Part I – Short Report (KIT, QuBRA - QSE)

Project Background and Objectives

Quantum computers promise to tackle optimization problems that are extremely difficult for today's classical computers. Many of these problems arise directly in industry, for example in vehicle configuration, supply chain design, fleet management, job-shop scheduling, and the Internet of Things. However, it remains an open question whether near-term quantum devices, from NISQ devices to full fault-tolerant quantum computers, can provide a practical advantage.

The QuBRA consortium was set up to investigate this question systematically. It brought together leading research groups in quantum information theory, classical algorithms, machine learning, and software engineering, alongside major industrial partners Infineon and Volkswagen. The Karlsruhe Institute of Technologie (KIT) subproject had two central roles:

- supporting the **implementation and benchmarking** of quantum algorithms **by creating development tools**
- and **investigating principles of quantum software engineering**.

The consortiums efforts were tied together through the KIT-led development of a **hybrid benchmarking framework QuBRABench**, and the TUBS-led **Benchmark Instances Project BIP** ensuring that claims of quantum advantage will always be compared against the best available classical and machine learning methods.

Project Execution

The work was organized across several application cases (AP2–AP6), including vehicle configuration, job-shop scheduling, supply chains, fleet management, and Internet-of-Things pickup and delivery.

KIT focused on the hybrid benchmarking framework, quantum algorithms for the vehicle configuration problems, and quantum software engineering. In particular, KIT addressed the verification of quantum software, quantum algorithmic constructs and programmatic design patterns, as well as quantum compilers.

Work began with the modelling of industrial problems as mathematical optimization tasks, followed by the development of classical and ML solvers. KIT then supported the development of quantum approaches for the same problems. These results were contributed to their integration into QuBRABench, which KIT established, as well as the TUBS-hosted BIP. Throughout the project, KIT developed and improved the provided tools and quantum software engineering methodologies, incorporating feedback from the consortium members.

Key Results and Collaboration

- **Applications**: KIT supported the application-oriented work packages and adapted several quantum algorithms to address vehicle configuration problems.
- **Hybrid benchmarking**: KIT and RUB developed QuBRABench, a platform comparing runtime and solution quality of quantum methods.
- **Quantum software engineering**: KIT and RUB have developed a novel methodology to ensure the correctness of quantum software. KIT's work on quantum patterns, software development and compilation lays a foundation for the scalable development of quantum algorithms and software.
- **Collaboration**: Close cooperation with Volkswagen and Infineon ensured that the chosen problems and solution methods had direct industrial relevance. Strong ties with academic partners (TU Braunschweig, RUB, KIT, University of Cologne, University of Innsbruck) ensured broad expertise.
- **Scientific impact**: The KIT project produced numerous scientific publications.

Conclusion

The KIT subproject successfully delivered on its aims: it provided tools for implementing and benchmarking quantum algorithms and investigated principles of quantum software engineering, contributing a novel methodology for ensuring the correctness of quantum software. Together with its academic and industrial partners, KIT contributed to a clear and realistic picture of the potential and limitations of near-term quantum computing for industrial optimization. This work strengthens Germany’s position in quantum technologies and lays the foundation for future scientific and industrial exploitation.

Part II – Detailed Report (KIT, QuBRA - QSE)

1. Introduction and project context

Quantum computing holds the promise of exponential speedups for solving computationally demanding problems, ranging from the simulation of complex materials to the optimization of industrial production processes. However, the practical benefits of quantum methods for real-world applications remains an open question. The collaborative research project **QuBRA** (Quantum Methods and Benchmarks for Resource Allocation) was established to address this gap by bringing together a strong, interdisciplinary consortium of partners from academia and industry. Experts in quantum information, classical algorithms, machine learning, and software engineering worked in close cooperation with the industrial leaders Infineon Technologies AG and Volkswagen AG. The shared goal was to explore and rigorously evaluate scalable methods for the design, analysis, benchmarking, and integration of quantum approaches to combinatorial optimization problems of significant industrial relevance.

