

# Decision Models for Selecting Architecture Patterns and Strategies in Quantum Software Systems

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Quantum software represents disruptive technologies in terms of quantum-specific software systems, services, and applications - leverage the principles of quantum mechanics via programmable quantum bits (Qubits) that manipulate quantum gates (QuGates) - to achieve quantum supremacy in computing. Quantum software architecture enables quantum software developers to abstract away implementation-specific details (i.e., mapping of Qubits and QuGates to high-level architectural components and connectors). Architectural patterns and strategies can provide reusable knowledge and best practices to engineer quantum software systems effectively and efficiently. However, quantum software practitioners face significant challenges in selecting and implementing appropriate patterns and strategies due to the complexity of quantum software systems and the lack of guidelines. To address these challenges, this study proposes decision models for selecting patterns and strategies in six critical design areas in quantum software systems: Communication, Decomposition, Data Processing, Fault Tolerance, Integration and Optimization, and Algorithm Implementation. These decision models are constructed based on data collected from both a mining study (i.e., GitHub and Stack Exchange) and a Systematic Literature Review (SLR), which were used to identify relevant patterns and strategies with their involved Quality Attributes (QAs). We then conducted semi-structured interviews with 16 quantum software practitioners to evaluate the familiarity, understandability, completeness, and usefulness of the proposed decision models. The results show that the proposed decision models can aid practitioners in selecting suitable patterns and strategies to address the challenges related to the architecture design of quantum software systems. The dataset is available at [6], allowing the community to reproduce and build upon our findings.

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## 1 INTRODUCTION

Quantum computing represents a transformative shift in computational paradigms, leveraging principles such as superposition, entanglement, and quantum interference to achieve capabilities beyond classical computing [40]. Unlike classical bits, which exist exclusively in binary states (0 or 1), Qubits can exist simultaneously in multiple states, exponentially increasing computational efficiency [24], and enabling quantum computers to tackle complex problems [51], as well as in optimization through quantum-enhanced machine learning [49]. The concept of quantum supremacy, wherein quantum computers outperform classical supercomputers on specific tasks, has driven substantial research in Quantum Software Engineering (QSE) [9]. Quantum Software Engineering (QSE) refers to the emerging discipline that integrates the principles of quantum mechanics with systematic software engineering practices to support the design, development, and evolution of quantum software systems [2]. However, developers often face challenges in building robust and scalable quantum applications due to the difficulty of applying classical software engineering practices [38] and the lack of established quantum-specific best practices [8]. The prospects of quantum computing are promising, with growing expectations driving significant global investments in quantum technologies [28]. Industry and academia have collaboratively launched development platforms and tools tailored for quantum programming, including IBM's Qiskit, Google's Cirq, Microsoft's Q#, and Intel's quantum C++ extensions [45]. These initiatives support the growing ecosystem for QSE and facilitate structured development workflows [5]. Amidst these advancements, quantum software architecture has emerged as a critical subdiscipline [67]. It provides high-level abstractions and design principles [30] for constructing both quantum and hybrid quantum-classical applications [61]. Software architects play a crucial role in designing systems that align with business requirements while integrating quantum capabilities [62]. However, designing robust quantum solutions remains highly challenging, especially for practitioners with little background in quantum mechanics [25] or quantum programming paradigms [3]. In response, recent studies have proposed early-stage modeling approaches [67] and architecture-centric frameworks, including extensions to well-known modeling tools such as UML [44] and BPMN [62] that aim to streamline the integration of quantum and classical components through clearer abstractions and modular design principles [35].

Building on these efforts, architecture patterns and strategies in quantum software systems offer reusable solutions to common design challenges in quantum computing [11], providing a structured framework for developing scalable and maintainable quantum software systems [16, 30]. In this context, architecture strategies (e.g., architectural styles and patterns) are high-level design approaches that support the achievement of Quality Attributes (QAs) such as interoperability [53]. As quantum systems increasingly integrate with traditional system infrastructure, high-level architecture design patterns are required to orchestrate services [38] and manage workflows across quantum and classical boundaries [69]. In classical software systems, architecture patterns such as layered [46], service-oriented [23], and microservices [47] architectures have been widely adopted

to improve various quality attributes (e.g., maintainability, scalability, and performance) depending on the specific pattern and system context [13]. However, these classical patterns can be extended to address the unique constraints of quantum software systems, including quantum resource management and error correction [10], the integration of classical and quantum components through hybrid execution models [61], and the challenges of orchestration and execution in hybrid quantum-classical systems [43]. Various architectural patterns have been introduced for designing quantum applications. For example, Khan et al. [30] identified Layer, Composite, and Prototype patterns tailored for quantum systems. Aktar et al. [7] highlighted that selecting appropriate architectural patterns is a key decision in quantum software development. Discussions on open-source platforms such as GitHub and Stack Exchange [32], along with a systematic mapping of research literature on quantum computing services [3], demonstrate ongoing efforts to identify, refine, and apply architecture patterns within the emerging domain of quantum software systems. Despite these developments, quantum software architecture still faces persistent challenges. Recent studies indicate that major difficulties arise in quantum communications [21], design issues, high error rates [7], classical-quantum integration [11], data encoding [63], fault tolerance and error mitigation [20], and algorithm implementation [64]. To address these recurring issues, there is a need for architectural solutions that systematically support decision-making across key design areas in quantum software development (e.g., communication, decomposition, data processing, and fault tolerance).

One key limitation in quantum software development is the absence of systematic support to guide practitioners in evaluating and selecting appropriate architectural solutions [38]. Especially, it is challenging for practitioners to balance competing Quality Attributes (QAs) such as performance, scalability, reliability, and interoperability [43, 61]. While architectural design in classical software engineering benefits from decision models that aid in the selection of architecture patterns and strategies across well-defined design contexts [29, 57, 66], QSE has yet to employ comparable frameworks. Previous studies have explored quality trade-offs in architectural decisions for quantum-classical hybrid systems [31], and proposed architectural patterns specifically designed for quantum-enhanced artificial intelligence systems [35]. However, these efforts lack structured, quality-driven decision models that systematically map architectural patterns and strategies to specific design concerns and quality trade-offs. This absence of decision models represents a critical gap in the field, as quantum software practitioners currently lack empirical and prescriptive models to support informed architectural decision-making during the development of quantum software systems.

To address this gap, this study aims to introduce comprehensive decision models tailored to designing quantum software systems, focusing on six crucial design areas: (1) Communication, (2) Decomposition, (3) Data Processing, (4) Fault Tolerance, (5) Integration and Optimization, and (6) Algorithm Implementation. These areas were initially derived from recurring architectural challenges reported in the quantum software engineering literature [10, 30]. These decision models were developed based on insights collected from a Systematic Literature Review (SLR) and a mining study of software repositories (namely GitHub issues, Stack Exchange sites) about architecture patterns and strategies in quantum software systems. These models can help practitioners select appropriate architectural patterns and strategies for quantum software systems. We evaluated the proposed models through semi-structured interviews with 16 quantum software practitioners, providing empirical validation of their applicability and effectiveness. The main **contributions** of this study are: 1) systematically developed six decision models that map architectural patterns and strategies to critical QAs in quantum software systems; and 2) empirically evaluated the proposed decision models through semi-structured interviews with quantum software practitioners; 3) We

have provided all identified patterns and strategies along with their corresponding references in our Replication Package [6].

The paper is structured as follows: Section 2 discusses the related work, Section 3 presents the research methodology, Section 4 presents the six decision models, Section 5 details the evaluation process of the proposed decision models, Section 6 discusses the implications and insights of the study results, Section 7 outlines the threats to validity, and Section 8 concludes this work with future directions.

## 2 RELATED WORK

### 2.1 Patterns for Quantum Software Engineering

QSE relies heavily on design and architectural patterns to address the unique challenges posed by quantum systems, especially in integrating quantum and classical components. Klymenko *et al.* [35] identified several architectural patterns that facilitate the integration of quantum components into classical inference engines, emphasizing key quality attributes (e.g., efficiency, scalability, and portability). These patterns enable developers to balance performance with hardware limitations when designing complex quantum AI systems, a class of quantum software systems integrating quantum computing to enhance AI tasks such as training and inference. Pérez-Castillo *et al.* [42] explored the application of design patterns in quantum circuits through an analysis of 80 Qiskit and OpenQASM source code files. Their study identified three recurring patterns: initialization, which involves preparing qubits into known basis states using gates; uniform superposition, a quantum-specific pattern that uses Hadamard gates to place all qubits into an equal probability superposed state; and oracle, which encodes problem-specific functions or conditions used in quantum algorithms like Grover's search. These patterns provide insights into common circuit structures and support more efficient quantum algorithm design. Bühler *et al.* [16] investigated the prevalence and relationships between quantum design patterns in over 2,600 Qiskit programs from GitHub. Their work reveals how these patterns frequently occur together, offering practical guidance for quantum developers aiming to optimize software extensibility and performance. Baczyk *et al.* [10] argued for the development of higher-level architectural patterns for hybrid quantum-classical systems. While low-level patterns for quantum circuits are well-established, there remains a notable gap in architectural patterns that address critical quality concerns, such as efficiency (e.g., optimizing quantum-classical interactions and resource usage), maintainability (e.g., enabling modular, adaptable architectures as quantum technologies evolve), and security (e.g., safeguarding classical-quantum communication and integration). They emphasized the need for architectural-level guidance to improve the robustness and extensibility of hybrid quantum-classical system design.

Recent studies have also highlighted emerging architectural solutions in hybrid quantum-classical systems. For example, Carneiro *et al.* [18] demonstrated how quantum microservices enable modular design by organizing applications into loosely coupled services that communicate through messages. Rojo *et al.* [48] further explored this approach in hybrid quantum-classical microservices systems, outlining both its advantages and inherent development challenges. To address issues related to backend heterogeneity, Garcia *et al.* [25] introduced quantum API gateways, which dynamically route requests to the appropriate quantum backends, thus improving system flexibility and interoperability. Additionally, Beisel *et al.* [12] emphasized the importance of error correction patterns in mitigating Qubits fragility, ensuring reliable computation even under noise and decoherence, thereby supporting the broader adoption and industrial viability of quantum computing.

