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Concept for the Identification of Applications for Paradigm-Shifting Technologies on the Example of Quantum Computing

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Abstract

In this paper, the challenge of identifying high-value applications of quantum computing is examined. Although quantum computing holds enormous potential, it requires significant investments and development efforts. Therefore, it is crucial to define precise applications that can guide its development for an efficient industrialization process. To accomplish this goal, a methodology that systematically identifies and evaluates potential applications of quantum is developed. The methodology is designed for a strong alignment between tasks and technology, identification of problem and solution types, a systematic process for identifying problems, and a focus on socioeconomic challenges. It is structured according to the TRIZ methodology and comprises five submodels to determine socioeconomic applications for quantum computing.

Keywords

Paradigm-Shifting Technologies; Quantum Computing; Socioeconomic Challenges, TRIZ Methodology; Task-Technology Fit

1. Introduction

Quantum computing is undoubtedly one of the most promising emerging technologies today [1]. With the ability to overcome the physical limitations of conventional computers, quantum computing is shifting away from established physical paradigms and opens up a new era of computational possibilities with disruptive potential in various application areas such as the simulation of natural systems or combinatorial optimization [2,3]. However, the path to fully realize he disruptive potential of quantum computing is full of challenges, given the still long development times and the funding required [4]. No quantum advantage has yet been demonstrated for a practical problem so that technology users and investors face the risk of not getting an early return for their upfront investments [2,5]. This could lead to disappointment among users and investors, resulting in a so-called quantum winter with less technology funding than required for bringing quantum computers into practical use [6]. To mitigate the risk of a quantum winter, the development of technology visions could help to keep funding high and to industrialize quantum computing. Technology visions provide a clear and easy-to-understand target in the development of radical innovations and serve as guiding stars for investment, research, and development decisions [7].

Selecting appropriate use cases for a technology vision requires careful consideration of the technology's unique characteristics [8]. Early industrial applications entail long development times and high costs for users [9], underscoring the need to ensure strong task-technology fit between corresponding problems and quantum computers [10]. However, the counterintuitive principles of quantum mechanics present a challenge for users to objectively evaluate the fit between the task and technology [11]. Furthermore, the selected

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applications should have significant potential for disruptive value to justify the resources required for development. Applications that are specific to a particular company often have limited value contribution [9].

Therefore, this paper aims to develop a methodology to systematically identify high-value applications for paradigm-shifting technologies such as quantum computing answering the underlying research question: How can users of quantum computing identify relevant applications for a technology vision at an early stage of development?

2. Research Methodology

As presented in the previous chapter the present paper focusses on a practical issue. Based on the outlined application context and due to its practice-oriented objective, the selected research methodology follows the process of applied science according to ULRICH [12]**.** Figure 1 shows the approach of ULRICH, whose goal it is to develop future-shaping models that describe, explain and configurate selected application areas. The procedure consists of seven successive steps. This paper addresses the initial five steps, while the final two stages, that involve testing and verification within industrial practice, are excluded from its scope.

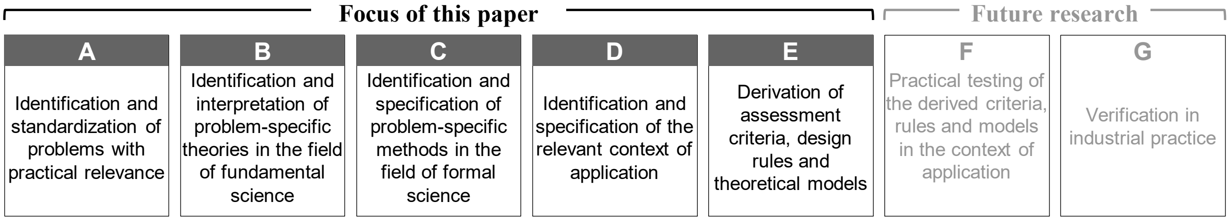


Figure 1: Research process according to Ulrich [12],[13]

In the first section, the practical challenges encountered in both ongoing and previous industrial and research projects are discussed (process step A). Sections 2 and 3 establish the theoretical foundation of process step B by presenting essential theories and hypotheses. Section 4 evaluates the current approaches described in literature and their inadequacies in resolving the research question posed in section 1 (process step C). Moreover, it outlines the requirements for the textual model. In section 5, the paper proposes a rough methodological structure that addresses process steps D and E. The conclusion summarizes and briefly discusses the paper's findings in section 6, followed by an outlook on future research.