The motivation for this endeavour lies in the complexity of modern industrial processes. The production of microchips at Infineon and the design and maintenance of automotive IT infrastructures at Volkswagen involve combinatorial optimization problems of extreme difficulty. Even small improvements in solution quality can yield substantial economic benefits: for example, a one percent improvement in factory utilization can translate into tens of millions of euros in additional profit. However, such problems are typically NP-hard, meaning that no fully general efficient solution is possible on either classical or quantum computers. Practitioners therefore rely on domain-specific heuristics and, increasingly, machine learning to obtain high-quality solutions within limited time and computational resources.

Against this background, quantum computing emerges as a potentially transformative technology. While its superiority has so far been demonstrated most clearly in areas such as cryptanalysis, it was unclear whether, and under what conditions, quantum algorithms could outperform the best classical methods for industrial optimization. Determining these conditions is of crucial importance for industrial stakeholders, but requires expertise across multiple disciplines as well as a close link to real-world applications.

The QuBRA consortium was designed to meet this challenge by pursuing three overarching objectives:

- Z1: to study quantum algorithmic methods for five concrete industrial resource-allocation problems and to identify the parameter regimes in which quantum advantage is achievable

- Z2: to develop objective benchmarks that allow the performance of quantum methods to be compared systematically with classical algorithms and machine learning approaches; and
- Z3: to investigate principles of quantum software engineering that can guide the scalable development of reliable quantum algorithms and software.

The subproject "QuBRA - QSE Quanten Software-Engineering" was carried out at the Karlsruhe Institute of Technology (KIT) by the Test, Validation and Analysis of Software-Intensive Systems research group. KIT specialized in developing the benchmarking framework and focussed on quantum software engineering, creating concepts, methods and tools for designing, implementing and validating quantum algorithms and software. KIT contributed to the exploration of quantum advantage in vehicle configuration problems.

The KIT subproject QuBRA - QSE provided essential results for Z1, Z2 and Z3, with a clear focus on quantum software engineering in Z3. This subproject successfully and comprehensively achieved the stated goals above.

2. Work Conducted Compared to the Original Plan

2.1 Planned Work

The work plan of the QuBRA was structured around a hybrid and agile approach, designed to ensure measurable progress while maintaining strong integration across disciplines. At its core, the consortium focused on a series of five work packages:

- AP2: configuration problems.
- AP3: job-shop scheduling.
- AP4: supply chain management.
- AP5: fleet management.
- AP6: pickup-and-delivery in IoT.

Each of these work packages addressed a concrete optimization challenge of critical importance to the partners Infineon and Volkswagen. These included configuration problems, job-shop scheduling, supply-chain management, fleet management, and pickup-and-delivery tasks in the Internet of Things. By addressing these problems in sequence, with increasing complexity, the project created a pathway of escalating challenges where insights from earlier work informed subsequent steps.

Each use case followed a modular workflow, beginning with a detailed requirements analysis to capture industrial constraints and objectives. Classical deterministic methods and machine learning techniques were then investigated to establish strong baselines. Building on these, quantum algorithms were explored in two phases: first by adapting established techniques to the industrial problems, and then by attempting the development of novel algorithms with higher potential impact. All algorithmic approaches—classical, machine learning, and quantum—were implemented using available solvers, simulation tools, and quantum hardware demonstrators, and their performance was systematically benchmarked against standardized datasets. This benchmarking effort was supported by a dedicated package (AP1), which provided shared datasets, a general benchmarking framework, and access to specialized computing infrastructure.

The five application-oriented work packages were complemented by two overarching activities. The first (AP7) focused on quantum software engineering, developing reusable methods, libraries, and design patterns to support the reliable implementation of quantum algorithms. The second (AP8) ensured agile project management, documentation, and dissemination of results, with regular milestones to enable adaptation to evolving requirements. Together, these elements provided the foundation for a coordinated, iterative program of research that advanced both the theory and practice of quantum optimization in an industrial context.

The subproject QuBRA-QSE carried out at KIT described the following activities:

- Design and implementation of tools for implementing and benchmarking quantum algorithms.
- Supporting the implementation of quantum approaches, particularly for configuration problems (AP2).
- Designing a catalogue of quantum algorithmic constructs and identifying recurring programmatic design patterns for quantum software.
- Researching techniques for establishing the correctness of quantum software.