## 2.2 Decision Models for Selecting Patterns in Software Development

Architectural decision-making is a fundamental aspect of software development, as the selection of appropriate patterns and strategies can significantly impact a system's quality attributes (e.g., scalability, maintainability). However, due to the increasing complexity and domain-specific constraints of modern systems, such as microservices, blockchain, IoT, and quantum software, practitioners often face challenges in identifying suitable architectural patterns. To address this, previous work proposed structured decision models that guide architects and developers in pattern selection by aligning decisions with design goals and contextual constraints. Waseem *et al.* [57] proposed decision models for microservices architecture, tackling the selection of patterns and strategies across four key design areas, including service decomposition, security, communication, and discovery within microservices systems. Their study utilized a multivocal review to establish a comprehensive base of patterns and strategies. The decision models proposed were then evaluated through interviews with practitioners, highlighting the practical effectiveness of these models in guiding microservices pattern selection. Lewis *et al.* [36] explored decision-making in the context of cyber-foraging systems, where the challenge lay in extending the capabilities of mobile devices through computational offloading. Their study also investigated the correlation of architectural tactics with both functional and non-functional requirements in their decision model, thereby guiding the development of cyber-foraging systems. Their work offers valuable insights that inform our analysis of decision models for selecting architecture patterns and strategies in quantum software systems.

Two critical studies focused on decision models in blockchain systems. Liu *et al.* [37] proposed decision models tailored for governance-driven blockchain architectures and emphasized the need for a structured approach to adopting architectural patterns that address governance dimensions such as decision rights, incentives, and accountability. Their proposed models facilitate the selection of patterns that enhance governance in blockchain systems, supported by a thorough evaluation involving expert opinions on usability, correctness, and completeness. Similarly, Xu *et al.* [66] addressed the challenges of selecting patterns in blockchain-based applications. Their study proposed a decision model that assists developers and architects in making informed choices about pattern adoption based on the characteristics of specific use cases and the associated trade-offs. Their work underscores the complexity and necessity of a methodological approach to pattern selection in blockchain applications, validated by expert feedback on the model's effectiveness in guiding architectural decisions. Zimmermann *et al.* [70] proposed a comprehensive design method that integrates pattern languages with reusable architectural decision models. Their method systematically derives architectural decisions from requirements models, provides domain-specific guidance for selecting appropriate patterns, and ensures traceability from platform-independent principles (e.g., general architectural patterns) to platform-specific implementation decisions (e.g., technologies tailored to environments such as .NET or J2EE). Their method was validated through applications in enterprise systems and a case study of a Service-Oriented Architecture (SOA) within the finance industry. Jacob *et al.* [29] proposed a model specifically tailored for selecting architecture patterns in Internet of Things (IoT)-based systems. Their model emphasizes the importance of non-functional requirements such as scalability, availability, reliability, security, and heterogeneity, which are crucial for making informed decisions in the IoT domain. Their model analytically validated a structured approach to pattern selection, offering IoT developers a valuable reference for optimizing architectural choices to address both functional and operational requirements.



### 2.3 Decision Models for Architecting Quantum Software Systems

In the context of quantum software systems, there is a crucial need for decision models that guide the selection of architectural design patterns and strategies. These models are essential for addressing the computationally intensive tasks that quantum technology promises. In the pursuit of architecting efficient quantum software systems, researchers consider key software quality attributes (e.g., modularity, maintainability, scalability, and reliability) to guide the creation of decision models. Akbar *et al.* [4] introduced a systematic framework that identifies, prioritizes, and develops decision-making strategies for QSE. They mapped challenging factors into seven core categories and assessed their criticality using methods such as Interpretive Structure Modeling (ISM) and fuzz Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). Their approach provided a structured way to tackle quantum software development challenges and highlighted the decisive influence of resources (e.g., quantum simulators and compilers) on the execution of the QSE process. Similarly, Vietz *et al.* [55] focused on the support mechanisms for quantum application developers. They categorized and classified available tools, services, and techniques that assist in quantum application development. Their work culminated in a comparison framework that supports developers in choosing appropriate technologies based on specific quantum computing use cases. Nallamothula *et al.* [39] employed a decision tree approach to facilitate the selection of suitable quantum computing architectures. Their study emphasized the need for tailored decision-making strategies based on the characteristics of a quantum project, including the device, algorithm, and programming languages used. Their approach can aid in identifying architectures that could offer a quantum advantage for specific applications. Grurl *et al.* [27] focused on incorporating decoherence errors into the simulation of quantum circuits and proposed solutions based on decision diagrams that significantly improve simulation performance by accounting for these errors. Their work was pivotal for decision models in QSE, as they provided insights into optimizing simulations in the presence of quantum mechanical instability.

In our previous study [7], we conducted an empirical study to analyze architecture decisions made in quantum software development using data collected from GitHub repositories and Stack Exchange discussions. Our analysis revealed a range of practical challenges related to maintainability, performance, and architectural design in real-world quantum software development. The findings from our prior work lay the foundation for the current study by pinpointing key design areas where structured decision support is crucial.

### 2.4 Conclusive Summary

Previous work on decision models in software engineering reveals a critical gap in addressing the unique architectural needs of quantum software systems. Notably, existing studies have primarily focused on conventional software systems, with a recent expansion into emerging domains (e.g., microservices architecture [57], blockchain architecture [37, 66], IoT-based systems [29], and cyber-foraging systems [36]). These studies have provided valuable insights into selecting patterns and strategies by employing decision models that leverage reusable knowledge to address specific design challenges. For instance, the idea of structured decision guidance proposed by Zimmermann *et al.* [70] inspires our work in identifying and organizing architecture patterns and strategies, along with their associated QAs, for architecting quantum software systems. However, when it comes to QSE, architectural design decisions are further complicated due to quantum computing's unique properties (e.g., entanglement, superposition, and decoherence), which render many conventional design practices insufficient [4, 27, 39, 55]. Designing effective quantum software systems requires careful consideration of critical challenges including quantum-classical communication [35], algorithmic decomposition to support hybrid computation [10], processing of entangled or

probabilistic data [16], maintaining fault tolerance in noisy environments [27], integrating quantum components with classical systems [35], optimizing resource-limited quantum workloads [42], and implementing quantum algorithms across diverse hardware and programming models [39, 55]. These challenges correspond to six critical design areas that define the core architectural context of quantum software systems: Communication, Decomposition, Data Processing, Fault Tolerance, Integration and Optimization, and Algorithm Implementation. Despite the increasing recognition of these challenges in recent literature, there remains a lack of structured, reusable decision support to guide architectural pattern and strategy selection, specifically tailored to quantum software systems.

### 3 RESEARCH DESIGN

In software architecture, decision models connect elements of the problem space with aspects of the solution space. The problem space encapsulates functional and non-functional requirements, while the solution space covers the design components [36]. For quantum software systems, the problem space is defined through a collection of QAs, and the solution space is determined by various quantum architectural patterns and strategies. In this study, we developed six decision models, each tailored to guide the selection of appropriate architectural patterns and strategies for a specific area of quantum software design. These six areas include: Communication, Decomposition, Data Processing, Fault Tolerance, Integration and Optimization, and Algorithm Implementation. These areas were selected based on recurring architectural challenges discussed in Section 1. The research process, illustrated in Figure 1, comprises three stages. *Stage 1*: Identifying architecture patterns and strategies through mining GitHub and Stack Exchange data, along with an SLR. *Stage 2*: Modeling six decision models based on the extracted patterns, strategies, and related QAs. *Stage 3*: Evaluating the decision models through interviews with 16 practitioners on quantum software to assess their usefulness, clarity, and completeness.

#### 3.1 Identifying Architecture Patterns and Strategies

To identify the architecture patterns, strategies, QAs, and the impact of patterns and strategies on QAs, we collected data from two sources. First, we conducted a mining study using open-source software projects on GitHub<sup>1</sup> (e.g., issues and pull requests) and posts from Stack Exchange sites<sup>2</sup> (e.g., Stack Overflow and Quantum Computing, focusing on questions and answers related to architecture patterns). Second, we performed an SLR to identify relevant studies discussing architectural design decisions in quantum software systems. The selection of GitHub and Stack Exchange sites was inspired by the guidelines for selecting empirical methods proposed by Easterbrook for software engineering research [22]. The SLR was conducted following the guidelines by Kitchenham and Charters for performing SLRs in Software Engineering research [33]. We explain each of the two studies below and outline the steps to extract relevant data for both the mining study (GitHub and Stack Exchange) and the SLR:

##### 3.1.1 Identifying Architecture Patterns and Strategies Using a Mining Study.

###### Phase 1 - Data Collection

**Step 1 - GitHub Projects:** In this study, we collected data from open-source quantum software projects. This includes both (i) core quantum frameworks (e.g., Qiskit, Cirq, PennyLane) and (ii) supportive tools (e.g., DeepChem, Covalent) that facilitate quantum software development. These projects were initially selected based on a rigorous keyword-driven search and filtering process. We conducted a pilot search using a variety of keywords to determine the most effective terms for