3. Fundamentals

The following section sets out the foundations for understanding the key aspects of paradigm-shifting technologies, quantum computing and the task-technology fit theory. These foundations and derived characteristics serve as pillars for the development of a user-friendly methodology and will help to conduct a focused literature analysis in Chapter 4.

3.1 Paradigm-Shifting Technology

An early definition of the term paradigm was introduced by KUHN in 1962. KUHN defined a paradigm as a scientific theory on which there is broad consensus among researchers [14]. Based on this definition, a paradigm shift is facilitated by new discoveries in science that fundamentally change previously prevailing scientific models. An example of a paradigm shift was the emergence of Einstein's Special Theory of Relativity, which provided a better explanation of reality compared to the previous paradigm of Newtonian physics. [15]

Following this understanding of a scientific paradigm, DOSI offers a widely cited definition for the term technology paradigm. He defines a technology paradigm as a “model and a pattern of solution of selected technological problems, based on selected principles derived from natural sciences and on selected material technologies” [16]. Technology paradigms thus provide clear guidelines for further technological development, so that according to DOSI a “direction of technical change to pursue and those to neglect” is given to technology developers. [16]

Furthermore, DOSI describes that continuous innovations typically occur along a predetermined path within a technological paradigm, while discontinuous innovations are linked to the emergence of a new technological paradigm [17]. Other authors like CHRISTENSEN link a paradigm shift to the theory of disruptive technologies. Once a new technology paradigm emerges, several technical approaches compete for a dominant design. They often have inferior characteristics compared to established technologies and are often used first in new, specific applications. [18]

Subsequently, for the purpose of this paper, the authors define the concept of a paradigm-shifting technology as follows: The technology disrupts existing technology paradigms and uses new scientific principles or materials enabling new patterns of solutions for a specific group of problems. Thus, a change in the technological paradigm fundamentally alters the ways in which technologies approach a specific problem or accomplish a task. As stated by CHRISTENSEN [18], these new technologies are initially clearly inferior to the established ones in their classic areas of application but are further developed via special use cases and are thus suitable for larger areas of application in the long run.

3.2 Quantum Computing

Quantum computing is an emerging technology that exemplifies a paradigm shift. Quantum computers, unlike their conventional counterparts, use the laws of quantum physics to create a novel computing paradigm. Quantum physics is particularly relevant for describing natural processes at the atomic or subatomic level and is very counterintuitive compared to the laws of classical physics [19]. The understanding of quantum computers requires a grasp of two fundamental principles in quantum mechanics, namely superposition and entanglement.

In classical physics, the state of an object at a given time is uniquely defined by certain parameters. Such parameters can be, for example, the position vector or the momentum of an object [20]. Quantum objects behave in a fundamentally different way. They can be in multiple states at the same time. The quantum particle is said to be in a superposition of several states [21]. A second fundamental principle in quantum mechanics is quantum entanglement. The term entanglement was first used in 1935 by SCHRÖDINGER, who defined quantum entanglement as the characteristic property of quantum mechanics [22]. Two systems are in quantum mechanical entanglement if the state of one system is conditioned by the state of the other. A measurement of the state of one object can provide information about the state of the other object, even if they are geographically separated [23].

Thus, quantum computing makes use of new physical principles that can trigger a paradigm shift in computing technologies and offer an enormous potential in certain applications [24]. Understanding these principles is counterintuitive compared to our classical understanding of physics and the technology is still on a low maturity level, having not yet demonstrated a practical quantum advantage [2, 20]. Further development and funding over a longer period are required to industrialize the technology for commercial use [25].

3.3 Task-Technology Fit

As explained in Section 1, selecting appropriate applications for a technology vision necessitates consideration of the technology's unique characteristics. Therefore, a task-technology fit (TTF) is necessary.

The TTF measures the degree to which a technology is suitable for solving a task or problem [26]. GOODHUE and THOMPSON developed this theory to demonstrate that technologies have a valuable impact only when the TTF is high. The TTF theory is often utilized in research on information systems but can also be applied to various other technologies [27].