2.2 Conducted Work

The implementation of QuBRA required several adjustments relative to the original plan, primarily due to delays in the provision of project resources and the recruitment of qualified personnel in the highly competitive quantum computing labour market. At the start of the project, pandemic-related restrictions, late availability of funding, and administrative hurdles led to delayed onboarding of key staff across several partners, including LUH, TUBS, RUB, and KIT, resulting in an initial effective delay of approximately six months. These delays affected early work packages, particularly AP7, where dependencies on domain knowledge and the sequencing of sub-tasks meant that some milestones, such as the half-time release of development tools and benchmarking frameworks, were only partially achieved on schedule. Nevertheless, KIT was able to mitigate the impact through parallelization of activities, ensuring that progress in critical areas could continue and that the overall project objectives remained achievable.

To fully accommodate the initial delays while ensuring completion of all planned work, the consortium requested and received a six-month cost-neutral extension. This adjustment allowed partners to align remaining tasks, finalize staff recruitment, and complete cross-dependent work packages without affecting the overall budget. Across all institutions, the extension enabled the realization of key outputs, including the deployment of benchmarking frameworks, the QbC methodology, and industrially relevant algorithmic studies, while maintaining milestone targets in subsequent years. The cost-neutral extension thus ensured that, despite initial staffing and logistical challenges, QuBRA could deliver its planned results comprehensively, preserving the integrity of both research goals and timeline expectations.

The most significant work steps conducted by partner KIT are summarised below.

Benchmarking Framework (AP1): Together with RUB, KIT developed the hybrid benchmarking framework QuBRABench[1], which enables direct comparisons between classical optimization solvers and quantum algorithms. The framework includes metrics for runtime, approximation quality, scalability, and robustness.

Vehicle Configuration (AP2): KIT analysed the potential and challenges of quantum computing for feature model analysis[2] and then developed quantum solutions to the configuration problems. The first algorithm addresses uniform random sampling[3] and is based on the Grover's search algorithm. The second algorithm solves the problems of configuration selection and prioritization[4], and is based on the NISQ Quantum Approximate Optimization Algorithm (QAOA).

Quantum Software Engineering (AP7): First, KIT participated in an investigation of the challenges that must be overcome in quantum software engineering[5]. In close collaboration with RUB, KIT created a project summarizing research on quantum algorithmic concepts. KIT developed methods for the automated recognition of quantum patterns[6,7] to validate a pattern catalogue of programmatic design patterns and evaluating the relevance and occurrence of the patterns in practice. Furthermore, KIT and RUB developed a methodology

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[1] QuBRA Benchmarking Framework — Available at: https://qubrabench.github.io/qubrabench/ (Accessed: 30 October 2025).

[2] D. Eichhorn, T. Pett, T. Osborne, and I. Schaefer, "Quantum Computing for Feature Model Analysis: Potentials and Challenges" SPLC 2023. https://doi.org/10.1145/3579027.3608971

[3] J. Ammermann, T. Bittner, D. Eichhorn, I. Schaefer, and C. Seidl, "Can Quantum Computing Improve Uniform Random Sampling of Large Configuration Spaces?" Q-SE 2023. https://doi.ieeecomputersociety.org/10.1109/Q-SE59154.2023.00012

[4] J. Ammermann, F. J. Brenneisen, T. Bittner, and I. Schaefer, "Quantum Solution for Configuration Selection and Prioritization" Q-SE 2024. https://doi.org/10.1145/3643667.3648221

[5] C. Carbonelli, M. Felderer, M. Jung, E. Lobe, M. Lochau, S. Luber, W. Mauerer, R. Ramler, I. Schaefer, und C. Schroth, "Challenges for Quantum Software Engineering: An Industrial Application Scenario Perspective" Quantum Software: 311-335, 2024. https://doi.org/10.1007/978-3-031-64136-7_12

[6] J. Shen, J. Ammermann, C. König, und I. Schaefer, "Quantum Pattern Detection: Accurate State- and Circuit-based Analyses" Q-SE 2025. https://doi.org/10.1109/Q-SE66736.2025.00008

[7] Quantum Pattern Detector — Available at: https://github.com/KIT-TVA/quantum-pattern-detector (Accessed: 30 October 2025).

for ensuring the correctness of quantum software: Quantum Correctness by Construction (QbC)[8] including a prototypical web application[9]. Finally, KIT developed a vision for a view-based development approach for quantum software with a quantum IDE[10], and investigated the configuration and retargetability of quantum compilers.