<sup>1</sup><https://github.com>

<sup>2</sup><https://stackexchange.com/sites>

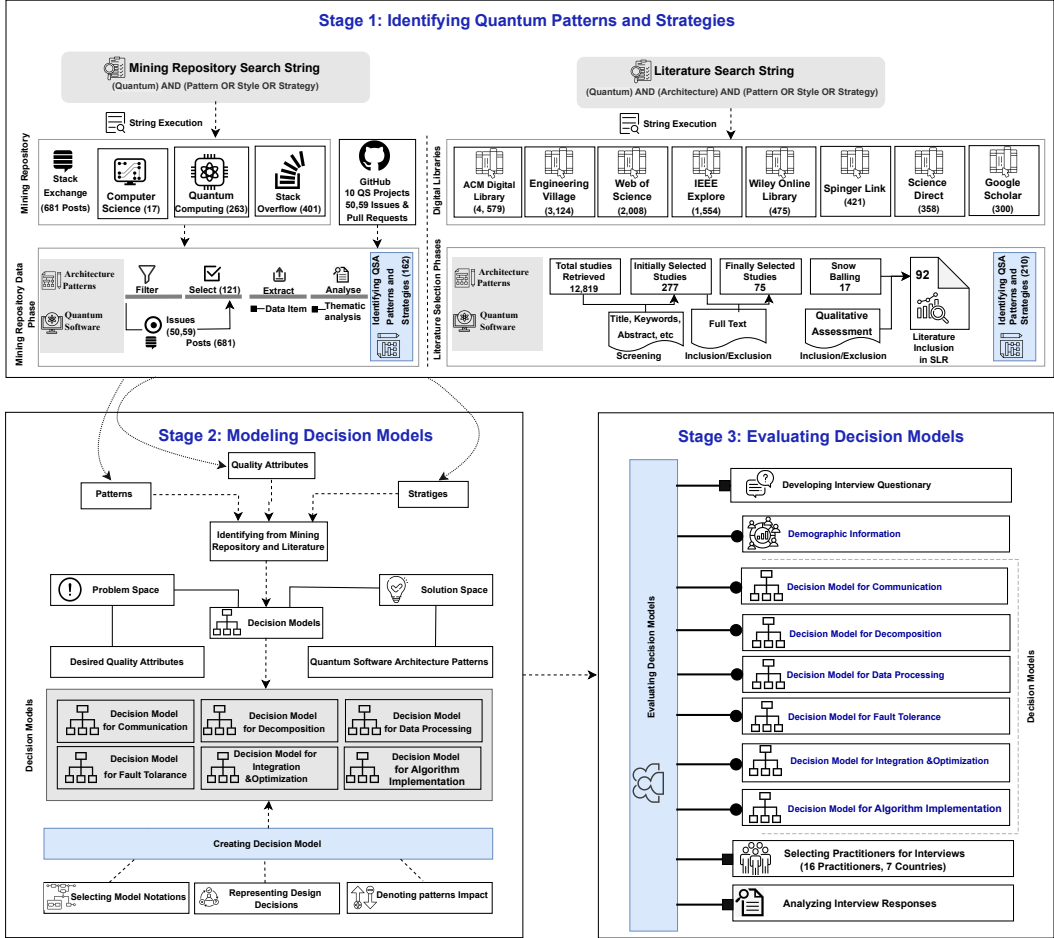


Fig. 1. Overview of the research process

identifying relevant quantum-related projects on GitHub. After evaluating different options, we selected “*quantum*” and “*quantum computing*” as our primary keywords. The search was performed across multiple project components, including names, topics, descriptions, and README files. The keyword “*quantum*” returned a total of 74,432 projects, whereas “*quantum computing*” yielded significantly fewer results—12,401 projects many of which were unrelated, such as other learning resources<sup>3</sup> and books<sup>4</sup>. Since “*quantum computing*” is a subset of the broader term “*quantum*”, and projects retrieved using “*quantum*” also included those related to “*quantum computing*”, we decided to proceed with “*quantum*” as our search keyword. To collect the project data, we utilized GitHub REST API<sup>5</sup>. We applied the following inclusion criteria: (1) the presence of the word “*quantum*” in the project metadata (name, description, topics, or README file) following a similar metadata-based project identification approach used in prior work [41], (2) a minimum of 50 stars, and (3) at least 15 forks, to reduce the likelihood of including small-scale or student projects, as suggested by prior

<sup>3</sup><https://github.com/desireevl/awesome-quantum-computing>

<sup>4</sup><https://github.com/JackHidary/quantumcomputingbook>

<sup>5</sup><https://docs.github.com/en/rest?apiVersion=2022-11-28>



Table 1. GitHub projects with the number of retrieved issues &amp; pull requests and related issues &amp; pull requests

#	GitHub Project	# of Issues & PRs	# of Retrieved Issues & PRs	# of Related Issues & PRs	# of Stars	# of Forks
GP1	Qiskit	3345	1169	30	4126	2153
GP2	Cirq	1855	703	25	4017	945
GP3	ARTIQ	1410	375	8	388	183
GP4	deepchem	1212	806	1	4801	1551
GP5	qmcpack	978	433	2	272	132
GP6	PennyLane	857	441	31	2008	514
GP7	QuTiP	743	171	7	1510	640
GP8	Covalent	743	171	1	1510	640
GP9	Mitiq	682	602	14	303	640
GP10	pyquil	551	286	2	1400	339
<b>Total</b>		<b>11957</b>	<b>5059</b>	121		

research [59]. Based on these criteria, we initially identified 1,226 relevant projects. Subsequently, we manually reviewed each repository's metadata, including its description, topics, and README file, to refine our dataset further. We excluded repositories that were purely educational (e.g., tutorials or documentation), not written in English, or unrelated to quantum software systems despite containing the keyword “*quantum*” (e.g., unrelated tools like FirefoxColor<sup>6</sup>). This resulted in a curated dataset of 347 quantum software repositories.

To further refine our data, we applied a keyword-based filtering strategy to the issues and pull requests (PRs) associated with a subset of these projects. First, we ranked the 347 quantum repositories by the number of issues and PRs and selected the top 10 most active projects for further analysis. We then conducted a keyword-based search over the titles and bodies of issues and PRs using terms specifically targeting architectural patterns and strategies: “*pattern*”, “*patterns*”, “*style*”, “*styles*”, “*strategy*”, and “*strategies*”. We found 5,059 issues and PRs containing the keywords. The ten projects and their corresponding retrieved and related issues and PRs are detailed in Table 1.

**Step 2 - Stack Exchange Sites:** We searched through questions and answers related to quantum architecture patterns on Stack Exchange sites (i.e., Stack Overflow, Quantum Computing, Computer Science, and Software Engineering). We selected the general terms “*pattern*” (i.e., “*pattern*”, “*patterns*”, “*style*”, “*styles*”, “*strategy*”, and “*strategies*”). Stack Exchange supports the use of wildcard (\*) searches, and we defined “*pattern\**”, “*style\**”, “*strateg\**” as the initial search terms related to architecture patterns. However, no relevant posts were found on the Software Engineering site, and our final dataset was derived from the first three Stack Exchange sites. Table 2 lists the search terms used and the number of posts retrieved from the three Stack Exchange sites. In total, we identified 681 posts. More specifically, 401 from Stack Overflow, 263 from Quantum Computing, and 17 from Computer Science.

**Phase 2 - Data Filtration:** We found issues and posts containing the terms “*pattern*”, “*style*”, and “*strategy*” but not in the context of software architecture and design, such as hardware (e.g., error pattern<sup>7</sup>), mathematical concepts (e.g., mathematical pattern<sup>8</sup>), and coding style documentation (Docstrings style<sup>9</sup>), when describing their concerns in the GitHub issues and Stack Exchange posts.

<sup>6</sup><https://github.com/mozilla/FirefoxColor>

<sup>7</sup><https://tinyurl.com/mr367anu>

<sup>8</sup><https://tinyurl.com/b3myzxdx>

<sup>9</sup><https://tinyurl.com/4wtawp7b>

Table 2. Stack Exchange sites with the number of retrieved posts and related posts

#	Stack Exchange Sites	Search Terms	# of Retrieved Posts	# of Related Posts
SEN1	Stack Overflow	"quantum pattern" <sup>*</sup>	114	2
SEN2	Stack Overflow	"quantum style" <sup>*</sup>	241	0
SEN3	Stack Overflow	"quantum strateg" <sup>*</sup>	46	0
SEN4	Quantum Computing	"quantum pattern" <sup>*</sup>	91	5
SEN5	Quantum Computing	"quantum style" <sup>*</sup>	56	3
SEN6	Quantum Computing	"quantum strateg" <sup>*</sup>	116	2
SEN7	Computer Science	"quantum pattern" <sup>*</sup>	8	0
SEN8	Computer Science	"quantum style" <sup>*</sup>	4	1
SEN9	Computer Science	"quantum strateg" <sup>*</sup>	5	0
<b>Total</b>			681	13

We also found that both Stack Overflow and Computer Science Stack Exchange featured posts with the term "quantum" but not in the context of a quantum software system, such as browser (e.g., Firefox Quantum<sup>10</sup>) and, Geographic Information System (GIS) software (e.g., Quantum GIS<sup>11</sup>). To analyze the collected data effectively, we filtered 5,059 issues and PRs from 10 quantum software systems, along with 681 Stack Exchange posts (i.e., 401 from Stack Overflow, 263 from Quantum Computing, and 17 from Computer Science) and excluded those posts that were not related to software architecture patterns and strategies in quantum software systems. This process involved conducting a content analysis and utilizing predefined inclusion and exclusion criteria (see Table 4) to systematically eliminate unrelated issues and posts. Before the formal screening process involving manual review, we performed an initial selection based on predefined inclusion and exclusion criteria detailed in Table 4. This preliminary phase aimed to identify issues from GitHub's project and posts on Stack Exchange related to architectural patterns and strategies in quantum software systems. During this step, the first author carefully read 250 GitHub issues and pull requests, and 50 Stack Exchange posts. Each data point was labeled as "related", "not related", or "doubtful". Among the GitHub items, 11 were labeled as "related", 222 as "not related", and 17 as "doubtful". For the Stack Exchange posts, 3 were marked as "related", 46 as "not related" and 1 as "doubtful". The doubtful cases from both sources were discussed among the second, third, and fourth authors to reach a consensus on their relevance to our research context. The first author conducted the formal data screening following the initial data filtering. This process involved evaluating all the issues and PRs extracted from GitHub projects and the posts from Stack Exchange sites, applying predefined inclusion and exclusion criteria. Given these inclusion and exclusion criteria, the first author could perform this task independently. Finally, 121 GitHub issues and PRs (Table 1) and 13 Stack Exchange posts (Table 2) were identified as "related" and were used for further analysis.