Figure 2 illustrates the fundamental concept in TTF theory, where the benefit of improved performance results from the actual use of technology and its TTF level. The TTF level is derived from a task and technology characteristic match [10]. In other words, higher task and technology alignment leads to greater technology value and performance benefits.

Figure 2: Basic concept of the Task-Technology Fit theory [27,10]

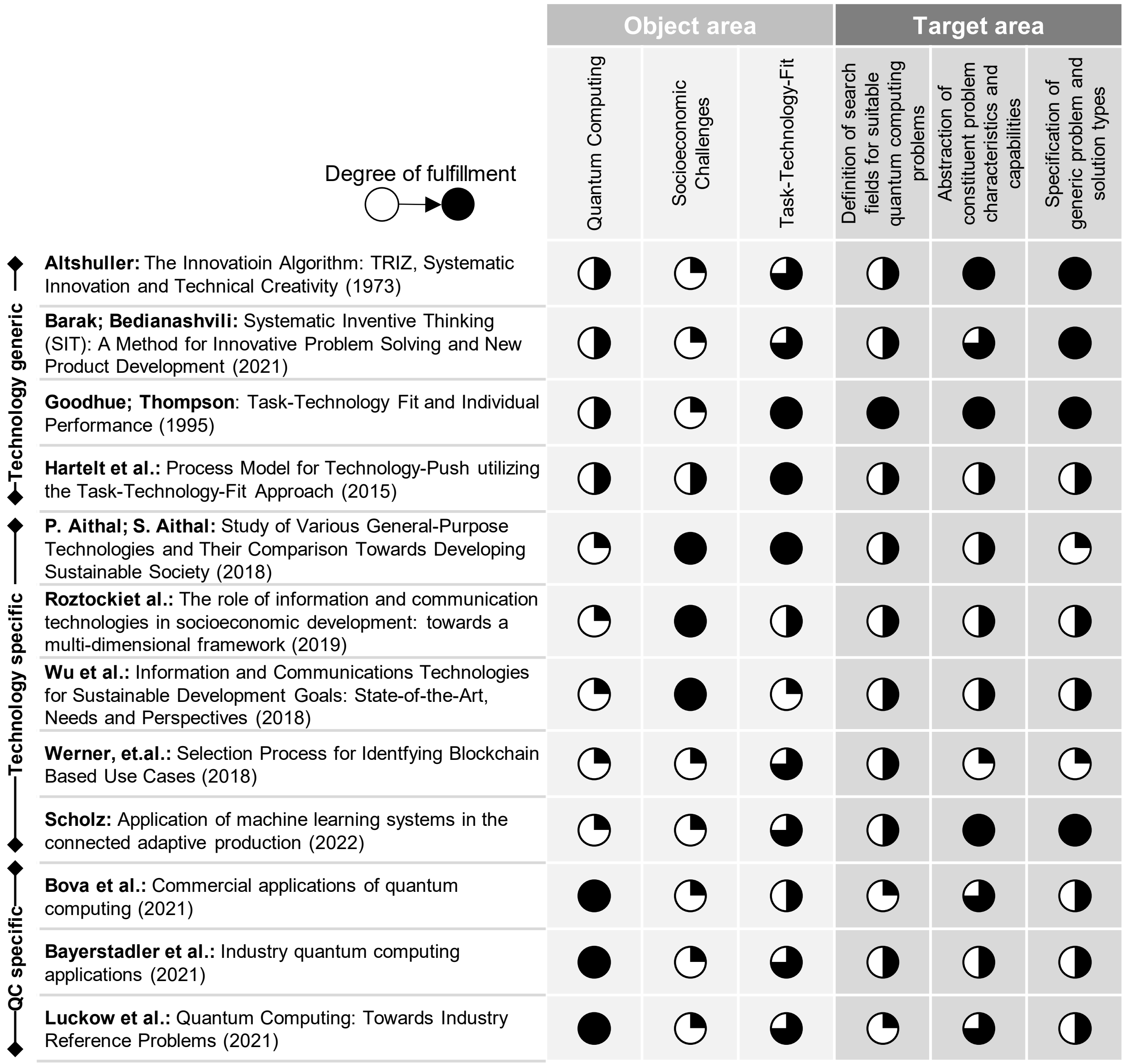
In the context of this paper the technology characteristics of quantum computing are derived from the paradigm shift from classical mechanics to quantum mechanics. Emphasis is placed on the implications of superposition and entanglement for practical use. Task characteristics mainly originate from identified data-based problems.