Support of application-oriented work packages: The tools developed by KIT and RUB were provided to the consortium, and their use resulted in the creation of the objective benchmarks.

Publications and Dissemination: Several key papers were submitted, with results presented at international conferences in quantum software engineering, software product lines and programming conferences.

3. Use of Funds

The funds were used in accordance with the grant agreement. The main expenditure categories included:

Personnel Costs: The majority of the funding supported doctoral researchers and student assistants who carried out the planned scientific work.

Travel: Funds enabled participation in project meetings, consortium workshops, and international conferences, ensuring dissemination of results and integration into the international research community.

The expenditures correspond directly to the originally planned budget positions.

4. Necessity and Appropriateness of Work

The project activities were both necessary and appropriate to achieve the overarching goals of QuBRA: In particular, a benchmarking framework was essential for meaningful direct comparison of classical optimization solvers and quantum algorithms. The contributions from KIT and RUB provided precisely such a framework. Furthermore, the work carried out by KIT on vehicle configuration made it possible to evaluate the possibilities and performance of quantum algorithms for this application. Finally, KIT investigated the principles of quantum software engineering. KIT and RUB developed a methodology to ensure the correctness of quantum software, an important step towards making it reliable.

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[8] Peduri, I. Schaefer, und M. Walter, "QbC: Quantum Correctness by Construction" OOPSLA 2025. https://doi.org/10.1145/3720433

[9] QbC Editor — Available at: https://qbc.kastel.kit.edu (Accessed: 30 October 2025).

[10] J. Ammermann, W. Mauerer, und I. Schaefer, "Towards View-based Development of Quantum Software" INFORMATIK 2024. https://doi.org/10.18420/inf2024_43

KIT's work on quantum patterns, software development, and compilation lays a foundation for scalable quantum algorithm and software development.

5. Results Achieved

Work carried out during the project yielded several significant results:

1. Quantum Algorithmic Templates: Variants of quantum algorithms tailored to configuration problems.
2. Contributions to the QuBRABench benchmarking framework: A comprehensive methodology, for assessing quantum algorithms relative to classical approaches was developed.
3. Quantum Software Engineering Tools: Software tools for the QbC methodology and automated quantum pattern detection.
4. Scientific Publications: Results disseminated through journal papers, conference proceedings, and invited talks.
5. Training and Capacity Building: Several doctoral researchers advanced training in quantum computing, software engineering, and optimization, thereby strengthening Germany's expertise in this field.

6. Anticipated Benefit and Exploitation Plan

In the original application, the KIT subproject QuBRA-QSE formulated a broad set of expected exploitation pathways: short-term contributions to project objectives, medium-term continuation of research efforts, and long-term strengthening of German and European technological competence in quantum computing. The particular methodological approach—an integrated comparison of classical, machine learning, and quantum methods—was designed to be both scientifically novel and practically useful, with modular results that could be flexibly applied and transferred.

All of the anticipated exploitation avenues have been realized during the course of the project:

- **Scientific Exploitation:** The KIT subproject produced a number of peer-reviewed publications and open-access preprints covering quantum algorithm application, quantum software engineering and verification. These results advance the state of the art and have already been cited and adopted by other research groups.
- **Educational Exploitation:** KIT integrated the results of QuBRA directly into master's and doctoral teaching. Several theses were completed on QuBRA-related topics, thereby training the next generation of quantum computing specialists. Several PhD students who worked on QuBRA priorities are shortly before submission of their thesis.
- **Technological Exploitation:** KIT contributed to the development of Open-Source benchmarking and software engineering tools (notably *QuBRABench,* the

QbC Editor and the *Quantum Pattern Detector*) that are accessible to both academic and industrial users. These tools have been used beyond the consortium, confirming their practical utility.
- **Industrial Collaboration:** Continuous interaction with partners Infineon and Volkswagen ensured that research results were evaluated for practical relevance. The modular approach allowed immediate identification of methods with transfer potential.
- **Novel Scientific Projects:** The success of the QuBRA project led to the creation of its successor, QuSol, which was funded by the BMFTR and the establishment of the DfG priority programme 2514, a basic research project focusing on quantum software engineering.