**Phase 3 - Data Extraction:** We defined a set of data items (see Table 4) to be extracted from the discussion of the 121 GitHub issues & PRs and 13 Stack Exchange posts. To check the reliability of the extracted data items, the first author conducted a pilot data extraction on 10 issues, 5 PRs and 5 posts, and the second, third, and fourth authors evaluated the extracted data. After evaluating the extracted data items, the first author used a revised set of data items for formal data extraction from the selected issues, PRs and posts. The first four authors then discussed the extracted data to reduce potential bias and ambiguity. Data items (D1-D3) are used to extract the general information of

<sup>10</sup><https://tinyurl.com/5b562yb6>

<sup>11</sup><https://tinyurl.com/ywfdt4dx>

the selected issues, PRs, and posts. The rest of the data items (D4-D9) are used to identify patterns, strategies, QAs, and impact. Finally, we used spreadsheets to record the extracted data.

Table 3. Inclusion and exclusion criteria to manually identify GitHub issues, PRs, and Stack Exchange posts

<b>Inclusion</b>	<b>I1.</b> We include an issue, pull request, or post if it addresses both architecture patterns and quantum software systems.
<b>Exclusion</b>	<b>E1.</b> We exclude an issue, pull request, or post if it is only related to quantum software systems and not to architecture patterns. <b>E2.</b> We exclude an issue, pull request, or post if it is only related to the architecture pattern and not the quantum software system.

**Phase 4 - Data Analysis:** To analyze our extracted data, we applied thematic analysis to qualitatively analyze the extracted data [14]. We used the following steps: (1) Familiarizing with data: we repeatedly read the selected issues and posts and noted down all kind of quantum software architecture patterns and strategies (D4), Pattern related to quantum software architecture design area (D5), Pattern and strategy key point (D6), Related QAs (D7), Positive impact QAs (D8), and Negative impact QAs (D9); (2) Generating initial codes: after data familiarization, we produced an initial list of codes from the extracted data about research pattern and strategies, QAs, and impact; (3) Searching for themes: In this step, the initially generated codes were analyzed and brought under the broader themes. For instance, “*We used a composite pattern and a list-based tracking of the elements in the IR*”; (4) Reviewing themes: The first authors reviewed and refined the coding results with related themes. Later, the second, third, and fourth authors review the results and dropped some themes during this step based on mutual discussion between first four authors; (5) Defining and naming themes: We defined and further refined all the themes under precise and clear names of the quantum software architecture patterns and strategy categories. For example, “*It maintained the identical iteration order to the previous iteration once the front-layer data structure was swapped from a raw list to hash-based (GitHub PR #9560)*” was named as Layered Pattern in this step. Finally, we identified a total of 164 patterns (strategies). More specifically, 145 patterns (strategies) from 121 GitHub issues and 19 patterns (strategies) from 13 Stack Exchange posts (i.e., 5 from Stack Overflow, 13 from Quantum Computing Stack Exchange, and 1 from Computer Science Stack Exchange).

### 3.1.2 Identifying Architecture Patterns and Strategies Using an SLR.

#### 1) Data Collection

**Phase 1 - Defining Data Collection Strategy:** This phase focuses on preparing for the SLR by identifying relevant data sources, formulating a search strategy, and defining inclusion and exclusion criteria for study selection.

**Step 1 - Identify Data Sources:** Electronic Data Sources (EDS) are pivotal in systematic review studies, where they enable automated searches through predefined or customized queries. These automated searches facilitate the identification of relevant literature in a particular domain [19, 54]. In our study, we adhered to the guidelines for performing systematic literature reviews in software engineering as proposed by Kitchenham *et al.* [34]. We selected eight widely recognized EDS: IEEE Xplore, ACM Digital Library, Wiley Online Library, ScienceDirect, SpringerLink, Engineering Village, Web of Science, and Google Scholar, based on their proven effectiveness and relevance to computing, software engineering, and software architecture research [68]. The selection of these EDS ensures the inclusion of high-quality, peer-reviewed publications and reduces the risk of missing critical research [19, 68].

**Step 2 - Defining Inclusion and Exclusion Criteria:** We defined a set of inclusion and exclusion criteria for selecting relevant studies. These criteria were applied to filter out irrelevant,

Table 4. Data items extracted from the selected GitHub issues, PRs, and Stack Exchange posts

#	Data item	Description
D1	Issues, PRs, & posts ID	A ID of the issues, PRs, & posts ID that were discussed on GitHub and Stack Exchange in the context of the quantum software architecture pattern and strategy
D2	Issues, PRs, & posts title	A title of the issues, PRs, & posts ID from a developer that describes what the quantum software architecture pattern and strategy is all about
D3	Issues, PRs, & posts link	The URL address of the issues, PRs, & posts ID
D4	Type of quantum software architecture patterns and strategies	Identification of quantum software architecture patterns and strategies type based on key points
D5	Pattern and strategy related to quantum software architecture design area	Identification of quantum software architecture patterns and strategies design area
D6	Pattern and strategy key point	Identification of quantum software architecture patterns and strategies key points
D7	Related QAs	Related QAs of patterns and strategies that occur in quantum software systems
D8	Positive impact QAs	Positively impacted QAs of patterns and strategies that occur in quantum software systems
D9	Negative impact QAs	Negatively impacted QAs of patterns and strategies that occur in quantum software systems

redundant, non-English studies, and duplicated studies, especially those appearing in multiple venues or overlapping due to shared libraries or cross-referencing. Table 5 lists our inclusion and exclusion criteria. The inclusion and exclusion process was followed by a quality assessment step to evaluate each included study's relevance and quality. Studies that did not meet the minimum quality score of 1.5 were excluded from the review (as detailed in Section 3.1.2 Phase 2 - Step 3).

**Step 3 - Perform Quality Assessment:** This quality assessment ensured that only high-quality, relevant studies were included in the final analysis.

Table 5. Inclusion and exclusion criteria for study selection

Code	Inclusion Criteria	Code	Exclusion Criteria
I1	Studies that focus on quantum software architecture patterns, strategies, styles, or QAs.	E1	Studies unrelated to quantum software architecture (e.g., studies focused on quantum computing applications in chemistry, biology, or physics).
I2	Studies that provide empirical data or conceptual frameworks related to the design and development of quantum software systems.	E2	Studies that do not include explicit information on architecture patterns, strategies, or design principles in quantum software systems.
I3	Studies published in peer-reviewed journals, conferences, or reputable repositories.	E3	Studies not published in peer-reviewed sources or not available in English.
I4	Studies available in the English language.	E4	Duplicate or secondary studies based on the search results.

**Phase 2 - Conducting the Review:** This phase involved executing the search, screening the results through multiple levels of review, and applying inclusion, exclusion, and quality criteria to identify the final set of primary studies.

**Step 1 - Selecting Primary Studies:** We used the following steps to select the primary studies.

- **String Execution:** The identification of primary studies began by querying the selected EDS with the predefined search string (outlined in Section 3.1.2). The initial search process retrieved a total of 12,819 studies aggregated across all EDS, which were further manually filtered by the first author based on the studies' titles, keywords, and abstracts against the inclusion and exclusion criteria (see Table 5) to identify studies that were potentially relevant for further evaluation. For example, we used the advanced search functionality in IEEE Xplore to apply the search string and retrieve relevant studies from the "Full Text & Metadata". This search returned 1,584 results, the majority of which focused on quantum systems in general, with a particular emphasis on quantum hardware. To narrow down the overwhelming number of results and assess the scope of relevant entries, we modified the search parameter from "Full Text & Metadata" to "Abstract". This refinement yielded 259 studies, but this abstract-only search missed several relevant articles captured by the broader full-text search, including known flagship studies in the field. To ensure the validity of our search strategy, we manually reviewed the results and verified that key benchmark studies were included, reinforcing the need for a comprehensive scanning process. Therefore, we decided to retain the more comprehensive search setting and proceeded with a manual examination of the 1,584 results. After applying IEEE Xplore-specific filtering to exclude non-peer-reviewed content such as books and magazines, we refined the dataset to 1,554 candidate studies. We manually examined the remaining retained studies that were directly related to architectural patterns, styles, or strategies within the domain of quantum software systems. Based on this repository-specific strategy, we extracted these studies for further screening, applying inclusion and exclusion criteria, and conducted a qualitative assessment, as illustrated in Figure 1.
- **Title, Abstract, and Keywords Based Screening:** After the initial search, we screened all retrieved studies based on their titles, abstracts, and keywords. The first author independently reviewed the studies, labeling each as "relevant", "irrelevant", or "doubtful". Doubtful studies were discussed among the first four authors to reach a consensus on their relevance. This process ensured that only the most relevant studies progressed to the next phase. Ultimately, 277 studies were selected based on the titles, abstracts, and keywords filtration (see Figure 1).
- **Full Text Screening:** The 277 studies that passed the abstract and topic-based selection were subjected to a more thorough full-text evaluation. The first author applied the inclusion and exclusion criteria, as outlined in Table 5 (I1 to I4 for inclusion and E1 to E4 for exclusion), to ensure that the selected studies met the necessary quality and relevance standards. After applying inclusion and exclusion criteria, we selected 75 primary studies for inclusion in the final analysis. To ensure the consistency and accuracy of the selection process, the second, third, and fourth authors independently reviewed the list of selected studies and verified the results.

**Step 2 - Snowballing:** To mitigate the risk of overlooking important studies during the automated search, we applied snowballing, following the method outlined by Wohlin *et al.* [65]. This process involved both forward snowballing, where we gathered studies citing the selected ones, and backward snowballing, where we reviewed the references of the selected 75 studies. Initially, this method returned a total of 451 studies based on the titles. After removing duplicates and performing a relevance check based on abstracts, keywords, and conclusions of 189 studies, we proceeded with a

detailed full-text screening of 189 papers. We applied a multi-level screening process, incorporating both general inclusion and exclusion criteria and specific quality assessment guidelines (see Table 6). Following this rigorous evaluation, a final set of 17 relevant studies was identified and incorporated into our primary dataset through snowballing.