4. Literature Review

The following chapter seeks to identify and evaluate theories and methodologies suitable for addressing specific problems in the field of formal science [12]. However, since the paper is focused on deriving a concept for the identification of quantum computing applications, it presents only a brief overview of existing methods, their limitations, and requirements. The goal is to identify shortcomings in problem-specific theories and establish requirements that will inform the design of the concept proposed in this study.

4.1 Theoretic Deficits

To address the practical challenges identified, this section reviews existing scientific approaches to determine the extent to which adequate solutions already exist in the literature. The evaluation criteria are divided into an object and a target area. The object criteria are used to assess the extent to which the approaches consider relevant objects from the previous section, which are quantum computing, socioeconomic challenges, and the task-technology fit. The criteria specific to the target area are used to assess the approaches and their relevance to the research question of this paper. These criteria encompass defining appropriate search fields, abstracting and specifying constituent problem characteristics and technological capabilities. Based on the object and target area, twelve approaches have been identified and subsequently grouped into three categories. Quantum computing studies focusing on specific applications and further studies on specific technologies, such as information and communication technologies, were evaluated alongside generic studies on technology applications like TRIZ or TTF. Figure 3 presents the consolidated results of the evaluation.



Degree of fulfillment ○→●

		Object area			Target area		
		Quantum Computing	Socioeconomic Challenges	Task-Technology-Fit	Definition of search fields for suitable quantum computing problems	Abstraction of constituent problem characteristics and capabilities	Specification of generic problem and solution types
Technology generic	**Altshuller:** The Innovatioin Algorithm: TRIZ, Systematic Innovation and Technical Creativity (1973)	◑	◔	◕	◑	●	●
	Barak; Bedianashvili: Systematic Inventive Thinking (SIT): A Method for Innovative Problem Solving and New Product Development (2021)	◑	◔	◕	◑	◕	●
	Goodhue; Thompson: Task-Technology Fit and Individual Performance (1995)	◑	◔	●	●	●	●
	Hartelt et al.: Process Model for Technology-Push utilizing the Task-Technology-Fit Approach (2015)	◑	◑	●	◑	◑	◑
Technology specific	**P. Aithal; S. Aithal:** Study of Various General-Purpose Technologies and Their Comparison Towards Developing Sustainable Society (2018)	◔	●	●	◑	◑	◔
	Roztockiet al.: The role of information and communication technologies in socioeconomic development: towards a multi-dimensional framework (2019)	◔	●	◑	◑	◑	◑
	Wu et al.: Information and Communications Technologies for Sustainable Development Goals: State-of-the-Art, Needs and Perspectives (2018)	◔	●	◔	◑	◑	◑
	Werner, et.al.: Selection Process for Identfying Blockchain Based Use Cases (2018)	◔	◔	◕	◑	◔	◔
	Scholz: Application of machine learning systems in the connected adaptive production (2022)	◔	◔	◕	◑	●	●
QC specific	**Bova et al.:** Commercial applications of quantum computing (2021)	●	◔	◑	◔	◕	◑
	Bayerstadler et al.: Industry quantum computing applications (2021)	●	◔	◕	◑	◑	◑
	Luckow et al.: Quantum Computing: Towards Industry Reference Problems (2021)	●	◔	◕	◔	◕	◑

Figure 3: Evaluation of existing literature approaches [28,29,10,30–36,25,37]

The analysis of existing approaches indicates that the research query, and its corresponding subject and area of focus, have not yet received sufficient attention. Although certain publications satisfy specific criteria of the subject and area of interest, none of the reviewed studies fulfil all the criteria.