Anticipated Exploitation

The exploitation of QuBRA results will continue beyond the project runtime. KIT foresees several concrete follow-up measures, both scientific and economic:

No.	Exploitation Measure	Time Horizon	Notes
1	Consolidated publications in high-impact journals	2025–2026	Several manuscripts under review or in preparation, focusing on quantum programming languages and quantum compilers.
2	Training of highly qualified specialists	Ongoing from 2025	Results embedded in MSc and PhD curricula at KIT; continuation through supervision of theses and doctoral research.
3	Further uptake using the provided tools	Ongoing from 2025	The open-source provision of developed benchmarking and quantum software engineering tools can enable further industrial and academic uptake.
3	Follow-up research proposals (BMFTR, DFG)	2025–2028	Building on QuBRA results to secure new projects in quantum software engineering.
4	Industrial transfer projects with Infineon, Volkswagen, and new partners	From 2026	Direct integration of developed algorithms into industrial workflows; pilots in configuration and supply chain optimization.

7. Progress in the Field

Hardware progress across multiple platforms. Significant technical advances were achieved internationally in superconducting qubits, trapped ions, photonic processors, neutral atom and Rydberg arrays, and NV centres. Improvements in coherence times, gate fidelities, and system sizes were reported, as well as first demonstrations of small-scale error correction. These developments underscored the increasing maturity of multiple hardware paradigms. At the same time, the pace of progress was slower than originally anticipated in the proposal. Medium-scale processors capable of running industrially relevant optimization problems by 2024 did not materialize. This delay had direct consequences for QuBRA: it reinforced the necessity of classical simulation and hybrid benchmarking methods, which became more important than ever for producing meaningful insights.

Realisation of hybrid quantum–classical workflows by international players. Major technology companies and research consortia increasingly adopted hybrid approaches in which quantum subroutines are integrated into broader classical optimization pipelines. This reflects a shift in the global research agenda: rather than positioning quantum devices as standalone solvers, the community now widely views them as accelerators embedded within hybrid workflows. This development validated the QuBRA approach, in which KIT contributed systematic benchmarking of hybrid methods to clarify the conditions under which quantum components provide incremental value.

Acknowledgement of challenges in demonstrating quantum speedups on NISQ devices. International studies highlighted the difficulty of showing practical advantages for noisy intermediate-scale quantum processors. Claims of speedup often diminished when carefully benchmarked against optimized classical and ML heuristics. KIT's hybrid benchmarking activities contributed to clarifying this landscape, by showing that while quantum algorithms offer clear long-term potential, near-term devices cannot yet surpass the performance of best-in-class classical methods on the targeted industrial optimization problems.

Advances in programmatic design patterns for quantum software. Other academic institutions have created a catalogue of programmatic design patterns[11,12]. This catalogue covers the fundamental components of quantum algorithms, but will likely be expanded in the future. Therefore, it has become more important to validate this catalogue and evaluate the relevance and occurrence of the patterns in practice.

8. Conclusion

The KIT subproject QuBRA-QSE within QuBRA successfully achieved its aims. It provided both methodological innovations and concrete results, strengthened Germany's position in the international quantum computing research landscape, and prepared the ground for future exploitation of quantum algorithms in industrial optimization.

[11] F. Leymann, "Towards a Pattern Language for Quantum Algorithms," in Quantum Technology and Optimization Problems, vol. 11413, S. Feld and C. Linnhoff-Popien, Eds. Cham: Springer International Publishing, 2019, pp. 218–230. doi: 10.1007/978-3-030-14082-3_19.

[12] M. Weigold, J. Barzen, F. Leymann, and D. Vietz, "Patterns for Hybrid Quantum Algorithms," in Service-Oriented Computing, vol. 1429, J. Barzen, Ed. Cham: Springer International Publishing, 2021, pp. 34–51. doi: 10.1007/978-3-030-87568-8_2.