**Step 3 - Quality Assessment of Primary Studies:** To ensure the rigor and relevance of the studies included in this SLR, we conducted a structured quality assessment based on established guidelines. Our assessment combined a general methodological evaluation with domain-specific criteria tailored to the context of quantum software architecture. The criteria were adapted from the methodological frameworks proposed by Kitchenham and Charters *et al.* [33], Brereton *et al.* [15], Waseem *et al.* [58] and Ahmad *et al.* [1]. The final framework comprised eight evaluation items – five generic (G1–G5) and three specific (S1–S3) as listed in Table 6. Each study was evaluated based on whether it fully addressed, partially addressed, or did not address each criterion. A score of 1 was assigned if the criterion was fully satisfied, 0.5 if partially satisfied, and 0 if not satisfied. To emphasize the relevance of domain-specific insights, the sum of scores from specific criteria was multiplied by a factor of three. The final quality score for each study was computed using the following formula:

$$\text{Quality Score} = \left( \sum_{i=1}^5 G_i + 3 \times \sum_{j=1}^3 S_j \right)$$

Studies that received a total quality score of 1.5 or higher were considered suitable for inclusion in the final dataset [58]. The initial assessments were conducted by the first author and independently verified by the second, third, and fourth authors to ensure consistency and reduce evaluation bias. All 92 studies (75 from string execution and 17 from snowballing) satisfied the inclusion criterion of a minimum quality score of 1.5 and were therefore included in the final dataset.

Table 6. Quality assessment criteria for primary studies

Code	Generic Quality Criteria
G1	Does the study explicitly define its research objectives and articulate the motivation behind the work?
G2	Is the context of the study—such as the domain, environment, or technology stack—clearly described?
G3	Is the research methodology sufficiently detailed and logically justified, including data sources, techniques, or analytical procedures?
G4	Are the key findings and interpretations clearly presented, well-supported by data, and critically discussed?
G5	Are the study's limitations, assumptions, or threats to validity transparently acknowledged and explained?
Code	Domain-Specific Criteria for Quantum Software Architecture
S1	Does the study contribute to quantum software architecture by discussing or applying patterns, styles, strategies, or decision models tailored for quantum software systems?
S2	Does the study address at least one of the six key design areas (Communication, Decomposition, Data Processing, Fault Tolerance, Integration & Optimization, Algorithm Implementation)?
S3	Does the study provide practical insights, empirical evaluations, or real-world use cases that inform architecture design decisions in quantum software systems?

### Phase 3 - Data Extraction and Analysis



For this study, we defined a set of data extraction items to systematically collect and synthesize relevant information from the selected primary studies. These data items (see Table 7) were designed to capture both general bibliographic information and specific content relevant to quantum software architecture patterns and strategies.

**Step 1 - Data Extraction Process:** The data extraction process was conducted in two phases. Initially, a pilot extraction was performed by the first author on a subset of ten studies to assess the clarity and applicability of the predefined data items. Based on the feedback and discussions among the first four authors, minor refinements were made to the extraction framework to improve consistency and remove ambiguities. Following this, the formal extraction process was conducted, with the first four authors equally distributing the selected studies among themselves based on their research expertise and interests. To reduce potential bias and ensure reliability, extracted data were reviewed collaboratively through regular meetings among the first four authors, where any discrepancies were discussed and resolved through a negotiated agreement approach [17]. All extracted data were systematically recorded in Excel sheets to support traceability and further analysis.

Table 7. Data items extracted from the selected primary studies

Code	Data Item	Description
D1	Index	ID of the study
D2	Study title	Title of the study
D3	Author(s) list	Full names of the authors
D4	Year	Publication year
D5	Venue	Publishing venue (e.g., journal, conference)
D6	Publication type	Type of publication (e.g., journal, conference)
D7	Authors affiliation	Academia, industry, or both
D8	Pattern and strategy related to quantum software architecture design area	Identification of quantum software architecture patterns and strategies design area
D9	Pattern and strategy key point	Key points summarizing the identified patterns and strategies
D10	Related QAs	QAs associated with the patterns and strategies
D11	Positive impact QAs	QAs positively influenced by the patterns and strategies
D12	Negative impact QAs	QAs negatively influenced by the patterns and strategies

**Step 2 - Data Analysis Process:** After data extraction, we conducted both descriptive and thematic analysis of the collected data. The general information (D1–D7) was analyzed using descriptive statistics to provide an overview of publication trends, author affiliations, and dissemination venues. The content-specific items (D8–D12) were analyzed qualitatively through thematic analysis, following the steps outlined by Braun and Clarke (2006):

- **Data Familiarization:** The authors carefully reviewed the extracted content to understand the patterns, strategies, and associated QAs.
- **Generating Initial Codes:** Initial codes were generated to identify key architectural challenges, solutions, and quality considerations in quantum software systems.
- **Searching for Themes:** Codes were organized into broader themes that captured recurring design concerns and strategic practices.
- **Reviewing Themes:** Themes were refined based on mutual discussions to ensure coherence and eliminate overlaps.

- **Defining and Naming Themes:** Themes were clearly defined and labeled to reflect the core architectural insights emerging from the primary studies.
- **Producing the Report:** The final set of themes served as the basis for presenting the findings related to quantum software architecture decision-making.

**3.1.3 Integration of Findings.** To comprehensively support the development of decision models for quantum software architecture, we systematically integrated the findings from both the mining study (GitHub issues and Stack Exchange posts) and the SLR. This integration process allowed us to synthesize information and gain a deeper understanding of quantum software architecture patterns and strategies.

In total, we identified 372 patterns and strategies across both the mining study and the SLR. Specifically, from the mining study, we identified 162 patterns/strategies, comprising 145 from 121 GitHub issues & PRs, 17 from 13 Stack Exchange posts, and 210 patterns from 92 reviewed studies. These patterns primarily correspond to the six architectural design areas our study focused on: Communication, Decomposition, Data Processing, Fault Tolerance, Integration and Optimization, and Algorithm Implementation. During integration, we observed that different studies and repositories often used varying terminologies to describe conceptually similar patterns and strategies. Moreover, the terms “*pattern*” and “*strategy*” were frequently used interchangeably across the sources. For example, “*Quantum Key Distribution Chain Patterns*” was categorized under the broader design area of “*Quantum Key Distribution (QKD) Protocols*”. To ensure consistency, we carefully analyzed the underlying concepts and standardized naming conventions across all collected data, aiming to unify patterns and strategies that reflected the same architectural concepts. Through an iterative qualitative synthesis process, including thematic analysis, we consolidated and de-duplicated the identified patterns and strategies. After removing duplicate patterns and using common naming for several patterns, we identified and unified 63 unique architecture patterns and strategies across six key design areas in quantum software systems. Specifically, we identified 18 Communication, 7 Decomposition, 12 Data Processing, 8 Fault Tolerance, 9 Integration and Optimization, and 9 Algorithm Implementation patterns and strategies. Furthermore, the analysis revealed that each identified pattern or strategy could have both positive and negative impacts on various QAs in quantum software systems.

## 3.2 Modeling Decision Models

Figure 2 illustrates the notations employed within the decision models proposed in this study. To represent decision flows, we adopted the Inclusive, Exclusive, and Parallel gateways from the Business Process Model and Notation (BPMN). Specifically, (1) a gray box indicates a *design area* within quantum software systems; (2) a circle signifies the *starting point* of a decision process; (3) an inclusive gateway may activate *multiple outgoing paths*; (4) an exclusive gateway allows only *one outgoing path*; (5) a parallel gateway initiates *all outgoing paths* simultaneously; (6) *architectural patterns and strategies* are depicted using rounded rectangles; (7) a QA that is *improved* by a pattern is indicated with a plus sign (+); (8) a QA that is *degraded* by a pattern is indicated with a minus sign (-); (9) *constraints* associated with a pattern are shown using an octagon connected to the pattern by a dashed arrow; (10) a line with a double-headed arrow between two patterns represents a *complements* relationship; and (11) a single-headed arrow indicates a *conditional flow* between patterns.

## 3.3 Evaluating Decision Models

In our study, we conducted a series of semi-structured interviews with quantum software practitioners to refine and evaluate our proposed decision models. The interview guide was adapted

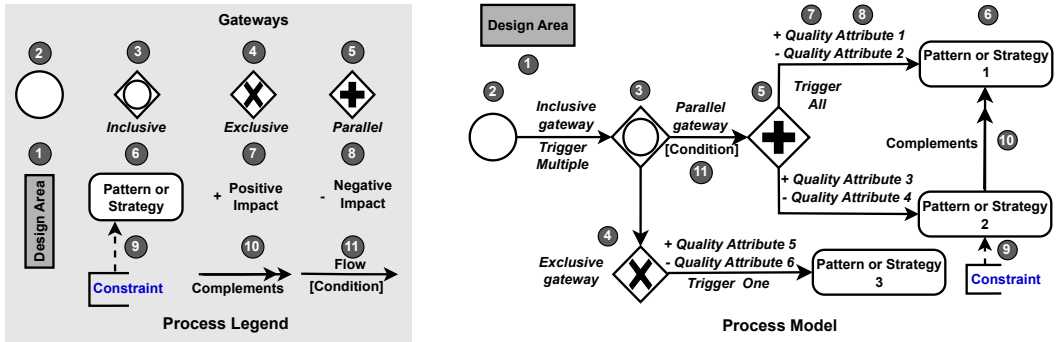


Fig. 2. Notations used in the decision models

from established questionnaires used in prior research (e.g., [57], [36], [66], [56]) to align with the objectives of this study. Our interview questionnaire was conducted using Google Docs and is publicly available online<sup>12</sup>. Additionally, a detailed document describing the architectural patterns and strategies with practical examples was shared with participants prior to the interview<sup>13</sup>.

**3.3.1 Developing Interview Questionnaire.** The interview questionnaire was developed into seven sections: (i) participant demographic information (5 questions), and evaluation of the decision models for (ii) Communication (8 questions), (iii) Decomposition (9 questions), (iv) Data Processing (8 questions), (v) Fault Tolerance (8 questions), (vi) Integration and Optimization (9 questions), and (vii) Algorithm Implementation (9 questions). The questionnaire included both closed-ended and open-ended questions.

### 3.3.2 Participant Selection.

**Phase 1 - Identifying Practitioners:** We followed the process outlined below to identify practitioners who are actively working on quantum software.

