements for the implementation of the envisioned software system are derived and validated (Dardenne et al., 1993; Nuseibeh and Easterbrook, 2000; Robertson and Robertson, 2012; Sommerville, 2011; Sutcliffe et al., 2007). In addition, some recent works put an effort on the central role of data within RE, resulting in data-oriented requirements (Janzen et al., 2022).

2.2. Quantum Computing and Software Systems

This paragraph describes the main differences between QC and software systems relevant to the RE process. For further comparisons revealing the differences between classical computing and quantum computing, see for example Chipidza et al. (2023), Rietsche et al. (2022) and Ali et al. (2022).

Bits vs. Qubits. One main difference between classical computers, enabling software systems and quantum computers is how data and information are stored and processed. Classical computers build on bits that can have either a value of zero or one. Quantum computers use quantum bits (qubits), which can contain any linear combination of zero and one simultaneously (Steane, 1998). This enables to leverage the beneficial properties of quantum mechanics, especially the concept of superposition. Thereby, a qubit is characterized by its probability to be either zero or one, and not by the unique value of zero or one, i.e., a qubit can be in multiple states in a single moment (Brooks, 2012). Only when the state of a qubit is measured it will break down to the defined value of zero or one (Ding and Chong, 2020). Superposition enables to represent 16-digit numbers with just four qubits, compared to four-digit numbers four bits (Rietsche et al., 2022). Most importantly, this enables quantum systems to perform an exponential amount of calculations at the same time Rietsche et al., 2022).

Deterministic vs. Probabilistic. Classical software systems generally dispose of a deterministic nature.

This relates to the fact that given a particular input, the same output will be created by a software system. Due to the principles of quantum mechanics QC systems and software build on, it can be described as inherently probabilistic (Ali et al., 2022). This means the output of a QC system cannot be determined precisely or predicted with certainty, i.e., there exist multiple possible outputs based on a particular input.

Solvable problem spaces. With growing amounts of data and ever-increasing problem complexity, classical software systems (and AI systems) and computational power reach their limits, e.g., when it comes to drug discovery or simulating complex systems such as supply chains or manufacturing processes. They are either unable to solve such problems or only in unreasonable amounts of time. The expected quantum advantage promises to solve primarily very large, linear equation systems, unstructured and heuristic search problems, factorization, or cryptography (Bova et al., 2023; Montanaro, 2016). The most known QC algorithms are Shor's, Grover's, or the Harrow-Hassidim-Lloyd (HHL) algorithm (Montanaro, 2016). Still, to solve real-world problems, most quantum algorithms need to be highly adapted to be used in QC applications. Furthermore, specific algorithms require specific data properties and representations, e.g., specific sparsity as a measure for sparsity of the input matrices are required.

Errors and Reliability. Current quantum hardware is still limited due to errors and noise that limit practical utilization of QC (Ali et al., 2022; Deshpande, 2022); Noisy Intermediate-Scale Quantum (NISQ) technology (Preskill, 2018) is most widely used and available. Qubits are processed via quantum models using error-prone quantum technologies that provide only limited control over qubits. Noise and resulting errors represent the biggest obstacle towards QC applications (Cai, 2021). Therefore, researchers implemented error correction or error mitigation successfully in experimental settings (Acharya and Saeed, 2020; Cai, 2021; Suzuki et al., 2022). Still, the error rates hinder the practical application of QC.