QC-specific studies: Current literature on quantum computing applications is often limited to routine, company-oriented issues, resulting in a narrow range of identified applications that dismiss socioeconomic challenges. (e.g., BOVA et al., BAYERSTADLER et al., and LUCKOW et al.) Hence, original and groundbreaking applications of quantum computing are routinely disregarded. Moreover, a systematic derivation of use cases is absent in these approaches, as they instead depend on specific industrial problems and allocate solutions in an approach that is hard to generalize and not easily transferable to new problems and technologies.

Technology-specific studies: Existing studies on information and communication technologies often omit the systematic derivation of use cases for the technologies being examined. This hinders the ability to easily generalize the procedure. SCHOLZ's work is the only one to adopt a systematic and user-friendly approach. However, this approach only focuses on company-specific issues and does not consider the definition of socio-economic search fields.

Technology-generic studies: A promising approach for a reproducible and easy-to-use methodology provides ALTSHULLER's Theory of Inventive Problem Solving (TRIZ). The concept of systemizing technology features and problems enables even an inexperienced user to find solutions for a specific technological problem. While ALTSHULLER's approach holds promise for potential adaptation across different application areas such as the field of quantum computing, the aspect of problem identification is not adequately considered. ALTSHULLER as well as other similar approaches (e.g., BARAK & BEDIANASHVILI; HARTELT et al.) assume that a relevant problem already exists, making the methodology an inadequate starting point for a systematic identification of future socioeconomic problems.

The literature analysis suggests that a systematic approach to identifying applications for paradigm-shifting technologies, including quantum computing, is currently not available. The existing methodologies cannot be applied for the scope of this work, necessitating a new approach which considers the specific requirements of quantum computing technology.

4.2 Derived Methodology Requirements

This chapter focuses on defining the formal and textual requirements of the methodology that is developed in this paper. To define the textual requirements, the fundamentals in section 3 as well as the identified literature gap in section 4.1 are considered. In summary, this chapter derives four textual requirements for the methodology.

Formal requirements: Empirical and formal correctness, manageability, and quality of results

Ensuring high formal quality is one of the most critical factors in successful model design. This can be achieved by adhering to the model-theoretical principles of optimal effectiveness. In this paper, the formal requirements for model design are based on the characteristics of PATZAK's work [38], which include empirical and formal correctness, manageability, and quality of results.

Textual requirement a: Optimizing for a high task-technology fit

Although section 4.1 explores various approaches that address the TTF implicitly, they frequently do not methodically determine the extent to which issues assimilate with technological solutions. This is a vital component in creating a methodology that users can effortlessly reproduce and employ. A high TTF is particularly important in quantum computing to develop appropriate technology goals, as outlined in section 1. Therefore, the methodology must incorporate a model for evaluating the correlation between generic problem and solution types.

Textual requirement b: Identification of generic quantum computing problem and solution types

To systematically assess the TTF, it is critical to identify the different characteristics of both the task and the technology according to the TTF theory described in Section 3.3. Quantum computing is an emerging, paradigm-shifting technology that continuously evolves and is unfamiliar to many potential users due to the counterintuitive principles of quantum mechanics, described in Section 3.2. Therefore, it is essential to construct the methodology in a manner that facilitates the assessment of TTF without extensive knowledge of quantum mechanics. One may apply and adapt ALTSHULLER's TRIZ methodology (see 4.1) to quantum computing to create a user-friendly methodology. TRIZ has proven to be a successful approach to systematically identify new technical solutions for specific problems. Therefore, it is advisable to consider the use of TRIZ's method for developing a generic set of problem and solution types. This approach allows for application in various fields and enables ease of use for individuals without extensive knowledge of quantum computing.

Textual requirement c: Establishing a comprehensive methodology by including the problem identification phase

As described in Section 1, selecting high-value problems is crucial in formulating technology visions. The literature review in Section 4.1 demonstrates that ALTSHULLER and other literature approaches disregard the need for a systematic problem identification process and presume that a problem already exists. Therefore, the methodological scope of the present model needs to be expanded to include a systematic procedure for identifying appropriate quantum computing problems.

Textual requirement d: Extended focus in problem identification by considering socioeconomic challenges

Current literature predominantly concentrates on issues specific to individual companies, which may be too limited for a paradigm-shifting technology. Due to the considerable development and research required for quantum computing, it is crucial to obtain funding and investigate additional investment opportunities. In this regard, creating innovative use cases is pivotal in persuading investors. Simultaneously, it is crucial to avoid disappointing investors with unrealistic expectations. To achieve this, the methodology must focus on identifying practical use cases that provide significant socio-economic impacts and high value. Therefore, the search scope for the methodology must extend beyond corporate boundaries and take into account socio-economic challenges, as discussed in section 1.