**1) Quantum Software Practitioners on GitHub:** Our study targeted individuals who actively contributed to quantum software projects on GitHub. We identified potential participants from the 347 quantum software repositories selected in our mining study (see Section 3.1.1). We prioritized projects that were directly related to quantum software development and extracted the publicly available contact information of 1,050 contributors. Invitations were sent via email to these contributors, providing them with access to two key documents: (i) an interview questionnaire titled “Decision Models for Selecting Architecture Patterns and Strategies in Quantum Software Systems” and (ii) a supplementary document containing detailed descriptions and practical examples titled “Architecture Patterns & Strategies in Quantum Software Systems with Practical Examples”. These materials were shared in advance to familiarize the participants with the scope and context of the interview and to facilitate meaningful discussion during the sessions.

**2) Social and Professional Platforms:** To further expand our participant pool, we were actively engaged with various quantum computing communities on platforms such as LinkedIn and Facebook. These groups bring together quantum software practitioners from diverse geographical regions to discuss challenges, share insights, and exchange expertise. We posted invitations in several professional groups, providing links to the interview questionnaire with the supplementary document describing the architectural patterns and strategies. Participants were encouraged to

<sup>12</sup><https://tinyurl.com/bdcvzjjb>

<sup>13</sup><https://tinyurl.com/2fwcbkmh>

review these materials prior to the interview sessions. The details of the groups where the invitations were shared are listed in our replication package [6].

**3) Other Contacts:** In addition to public platforms, we leveraged our professional networks to recruit qualified participants. Email invitations were sent to individuals involved in quantum software organizations and to authors of industrial track research papers and online blogs that focused on quantum software development. We also encouraged recipients to forward the invitation to their colleagues or collaborators with relevant expertise, thus extending our reach through snowball sampling.

**Phase 2 - Obtaining a Valid Sample:** To ensure the validity and reliability of the interview data, we applied a set of inclusion and exclusion criteria, detailed in Table 8. Participants were included if they fulfilled criterion I1, namely, having professional responsibility for the development, design, or operation of quantum software systems. During the interview process, participant eligibility was assessed based on their responses to demographic questions concerning their professional role, years of experience in software development, and specific experience with quantum software systems. Conversely, exclusion criteria were applied to maintain data quality. Criterion E1 was used to exclude interviews that exhibited inconsistent, random, or meaningless responses. Additionally, under criterion E2, we excluded participants from the sample if they had more than five key questions answered inconsistently, randomly, or without meaningful engagement. For example, one excluded participant responded with “I do not know” to over five key questions, including those regarding familiarity, usefulness, and completeness of the decision models. This indicates a lack of engagement and understanding, and the interview was excluded under criteria E1 and E2. This approach was adopted to mitigate the risk of including participants who may not have sufficient knowledge or interest to contribute meaningfully to the evaluation of the decision models.

Table 8. Inclusion and exclusion criteria for selecting valid interview responses

Inclusion Criterion	Description
I1	The participant must be professionally responsible for the development, design, or operation of quantum software systems.
Exclusion Criterion	Description
E1	An interview exhibiting inconsistent, random, or meaningless responses is excluded.
E2	If more than five core interview questions are answered inconsistently, randomly, or without meaning, the entire response is excluded.

**Phase 3 - Filtering Interview Data:** Before initiating the formal round of interviews, we conducted pilot interviews involving five quantum software practitioners. These pilot participants represent diverse geographic and professional backgrounds: three were based in Bangladesh, one in China, and one in Senegal. Their roles include researchers and developers working in domains such as quantum cryptography, simulation and optimization, education, machine learning, and quantum software frameworks. In terms of experience, one participant had more than 10 years of experience, seven participants had between 6-10 years of experience, and the remaining participants had between 2-5 years of experience in software development. In contrast, the majority of the participants had between 2-5 years of experience in quantum software development. The primary objective of this phase was to preliminarily assess the clarity, structure, and practical relevance of the proposed decision models across the six architectural design areas: Communication, Decomposition, Data Processing, Fault Tolerance, Integration and Optimization, and Algorithm Implementation.

The pilot interviews also helped us refine the interview questionnaire and validate whether the proposed decision models were understandable and applicable in real-world QSE contexts.

Based on the valuable feedback from these pilot participants, we revised three of the decision models, specifically, Communication, Data Processing, and Fault Tolerance, by adding new architectural patterns (e.g., Quantum Teleportation, Amplitude Encoding, Error Correction) and restructuring decision flows to distinguish fault detection from correction paths. Correspondingly, we updated the multiple-choice options in the interview questionnaire to reflect these additions. For instance, in the question “13) (Multiple Choice) Which of the following architectural patterns have you implemented in your quantum software systems for Communication?”, “30) (Multiple Choice) Which of the following architectural patterns have you implemented in your quantum software systems for Data Processing?”, and “38) (Multiple Choice) Which of the following architectural patterns have you implemented in your quantum software systems for Fault Tolerance?”. We expanded the response options to include newly incorporated patterns and strategies. While the overall structure and wording of the interview questions remained unchanged, these adjustments ensured better alignment between the refined models and the evaluation instrument. We also improved the visual presentation of the decision models and clarified the technical terms used to improve participant comprehension. The pilot interviews were also included in the final interview results because the changes made to the models were relatively minor and did not significantly alter the core concepts evaluated. Therefore, the feedback from the pilot phase remained relevant and contributed to the overall insights gathered during the interviews.

Following this refinement, we proceeded with the formal interview phase, during which we interviewed 11 quantum software practitioners. Participants were invited via professional email contacts, relevant online groups (e.g., Facebook, LinkedIn), and personal outreach. A total of 17 confirmations were initially received. One participant’s response was later excluded due to inconsistency or lack of meaningful engagement, as per the exclusion criteria defined in Table 8. This resulted in 16 valid interviews (including 5 from the pilot phase) used for the final analysis. All interviews were conducted with informed consent, recorded, transcribed, and translated into English by the first and second authors. The interview results were independently reviewed by the second and third authors to remove irrelevant content and ensure alignment with the study objectives. MS Excel was used to support data organization and categorization.

**Phase 4 - Interview Data Analysis:** We employed two complementary analysis techniques for the interview data. First, descriptive statistics were applied to analyze closed-ended responses regarding participant demographics, familiarity with decision models, perceived understandability, and completeness. Second, we utilized open coding [50] and constant comparison techniques [26] from Grounded Theory methodology [52] to analyze qualitative data obtained from open-ended questions. In the open coding phase, raw textual data were segmented into discrete codes representing key ideas expressed by participants, focusing on aspects such as perceived correctness, sufficiency, usefulness, suggestions for improvement, and real-world usage of the decision models. These responses were manually coded by the first author and verified by the second author. Key phrases and statements were extracted from the interview transcripts and assigned initial codes, such as “The decision model correctly defines all decision paths and flows”, “Extremely helpful in guiding us toward the appropriate patterns and strategies”, “The model clearly outlines the trade-offs involved in different communication patterns”, and “I have a suggestion to enhance the model, we could introduce resource-aware processing approaches”. These initial codes were then grouped into higher-level concepts and iteratively refined into broader analytical categories, including Model Correctness, Evaluation Usefulness, and Suggestions for Improvement. This systematic approach facilitated a rigorous and structured interpretation of the qualitative feedback, allowing for the refinement of the decision models.

## 4 DECISION MODELS

In software architecture, decision models connect elements of the problem space with aspects of the solution space. The problem space encompasses both functional and non-functional requirements, while the solution space encompasses the design components [36]. In this study, the problem space is defined through a collection of QAs for quantum software systems. The solution space comprises various architectural patterns and strategies for quantum software systems. These decision models were crafted for six critical areas of quantum software design: Communication, Decomposition, Data Processing, Fault Tolerance, Integration and Optimization, and Algorithm Implementation.

### 4.1 Communication Decision Model

The Communication Decision Model provides a structured framework to guide practitioners in choosing suitable architectural patterns and strategies based on specific conditions and communication impacts within quantum software systems. The decision model guides the selection of communication patterns for both quantum-to-quantum and quantum-to-classical communication. It covers various architectural patterns and strategies, each associated with clearly outlined positive and negative QAs, which are informed by findings from the mining study and the SLR on quantum software communication. It is structured through various decision gateways — Inclusive, Exclusive, and Parallel — representing the decision-making flows required for architecting quantum communication systems. Table 3 lists the patterns and strategies covered by the Communication Decision Model (see Figure 3).

For the interaction between quantum and classical systems, an **Inclusive Gateway** initiates the decision process by evaluating various quantum communication requirements. **Quantum API Gateway** is employed when a unified interface is needed to manage this interaction. For example, IBM's Qiskit Runtime employs a centralized gateway to manage submissions from classical clients to quantum backends. It improves *Flexibility* and *Modularity* by encapsulating diverse services under a single access point, and enhances *Interoperability* and *Security* through centralized control. It also supports *Scalability* by managing increasing client requests efficiently. However, it introduces a single point of failure, which affects its *Availability*. Additionally, the need for extra processing degrades *Performance* and increases *Cost* due to management overhead. If managing workflows becomes necessary, the decision flow proceeds through another **Inclusive Gateway** to **Quantum Workflow Orchestration**. This pattern improves *Scalability* and *Performance* by coordinating distributed tasks and increases *Modularity* and *Reliability* by clearly defining execution logic. However, it adds *Complexity* and may reduce *Performance* in tightly coupled workflows. Alternatively, **Quantum Proxy** is chosen to abstract client-service interactions. It enhances *Maintainability* by isolating clients from implementation changes, strengthens *Interoperability* by managing protocol translations, and improves *Security* by controlling access. It may slightly reduce *Performance* due to request forwarding overhead. **Broker-Client Separation** supports the separation of concerns between service consumers and communication brokers. It boosts *Modularity* and *Security* by isolating messaging components and improves *Scalability* by decoupling senders and receivers. However, it introduces *Complexity* due to additional configuration and coordination logic.