2.3. Simulations in Manufacturing

As our RE process for QC applications is settled in the manufacturing domain and aims to derive requirements for simulation of manufacturing processes in laser cutting and milling of integral compressor-rotors, like blade integrated disks (blisks), we give an overview on simulations in manufacturing. Blisk milling and laser cutting are machining techniques representing a key manufacturing technology, e.g., in the metalworking industry that is central for mold and die making, the semiconductor industry, or engine construction. Due to the importance of machining, companies are interested in continuously optimizing machining processes in terms of quality, productivity, economic efficiency, and, increasingly, sustainability (Margherita and Braccini, 2020). Through digitization, machining processes are represented by digital twins, which enable end-to-end planning, manufacturing, and quality assurance (Bergs et al., 2021; Ganser et al., 2021; Q. Qi et al., 2021). Due to the high quality requirements and the usually considerable costs for scrap, simulations based on digital twins enable the planning of optimized manufacturing processes (Kritzinger et al., 2018). The technology-specific simulation models mainly come from the three categories of analytics (e.g. Euler-Bernoulli bending beam model), numerics (e.g. Dexel-based meshing simulation), and increasingly also from the field of machine learning (ML) (e.g. neural networks) (X. Qi et al., 2019). Still, simulations based on digital twins are often neglected due to the required high computational resources and expert knowledge (Schröder et al., 2023). In consequence, important physical aspects are often either neglected or solely approximated (Schröder et al., 2023). In particular, the models from the numerics (e.g., Finite-Element Method) and ML categories (e.g., Neural Networks) regularly take even powerful digital infrastructures to their limits, as they are still based on conventional computers (Kück et al., 2017; Reddy, 2019; Zimmerling et al., 2020). The resulting lengthy calculation times, erroneous calculation results, or unsolvable simulation issues make it difficult to transfer the Industry 4.0 framework models to industry today. These shortcomings require new solution approaches for performing adequate simulations in manufacturing. First investigations show that quantum mechanical functional principles have decisive advantages in solving numerous algorithmic problems, i.e., significant accelerations in numerical procedures and result improvements (Baiardi et al., 2021; Paudel et al., 2022).

3. Methodology

Our case study follows the principles of consortium research, which aims to develop artifacts in a collaborative environment that includes researchers and practitioners (Österle and Otto, 2010). Consortium research ensures that researchers and practitioners commonly define research objectives, assess work progress and evaluate results; in addition, multiple research partner companies contribute their expertise and grant access to knowledge sources for researchers

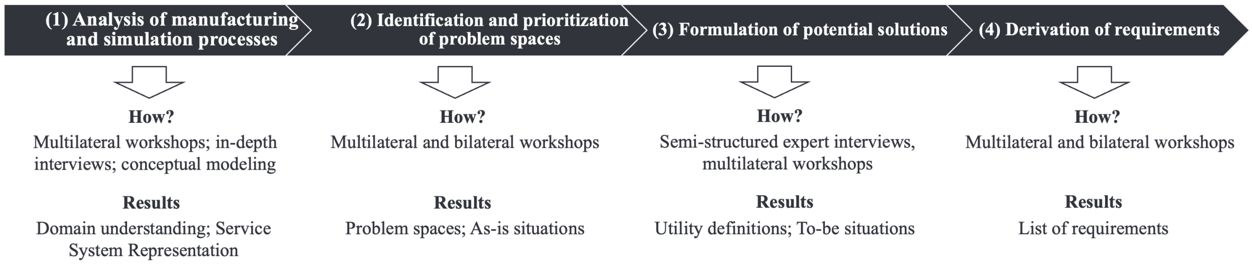

Figure 1. Requirements engineering process applied; including process steps, applied methods, and results of the process step.

(Österle and Otto, 2010). Marked by intense interaction between researchers and practitioners, the case study allows the creation and transfer of knowledge within the development of QC applications for manufacturing (cf. (Otto and Jarke, 2019)). As this paper aims to analyze the process of RE for QC applications, we focus on the phases of analysis and partially the design phase. As proposed by Österle and Otto (2010), we combine action research and expert interviews within our case study.

Building on related work in RE, we adopted a four step RE process for QC applications: (1) analysis of manufacturing and simulation processes, (2) identification and prioritization of problem spaces, (3) formulation of potential solutions, and (4) derivation of requirements (cf. Figure 1). Each step applied different method(s) to gather or produce the relevant information for the respective process step, i.e., the ”How” of each step (cf. Figure 1). Table 1 represents the participants involved in the RE process. In addition, we conducted three expert interviews in process step 3 (cf. Figure 1).

In step (1), we conducted a multilateral workshop with the participants of the RE process (cf. Table 1. In the workshop, we analyzed two manufacturing processes, i.e., milling of blisks and laser cutting of metal sheets, and their associated simulation processes with respect to the stakeholders involved, key processes, goals, and challenges. We enriched the results by two in-depth interviews with experts involved in these manufacturing and simulation processes. Step (1) resulted in a deepened domain understanding for the team. The laser cutting and blisk milling processes were documented in a conceptual model described as service system architecture (Patrıcio et al., 2011). Within a second multilateral workshop, these were discussed and agreed on. This helped the interdisciplinary team to better understand the processes and existing issues or bottlenecks in step (2) and, in consequence, to formulate potential solutions and to-be situations (step 3).