5. Results

Based on the defined formal and textual requirements, a methodology structure for the identification of applications for paradigm-shifting technologies on the example of quantum computing can be derived. It refers to step E of ULRICH's applied science research process (see figure 1).

5.1 Derivation of Model Structure

The overall structure of the methodology is oriented on the TRIZ methodology and follows the approach of mapping specific problems and solutions to generic problem and solution types (a). The methodology consists out of five submodels. Submodel 1 and 2 define these solution and problem types which according to requirement (a) must be done in a user-friendly language. To ensure a high TTF (d), the defined problem types are matched with the appropriate solution types in submodel 3. Thus, a generic quantum computing application matrix is synthesized. Submodel 4 defines a socioeconomic search field for problem identification (b) ensuring that not just company-specific problems are identified (c).

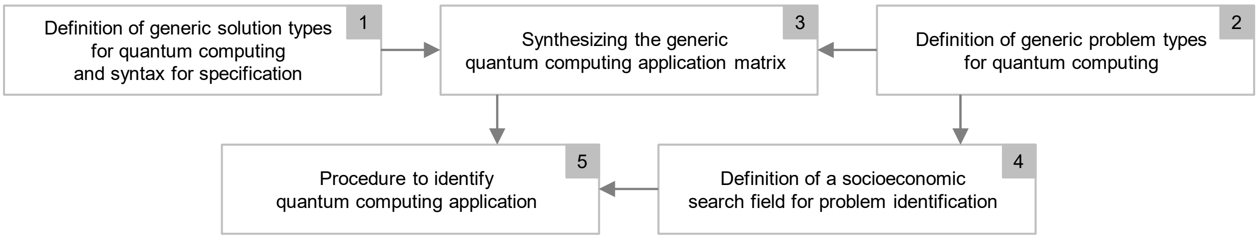


Figure 4: Methodology of identifying applications for paradigm-shifting technologies on the example of quantum computing

5.2 Characterization of the Submodels

In the following, the five previously introduced submodels are conceptualized in more detail regarding their objective and their relationship with other models.

1) Definition of generic solution types for quantum computing and syntax for specification

As stated in requirement (b), submodel 1 is devoted to the derivation of generic solution types for quantum computing. Initially, a comprehensive overview of the main application domains and objectives of quantum computing should be provided. This offers insight into the vast range of areas where quantum computers can add value. Based on designated application domains, a thorough database of currently explored quantum computing use cases is developed. The identified use cases are systematized to derive a generic set of solution types for quantum computing including corresponding application-oriented capabilities (e.g., combinatorial optimization). Two approaches are employed to define the solution types. First, an in-depth review of literature and monitoring of emerging literature over an extended period is conducted to create a comprehensive and up-to-date application database. Second, a series of expert interviews is performed to validate the findings of the literature research and the defined solution types. To further enable users transforming the generic solution types into precise quantum computing use cases, a syntax for specification is developed.

2) Definition of generic problem types for quantum computing

To complement the generic solution types, submodel 2 defines a set of generic problem types. Generic problem types are constituent characteristics of data-based problems that make them suitable for the use of quantum computers. The approach in submodel 2 is based on the approach in submodel 1. To identify generic problem types, the database established in submodel 1 is enhanced with the problems associated with the previously identified use cases. This set of specific problems is analysed and organized with the assistance of additional expert interviews and literature research. In addition, further research of literature is conducted to distinguish quantum computers from classical computers.

3) Synthesizing the generic quantum computing application matrix

Submodel 3 creates a generic matrix for quantum applications. It summarizes the outcomes of submodels 1 and 2 by generalizing solutions for each type of problem. This process aims to guarantee a high TTF as demanded in requirement (a). Nonetheless, not all generic solutions are equally effective for a specific problem. To evaluate the assignment, a literature review is performed, which also involves analysing initial practical results from use case explorations. Furthermore, a comprehensive interview study is conducted with firms that possess early involvement with quantum computing use cases.