For enabling long-distance communication, teleportation, and networking via entanglement management, **Entanglement Distribution Strategy** is used with techniques, such as repeater purification and entanglement swapping. This strategy enhances *Scalability* by enabling broader communication ranges, *Security* through controlled entanglement paths, *Adaptability* and *Configurability* by allowing flexible routing, *Modularity* by encapsulating the communication logic as a separate module, and *Performance* due to efficient Qubits transfer, albeit with increased *Complexity* from entanglement management overhead. **Quantum Teleportation** is used to transfer



Table 9. Architecture patterns and strategies for communication

Pattern Name	Summary
Quantum API Gateway	Provide a unified interface for accessing quantum services, optimizing deployment, and resource selection dynamically.
Quantum Workflow Orchestration	Manage quantum-classical workflows, ensuring optimized resource allocation and task coordination.
Quantum Proxy	Abstract client-service interactions to enhance maintainability and interoperability with secure communication.
Broker-Client Separation	Clearly separates broker and client responsibilities, enhancing modularity, scalability, and security at the cost of complexity.
Entanglement Distribution Strategy	Enable long-distance quantum communication via repeaters, purification, and swapping techniques.
Quantum Teleportation	Transfer quantum information securely and efficiently between distant quantum nodes using entanglement.
Quantum Point-to-Point Communication	Facilitate secure direct communication between two quantum nodes through entanglement (e.g., QKD).
Quantum Collective Communication	Enable efficient multi-node quantum communication leveraging entanglement distribution and swapping.
Connection-Oriented Strategy	Use dedicated paths and resources to manage stable quantum entanglement distribution.
Connectionless Strategy	Dynamically manages on-demand quantum entanglement distribution without fixed resources.
Quantum Overlay	Define abstraction layers for quantum communication, standardizing interactions across quantum protocols.
Quantum Communication Layered	Adopt a layered architecture facilitating interoperability among different quantum protocols and implementations.
Entanglement-Assisted Channels	Optimize communication by leveraging entanglement, enhancing security, performance, and scalability.
Basic Broadcasting	Enable secure quantum state broadcasting from one sender to multiple receivers.
Multi-Sender/Multi-Receiver Broadcasting	Extend basic broadcasting to multiple senders and receivers, increasing system flexibility and scalability.
QKD Protocols	Implement secure quantum key distribution protocols (e.g., BB84, E91) to ensure secure node communication.
Quantum Teleportation Protocol	Facilitate secure, efficient quantum state transfers across extensive distances.
Quantum Burst Communication	Optimize quantum communication by grouping tasks into bursts, reducing communication latency and resource use.

quantum information between distant nodes. It supports *Security* and *Reliability* by avoiding direct transmission, and improves *Loss Tolerance* in noisy environments, but trades off *Scalability* and introduces *Latency* due to the need for classical communication and entanglement setup. Depending on the communication scenario, an **Exclusive Gateway** selects either **Quantum Point-to-Point Communication Pattern** or **Quantum Collective Communication Pattern**. **Point-to-Point Pattern** improves *Performance* and *Reliability* by providing direct, dedicated channels between nodes, but introduces *Latency* and limits *Scalability* as it only supports one-to-one links. **Collective Communication Pattern** supports multi-node entanglement-based messaging, which increases *Scalability*, *Performance*, and *Reusability* by sharing communication logic and resources, and reduces *Cost* through shared infrastructure. However, it limits *Flexibility* due to predefined communication topologies. The decision model also includes **Connection-Oriented Strategy**, which reserves fixed paths for communication. This ensures *Scalability*, *Security*, *Reliability*, and *Performance* through stable connections, but reduces *Flexibility* and increases *Cost* due to pre-established resource allocation. In contrast, **Connectionless Strategy** enables dynamic, on-demand communication. It

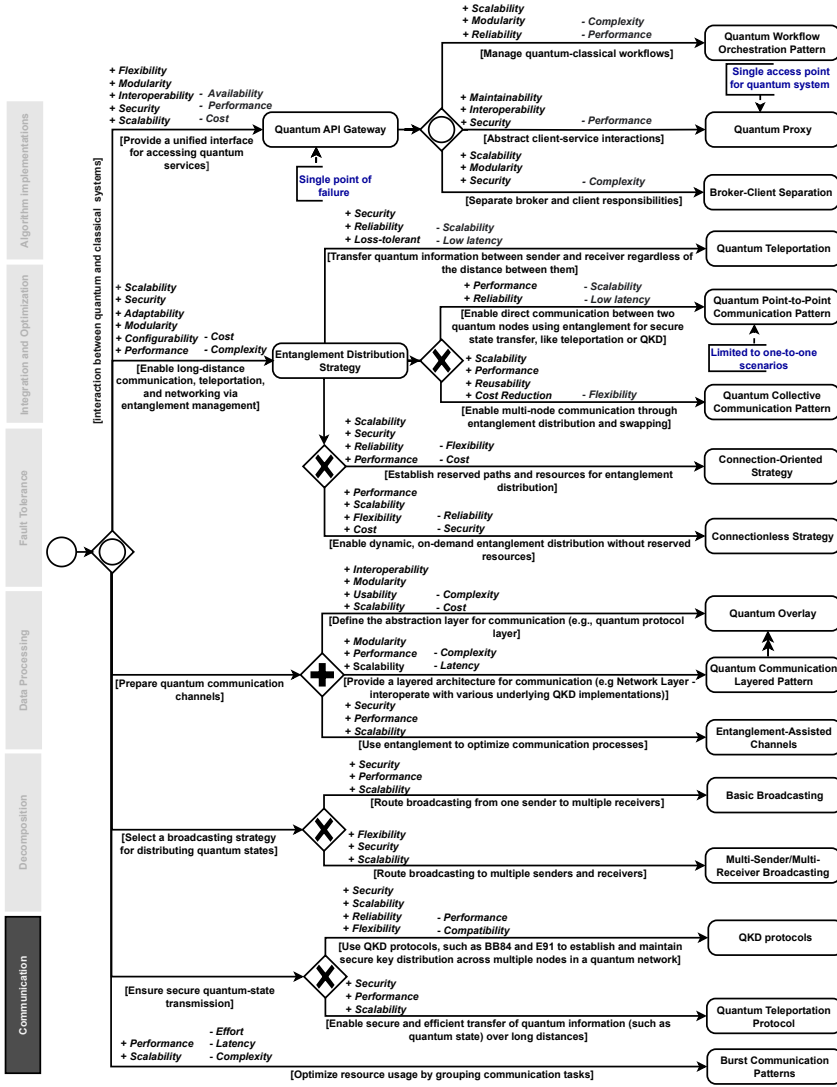


Fig. 3. Decision model for selecting architecture patterns and strategies for communication

enhances *Performance*, *Scalability*, *Flexibility*, and *Cost-Efficiency* by avoiding fixed routing, but compromises *Reliability* and *Security* due to the lack of guaranteed delivery paths.

For channel preparation, the decision model uses **Parallel Gateways** to evaluate multiple configuration paths. **Quantum Overlay** introduces an abstraction layer between network components, which improves *Interoperability* by standardizing interactions, *Modularity* by isolating layers, *Usability* through simplified interfaces, and *Scalability* by supporting layered expansion. However, it also increases *Complexity* due to layered architecture and adds *Cost* from additional infrastructure needs. Alternatively, **Quantum Communication Layered Pattern** organizes communication functions into dedicated layers, enhancing *Modularity* and *Performance* by isolating responsibilities and optimizing each layer. This layered approach supports *Scalability* across different hardware or

protocol types but introduces *Complexity* in managing dependencies and *Latency* due to multi-step message processing. For performance optimization, **Entanglement-Assisted Channels** utilizes pre-shared entanglement to streamline quantum communication, resulting in improved *Security*, *Performance*, and *Scalability*, as entanglement can reduce the need for repeated key exchanges and boost throughput.

For broadcasting quantum states, an **Exclusive Gateway** is used to choose between two different communication strategies. **Basic Broadcasting** distributes entangled states from one sender to multiple receivers, which increases *Security* through quantum-safe distribution, improves *Performance* via parallel delivery, and supports *Scalability* across multiple nodes. **Multi-Sender/Multi-Receiver Broadcasting** builds upon the concept of **Basic Broadcasting** by allowing multiple communication points, thereby enhancing *Flexibility* in network configuration, strengthening *Security* through distributed routing, and increasing *Scalability* by supporting more nodes concurrently.

For establishing secure quantum communication channels, the decision model evaluates **Quantum Key Distribution (QKD) Protocol** through an **Inclusive Gateway**. **QKD Protocol** supports secure key exchange across quantum network nodes, thereby enhancing *Security* and *Reliability*. Its *Scalability* stems from its applicability to multi-node networks, and *Flexibility* is supported by its use in various quantum architectures. However, it may lead to reduced *Performance* due to key negotiation overhead and face *Compatibility* issues with some classical systems. Similarly, **Quantum Teleportation Protocol** is selected to enable the transfer of quantum information over long distances. It improves *Security* and *Scalability* by eliminating the need for direct quantum links between nodes and enhances *Performance* through instantaneous state transfer, although this depends on the quality of entanglement and classical signaling.

For identifying optimal Qubits-node interaction patterns and strategies, the decision model includes an **Inclusive Gateway**, which leads to the selection of **Quantum Burst Communication Pattern**. This pattern groups communication tasks for joint execution, which increases *Performance* and *Scalability* by minimizing idle time and optimizing channel use. However, it introduces greater *Latency*, *Effort*, and *Complexity* due to the coordination required for burst scheduling.

The Communication Decision Model offers a structured approach for practitioners to select communication patterns and strategies in quantum software systems, aligning system communication requirements with trade-offs among various QAs, including security, scalability, and performance.

## 4.2 Decomposition Decision Model

The Decomposition Decision Model provides structured guidance to practitioners in selecting appropriate decomposition patterns for quantum software systems. This decision model is designed to evaluate various decomposition strategies, each triggered by specific conditions and affecting distinct QAs. The decision model begins with an **Inclusive Gateway**, which triggers multiple decision paths depending on whether the system benefits more from separating quantum and classical components, adopting architectural layering, or aligning decomposition with functional or business capabilities. Table 10 lists the patterns and strategies covered by the Decomposition Decision Model (see Figure 4).