Based on the outcomes of (1), problem spaces of the simulation processes were defined and prioritized in step (2). Making use of existing templates (cf. (Robertson and Robertson, 2012)), the as-is situations were formulated with respect to stakeholders, pre-conditions and triggers, exceptions, business rules, and goals.

Step (3) analyzed the as-is situations and problem spaces to derive potential solutions, i.e., to-be situations, to solve the prioritized problems in simulation through QC. Here, the utility definition of QC was included. To support this, we conducted three semi-structured expert interviews with manufacturing professionals who are currently using simulation to improve their machining processes. The aim was to identify the potential utility of applying QC in simulations, tackling existing problems and shortcomings. The semi-structured design allowed deviating from the questionnaire, posing in-depth questions and adapting question wording to keep the discussion flowing (Döring and Bortz, 2016). The questionnaire comprised twenty questions (Gläser and Laudel, 2010), including introductory questions, questions about simulation in manufacturing and their relevance in the companies, simulation services used, problems, and the potential of QC in simulations. The interviews took 40 minutes on average; profiles of the interviewees can be found in table 2. All experts had high expertise in manufacturing, simulation, and application of new technologies. We transcribed the interviews verbally and conducted a pre-analysis with the raw, anonymized data. Next, we adopted thematic coding for content analysis (Gibbs, 2007) by applying the following steps: 1) descriptive coding: summarizing or labeling relevant sentences or phrases in a few words, 2) categorical coding: combining descriptive codes having things in common to categories, 3) analytic coding: examining connections between categories. We took countermeasures to avoid the five threats to validity (Maxwell, 2012).

In step (4), we derived requirements through an iterative process. Within several bi- and multilateral workshops, we analyzed to-be situations and the envisioned solution with respect to functional, non-functional, and QC-oriented requirements and listed them accordingly.

Table 1. Overview of Participants in RE Process.

No. of Participants	Domain	Role
2	Manufacturing - Blisk Milling	Prototype Developer, High Performance Cutting
1	Manufacturing - Laser Cutting	Data Scientist
3	Quantum Computing	(Senior) Researchers
3	Artificial Intelligence	Head of Research Group, Researchers
2	Simulations in Manufacturing	Research Manager, Researcher
1	Business Economics	Researcher

Table 2. Profiles of expert interviewees.

ID	Role	Organization	Years of Experience
E1	Lead R & D, Application Engineer	Computer Aided Manufacturing	12
E2	Lead Manufacturing	Manufacturing of Individual Machine Components	17
E3	R & D Applied Simulations	Machine Tool Supplier	15

4. Results

We now present the results generated within the QC RE process for QC-enhanced applications to improve simulations in manufacturing, focusing on the machining processes of blisk milling and laser cutting.

4.1. Analysis of Manufacturing and Simulation Processes

The analysis of manufacturing and simulation processes aimed at an in-depth domain understanding, which is divided into two layers. First, understanding the machining processes of blisk milling and laser cutting, and second, the according simulation processes that support predicting the outcome of the production process (cf. Figure 2). After knowledge transfer on the production process flows, the main focus in the RE process was on the simulation processes. The results were gathered from multilateral workshops and two in-depth interviews with simulation experts.

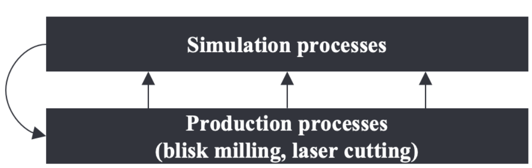

Figure 2. Layers of domain understanding.

Goal of both simulation processes (blisk milling and laser cutting) is to perform a timely, cost-efficient, and high-quality simulation of the production process, covering all potential incidents and being able to prevent them to guarantee high-quality products. In our specific case, the generated products are mostly applied in aviation, which only allows small tolerances. Beneath the individuals conducting the simulations, machine operators, manufacturers in aircraft axle segment, aviation companies, supply chains, manufacturing suppliers, component suppliers, process and production managers, reworkers, as well as finance and management, represent **stakeholders** of the simulation process. Different **inputs and key artifacts** are necessary to perform the simulations. These range from order data for the product to be manufactured over geometries to physical and mathematical formulas. The **services** used for conducting the simulations range from pre-assembled solutions to highly customized and specialized approaches. After gathering the domain understanding, a so-called service system navigation was modeled (Patrıcio et al., 2011), representing the current simulation process concerning the customer journey (i.e., the individual performing the simulation), the service interface, and backend support. The graphical representation facilitates the discussion of the simulation processes in multilateral settings and lays the foundation for describing the as-is situations and derivation of problem spaces within the RE process.