4) Definition of a socioeconomic search field for problem identification

According to requirement (c), identifying adequate problems is the initial step for application identification. Submodel 4 addresses the identification of appropriate problems that have a high-value impact and broad socioeconomic effects as stated in requirement (d). Socioeconomic innovation systems constitute the search field for problem identification. An innovation system comprises the private and public sector organizations and institutions engaged in the development, modification, and dissemination of scientific and technological innovations. [39] Identification of development needs within innovation systems can be facilitated by using the Sustainable Development Goals (SDG) framework. The UN created the SDGs as objectives to foster long-term social and economic development while considering environmental sustainability [40]. The combination of SDGs and innovation systems generates several innovation fields. In the final step of the submodel, the innovation fields are mapped to appropriate key technology fields. Thus, the output of submodel 4 are key technology fields with allocated socioeconomic development needs.

5) Procedure to identify quantum computing applications

Submodel 5 develops a procedure of formulating applications for paradigm-shifting technologies on the example of quantum computing. It links the results of submodel 1 to 4 into a comprehensive approach. Core of the approach is the mapping of specific problems to the defined generic problem and solution types as well as specifying generic solution types into specific use cases Figure 5 displays the simplified procedure that builds on the TRIZ methodology described in Section 2.

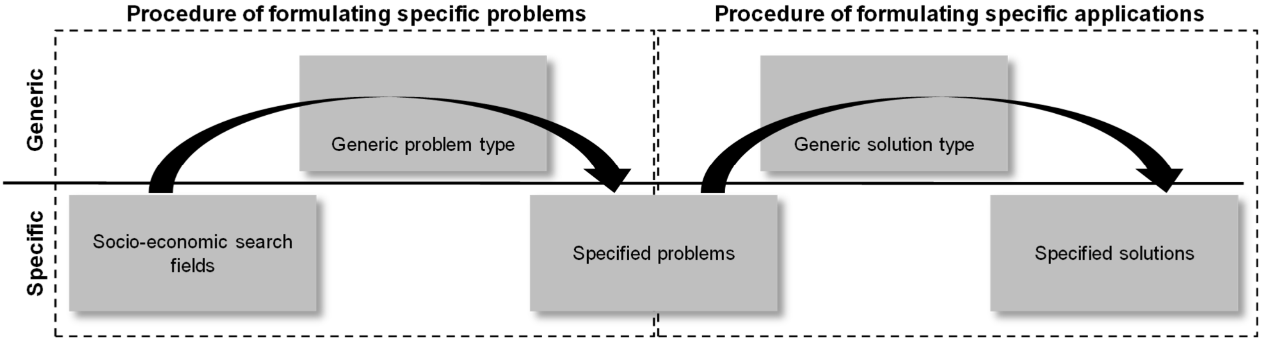


Figure 5: Simplified procedure to identify quantum computing applications

6. Conclusion and Outlook

In this paper, the critical challenge of identifying high-value applications for paradigm-shifting technologies on the example quantum computing have been addressed. To overcome this challenge, a methodology has been developed to systematically identify and evaluate potential applications for quantum computing. The presented methodology is intended to serve technology users and investment decision maker as a tool for systematically select use cases for paradigm-shifting technologies such as quantum computing which serve as a foundation for technology visions. This methodology is designed to meet specific requirements, including a high task-technology fit, identification of generic quantum computer problem and solution types, a systematic problem identification process, and a focus on socioeconomic challenges. To sufficiently satisfy these requirements, the methodology is structured according to the TRIZ methodology and consists of five submodels, that work together to create a comprehensive approach for identifying high-value quantum computing applications.

Since the methodology is undergoing continuous research, additional detailing and testing are required to validate its effectiveness and fine-tune its components. In particular, the five models of the methodology need to be concretized. At present, each model relies on proposed solution hypotheses derived from identified challenges associated with the research question. Interviews are necessary to validate the practical problems and derive practical solutions. Furthermore, a thorough literature review for each field must be undertaken. It must be noted, that the methodology can only serve as a guide for identification, but due to its strong dependence on the application context (e.g., issues specific to a particular industry), it is not possible to derive a universally valid technology vision for quantum computers.

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