4.2. Identification and Prioritization of Problem Spaces

Based on an iterative process in discussing the service system navigation of current simulation processes, the as-is situations were formulated using business use case templates (Robertson and Robertson, 2012). Accordingly, pre-conditions, triggers acuating the simulation process, involved stakeholders, step-by-step descriptions of the process scenario, exceptions, business rules, and goals were documented.

Next, it was analyzed which problem spaces within the simulation processes exist. As described in section

2.2, QC applications are subject to boundary conditions, especially concerning solvable problem spaces, noise, or errors. The solvable problem space represents a boundary condition within this RE process step for QC applications. From the beginning, it was very clear from the practitioner's side on which aspects the main problems in the simulation would focus. In blisk milling, vibrations in the production process lead to quality losses. As simulation is very time-consuming, this complex impact often cannot be simulated fully as the number of evaluated intersections is limited. In laser cutting, simulating thermal expansion during laser cutting, i.e., unwanted expansion of the material due to excessive temperatures, represented the main issue. Two approaches were applied to identify and prioritize specific problems of simulating vibrations in blisk milling and thermal expansion in laser cutting to be solved by QC-enhanced applications. In the context of **simulations in blisk milling**, on one hand side, each sub-process step for simulating vibrations were analyzed with respect to run-time. On the other hand side, each step was analyzed with respect to solvability by QC. Next, the sub-process step with the highest run-time that QC could solve was identified, i.e., finding a "sweet spot" to be solved by a later QC-enhanced application. We note that several bilateral workshops between the simulation process and QC experts were necessary in order to specify the solvability by QC. Within the **laser cutting simulation**, problem identification and prioritization was more straightforward. The laser cutting company disposed of in-house QC knowledge. Therefore, they analyzed the simulation process in advance with respect to mathematical problems or equations that can be solved by QC, i.e., linear algebra, and selected a subproblem that could not be solved (adequately) so far. Here, the number of discussions with QC experts concerning QC solvability was reduced.

4.3. Formulation of Potential Solutions

Within the formulation of potential solutions, we analyzed the as-is processes with respect to the defined problems. Each as-is process step was examined to determine whether it could be replaced or enhanced to solve the respective problem. The result was documented as a to-be situation building on the service use case template by Robertson and Robertson (2012). This also included the required artifacts, i.e., necessary data, equations, and potential tools to develop the QC applications for solving the defined problems.

During the process, it became clear that the utility of QC was partially elusive. Thus, we aimed to extract reasons for uncertainties regarding QC applications' utility and to derive the potential utility through bilateral workshops. Expert interviews with parties uninvolved in the RE process were conducted complementary to acquire external validation. The experts' profiles are shown in Table 2. The combined results on uncertainties about and utility of QC are described below.

Uncertainties concerning the utility of QC applications in manufacturing. Several reasons lead to uncertainties concerning the utility of QC in manufacturing. First, the applicability of QC and its potential is regarded as intangible. One interviewee stated they would be open to anything that makes simulations easier or faster, and they wouldn't care whether a CPU, GPU, or QPU would be behind the solution. Second, QC solves only specific problems - it represents no panacea. Especially for researchers and practitioners inexperienced with the solvable problem spaces of QC, uncertainties about the suitability of QC applications for their respective problems arise. Third, QC represents a black box and therefore is in charge of the lack of explainability which reduces trust in QC applications. Fourth, errors produced by QC applications running on NISQ hinder producing useful results for simulations in manufacturing. Fifth, the costs of applying QC are considered opaque or so high that they would exceed the benefits.

Utility of QC applications. Despite the uncertainties and obstacles towards QC, several aspects of how QC applications could create utility could be derived. The individuals involved in the RE process and the expert interviewees expect large utility from QC in terms of the efficient solution of very large, linear equation systems, e.g., for solving water jet simulations, simulating thermal expansion, or distortion of materials. Furthermore, this could lead to solving previously unsolved problems, analyzing larger data sets, and embedding equations crucial for simulation processes. In addition, utility is expected from larger computing capacities and higher-resolution results. Next, higher quality simulations are also expected to increase the quality of end products. Furthermore, monetary savings are expected through the utilization of QC in simulations by preventing downtimes in the production process, by time savings as well as by detailed on-the-fly calculations. Next, the combination of models from numerics with QC and AI models (especially machine learning) with QC or outsourcing parts of these rather classical approaches to QC could lead to high utility gains according to the interviewees and participants of the RE process. Finally, it is expected to gain advantages through high scalability when executable hardware is available.

Table 3. Initial Set of Requirements.

ID	Requirement	Type
R1.01	The QC application shall be easy to use	NF
R1.02	The QC application shall be provided as a service	NF-QC
R1.03	Results of QC application are generated near-realtime	NF-QC
R1.04	QC algorithms in the application can be combined with numerics or AI algorithms	QC
R1.05	QC application offers error analysis	QC
R1.06	QC application provides accuracy rates of results	F
R1.07	The QC application results are traceable	NF-QC
R1.08	Real data are available for validation of results	NF
R1.09	The quality of data used in the QC application shall only be reduced by 1-2% on maximum	QC
R1.10	QC application can process multiple relevant geometries	QC
R1.11	QC application can process multiple relevant material properties	QC
R1.12	QC application can process multiple relevant mathematical and physical equations	QC
R1.13	Results of the QC-enhanced application are available in a format that can be integrated into the simulation process	QC
R1.14	The QC application supports the coupled simulation of multiple systems	F
R1.15	The QC application requires reduced computing power compared to classical software systems	NF
R1.16	The QC application supports coupling with multi-processors (CPU, GPU)	QC
R1.17	APIs allow easy access to the QC application	NF-QC
R1.18	QC algorithms shall be designed for next-generation quantum computers	QC
	Legend: F = functional, NF = non-functional, QC = QC-specific requirements	

4.4. Derivation of Requirements

Based on the to-be situations defined by the consortium, a set of 18 initial requirements for QC-enhanced applications for simulations in manufacturing were derived (cf. Table 3). They were categorized after functional (F), non-functional (NF), and QC-specific (QC) requirements. QC-specific requirements describe such that would not at all or not in that form have been arising from a RE process for classical software applications. The QC-specific requirements mainly focus on enabling specific input and output parameters (data) to be processed and how their quality is allowed to change, the combination of QC algorithms with AI algorithms or numerics, the easy utilization, integration, or combination of QC applications into and with existing hard- and software. In addition, several non-functional requirements are marked as "NF-QC" as they represent borderline functionalities that might arise in classical RE as well as in QC RE. They have been labeled NF-QC because the participants in the RE process believe that they represent the distinctive features of QC. These mainly focus on easy usability and interoperability with QC applications and traceability of the results.

The QC-specific requirements, as well as the specifics of the QC RE process, will be discussed in the next chapter.

5. Discussion

Based on our case study on RE for QC applications, we found some differences in the QC RE process, and in resulting requirements compared to RE for conventional software systems. We will now discuss these differences that need to be taken into account in future QC RE. We distinguish differences in the RE process as well as QC-specific requirements. The QC RE process-oriented findings were:

- Basic QC knowledge is required
- QC solvability space hinders the specification of to-be situations and deduction of requirements
- Status quo of QC hardware hinders the specification of to-be situations and deduction of requirements

To specify and prioritize problem spaces, define to-be situations, and derive requirements, we found that basic QC knowledge is required among the RE process contributors. It helps to assess what is possible with QC, to select and, later on, manage quantum-based applications (Chipidza et al., 2023). Furthermore, to prioritize problems to be solved (step 2), QC knowledge is required. Contrary, in RE for software systems, it is proposed to neglect what is possible but to focus on aspects that should be solved or improved. With

QC as an emerging technology, several uncertainties about solvability spaces (QC algorithms) and feasibility (QC hardware) were recognized. With respect to the solvability space it became clear that despite the definitions of as-is situations and problem spaces, the definition of to-be situations was aggravated. This is mainly anchored in the need for high customization of existing QC algorithms. Despite the existence of perfect quantum simulators and cloud-based access to quantum computers with low qubit numbers, the currently limited hardware hinders the development of satisfactory to-be situations. Especially as current quantum computers are subject to a high number of errors and noise (i.e., NISQ). Therefore, the specification of to-be situations (step 3) and deduction of requirements (step 4) was characterized by many iterations. For future QC RE processes, it will be crucial to communicate utility and especially business value from QC applications (Chipidza et al., 2023). For example, it could be of strategic value to investigate potential QC applications early and profit from scaling effects as soon as performant and practical usable hardware is available. Best practices of design, development, and utility specification for QC applications could support the openness towards applying QC in practice.

Beneath the differences within the QC RE process, we also found differences in QC-related requirements compared to classical software RE:

- High focus on interoperability and integrability of the QC application
- High focus on timeliness of results
- High focus on traceability of results and errors
- High focus concerning input and output for the QC application
- QC algorithm design for different states of hardware
- Hybrid QC models

Aspects of interoperability and integrability are relatively common in software engineering. Still, as QC is an emerging technology, future users put a specific focus on the easy integration of the QC application into existing tools and interoperability with existing systems. This leads to the wish for ”QC as a service”. The focus on timeliness arises mainly due to the errors and noise of current quantum hardware. The participants of the RE process and interviewees currently only could imagine using QC if the application would outperform current solutions with respect to time. I.e., if they are faster but more faulty, they could at least support a first estimation in the context of the manufacturing process simulation, which could lead to first advantages from their view. Furthermore, the traceability of the results, i.e., prevention of black boxes and statements concerning the extent of errors, is necessary at this point in time in order to retrieve reliable estimations. This also could lead to higher trust in the applications in terms of explainability (cf. AI explainability (Lukyanenko et al., 2022)). Nevertheless today it is unclear, whether AI explainability methods could be simply adopted for QC explainability or whether - more realistic - new approaches are required. Next, input and output data and models are specifically focused. QC algorithms require different data formats and representations. In addition, they pose only an advantage over state-of-the-art if they incorporate and process all input data concerning numerous material properties as well as physical equations. Another QC-specific requirement derived in our case study states that the QC algorithms developed should be designed for the next generation of quantum computers. I.e., they should not aim to run and perform well on NISQ, but on quantum computers with sufficient numbers of qubits and low error rates to use scaling effects and create business value as soon as appropriate hardware is mid- or large-scale available. During current QC RE processes, project teams need to decide whether they aim to use current NISQ hardware or, e.g., perfect quantum simulators, in order to prepare for high-performing hardware. Finally, investigating hybrid QC models, i.e., combinations of numerics and QC or AI and QC (Quantum AI) can pose advantages in higher performance and accuracy (Havlıček et al., 2019).

6. Conclusion

We presented the results of a RE process for QC applications performed through consortium research. As RE presents a major aspect in the software development lifecycle and is, in particular, an open field with respect to QC applications (Ali et al., 2022), we focused on this specific aspect and omitted the further steps such as quantum software development, testing or debugging. These aspects of the quantum software development lifecycle need to be investigated in further studies. We also recognize that the focus of the derived requirements was mainly on non-functional and QC-specific requirements, while some of the QC-specific requirements replace functional requirements, e.g., R1.05, R1.10 (cf. Table 3). We note that we present a set of initial requirements, that will be further detailed within the research project. Future work could enhance our results by performing an in-depth analysis and more fine-granular differentiation of QC-specific and functional requirements. Nevertheless, our results are valid as they represent the perspective of a multidisciplinary research consortium composed of experienced practitioners and researchers.

This paper represents a first study on the RE process for QC applications. The existence of best practices and basic QC knowledge within the RE process were found to be crucial. With respect to requirements, timeliness of QC applications, traceability of errors, incorporation of relevant input and output data, interoperability, decision for hardware type and the possibility of applying hybrid QC models are QC-specific. Despite the RE process was performed in manufacturing, our results are transferable to other domains such as finance or supply chains. Facing similar challenges, participants of future RE processes for QC applications can build on our findings.

7. Acknowledgement

This work is part of the research project QUASIM (grant number: 01MQ22001A, www.quasim-project.de), funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), supported by the DLR project management agency. We are grateful for the exchange with the QUASIM project team and especially for the feedback from Prof. Wolfgang Maass.

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