For splitting quantum and classical logic, a **Parallel Gateway** activates two concurrent paths. **Quantum-Classic Split** is selected for dividing the system into distinct quantum and classical parts. This enhances *Flexibility* and *Modularity* by isolating concerns, supports *Maintainability* and *Usability* by simplifying component responsibilities, and improves *Scalability* through parallel development. However, integration overhead may reduce *Performance*. In contrast, **Quantum Microservices** is selected for modular deployment using isolated quantum services. This increases

Table 10. Architecture patterns and strategies for decomposition

Pattern Name	Summary
Quantum-Classic Split Pattern	Split the system into quantum and classical components, enabling flexibility, modularity, and scalability. Facilitates the integration of NISQ devices and classical controllers to leverage both computation paradigms. Applied in Quantum Computing as a Service (QCaaS) and hybrid systems.
Quantum Microservices Pattern	Decompose the system into modular quantum microservices for distributed deployment. Promotes maintainability, scalability, and performance. Used in QCaaS and container-based quantum development frameworks.
Layered Architecture Pattern	Decompose the system into hierarchical layers (e.g., hardware, middleware, application), improving consistency and extensibility. Supports the layering of error correction, quantum-classical coupling, and facilitates incremental development of quantum software. Common in compiler infrastructures (e.g., XACC) and design flows.
Quantum Multi-Tier Architectural Pattern	Divide the system into multiple tiers (presentation, logic, quantum algorithms), enhancing security and scalability. Useful for hybrid quantum-classical information systems and orchestrating multiple quantum algorithms.
Recursive Containment	Structure the system as multi-layer interrelated components, promoting compatibility, modularity, and portability. Suitable for complex systems where each layer abstracts certain functionalities.
Single Responsibility Pattern	Decompose based on single functionality responsibilities, maximizing maintainability. Applied to isolate concerns and simplify unit testing in quantum-classical software modules.
Decomposed by Business Capabilities	Divide the system components based on business domains or distinct capabilities, improving performance. Facilitates aligning quantum solutions to domain-specific requirements (e.g., finance, logistics).

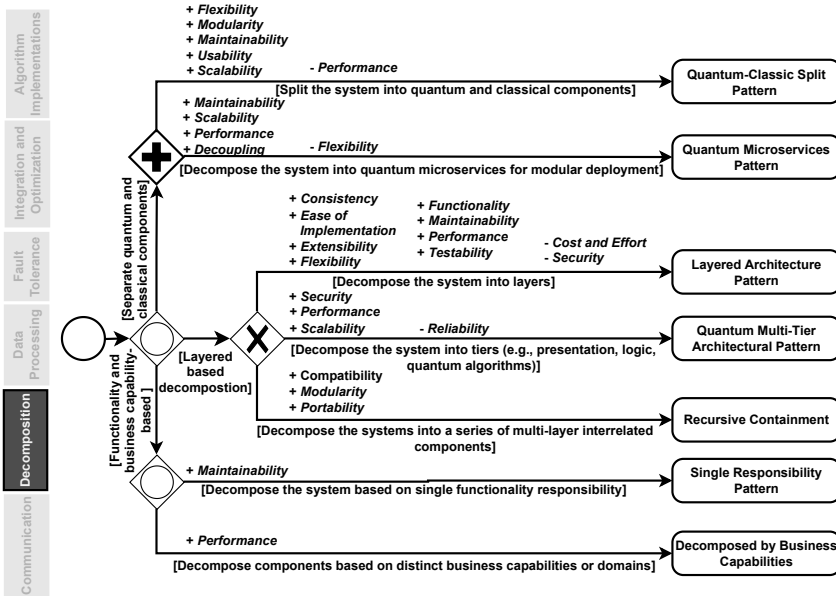


Fig. 4. Decision model for selecting architecture patterns and strategies for decomposition

*Maintainability* and *Scalability* by enabling independent service management and boosts *Performance* through parallel execution. However, it reduces *Flexibility* as interactions between tightly scoped services require predefined coordination.

For selecting layered decomposition approaches, an **Exclusive Gateway** offers three alternative paths based on system structuring needs. **Layered Architecture** is selected when the system requires separation of responsibilities into horizontal layers. This improves *Maintainability* by isolating layer-specific logic, enhances *Performance* by enabling efficient execution within each layer, and supports *Testability* through clear interface boundaries. However, it increases development effort due to the need for multiple abstraction layers and reduces *Security* as each exposed layer interface becomes a potential vulnerability. **Quantum Multi-Tier Architecture** is selected for systems that interact with diverse clients or user interfaces. It enhances *Compatibility* by decoupling presentation and logic tiers, improves *Modularity* by allowing independent updates across tiers, and supports *Portability* by adapting easily across different platforms. At the same time, it reduces *Reliability* due to increased inter-tier dependencies that complicate failure handling. **Recursive Containment** is selected for designs requiring nested structural relationships among components. This increases *Security* by encapsulating internal operations, improves *Performance* through localized processing within each nested unit, and enhances *Scalability* by allowing recursive extension of system components. However, it reduces *Reliability* as tightly coupled dependencies across nested layers make fault isolation more difficult.

Lastly, for selecting functionality or business capability-based decomposition, the process employs another **Inclusive Gateway**, enabling two alternative paths. **Single Responsibility** is selected when the system is decomposed based on singular functional responsibilities, which enhances *Maintainability* by isolating each task within a dedicated unit. Alternatively, **Decomposed by Business Capabilities** is selected when components are structured around distinct business domains, improving *Performance* by aligning processing with domain-specific logic.

The Decomposition Decision Model provides a structured approach for practitioners to select decomposition patterns and strategies in quantum software systems, aligning system decomposition needs with trade-offs across various QAs, including flexibility, scalability, maintainability, and performance.

### 4.3 Data Processing Decision Model

The Data Processing Decision Model provides a structured flow that assists practitioners in selecting appropriate architecture patterns and strategies based on data transformation needs, workload characteristics, and QAs trade-offs. It leverages gateways to guide pattern selection according to specific system conditions and quality considerations. The decision flow begins with an **Inclusive Gateway**, enabling multiple paths to proceed simultaneously. Table 11 lists the patterns and strategies covered by the Data Processing Decision Model (see Figure 5).

For multi-stage quantum data processing, **Pipe and Filter** is triggered. It enables structured data flow, supporting *Functionality* through modular processing, *Security* by isolating components, *Maintainability* due to separation of stages, and *Flexibility* for easy replacement or reordering of filters. However, it may affect *Performance* because of processing overhead. Within the same decision flow, an **Inclusive Gateway** identifies further paths. If the system requires on-demand data handling and dynamic resource allocation, **Consumer** is selected. It improves *Performance* by enabling efficient data retrieval and processing based on demand. If the goal is to isolate test logic from data, **Data-Driven Testing (DDT)** is selected. It supports *Interoperability* by allowing flexible data input formats, *Maintainability* through centralized test data, *Modularity* by decoupling test logic, and *Security* by enabling controlled test environments.

For multi-faceted quantum data handling, an **Exclusive Gateway** activates one suitable path depending on system needs. When managing data conversion, schema adaptation, and query execution across diverse quantum data sources, **Quantum Mediator Wrapper** is selected. It

Table 11. Architecture patterns and strategies for data processing

Pattern Name	Summary
Pipe and Filter Pattern	Process data through multiple sequential stages, supporting complex quantum-classical workflows with modular and scalable architecture.
Consumer Pattern	Dynamically manage quantum data and allocate resources on-demand, promoting flexibility and efficient resource utilization.
Data Driven Testing (DDT)	Separate test logic from data, enabling dynamic testing of diverse quantum states and operations for adaptability and efficiency.
Quantum Mediator Wrapper	Handle data conversion, schema adaptation, and query execution between varied quantum data sources, supporting system flexibility and scalability.
Quantum Broadcast Pattern	Distribute quantum states to multiple subsystems, enhancing flexibility and enabling parallel quantum data dissemination.
Quantum Data Encoding	Convert classical data (bits, strings, numbers) into quantum states, facilitating quantum computation readiness.
Basis Encoding Strategy	Represent classical data elements as quantum computational basis states, allowing direct quantum calculations.
Quantum Associative Memory (QuAM)	Store and retrieves collections of data elements in quantum memory structures, enabling efficient quantum-based data processing.
Amplitude Encoding Strategy	Encode data compactly using amplitudes, minimizing computational requirements for efficient quantum data representation.
Angle Encoding	Represent each data point with separate Qubits through angle encoding, enabling flexible data mapping to quantum states.
Quantum Random Access Memory (QRAM)	Provide random access to quantum data values as required by algorithms, enhancing data retrieval flexibility in quantum computations.
Measurement Pattern	Defines protocols for measuring quantum states and extracting classical data, enabling the integration of quantum outputs into classical systems.

improves *Modularity* by isolating adaptation logic from core functionalities, facilitates *Interoperability* by translating between heterogeneous data formats, and supports *Scalability* by decoupling services for easier integration of new sources. However, it may reduce *Maintainability* due to the complexity of managing adapters, impact *Performance* owing to added translation overhead, and increase *Cost* due to required middleware infrastructure. In contrast, when broadcasting quantum states to multiple subsystems, **Quantum Broadcast** is selected. It promotes *Flexibility* by enabling simultaneous state sharing with minimal coupling between receivers, allowing receivers to process data independently based on their role.

For translating classical data into quantum states, **Quantum Data Encoding** strategy is employed, contributing to *Scalability* by supporting the encoding of large and high-dimensional data across Qubits, and to *Flexibility* by enabling the use of various encoding schemes tailored to different computational needs. In another scenario, the decision flow uses an **Exclusive Gateway** to trigger one path based on specific conditions. **Basis Encoding** is selected when a straightforward mapping of classical bits to quantum states is sufficient. It enhances *Ease of Implementation* due to its simplicity and promotes *Flexibility* in data processing experiments, though it can negatively affect *Performance* and *Scalability* because its naive structure does not compress data or minimize qubit usage. In contrast, **Quantum Associative Memory (QuAM)** is selected when associative retrieval is needed in quantum computations. It boosts *Efficiency* through rapid pattern search and improves *Interoperability* by integrating different types of quantum data. However, its rigid structure may reduce *Flexibility*, and its complex architecture adds to the overall *Complexity* and implementation difficulty. Another path activates **Amplitude Encoding**, which compactly encodes classical data into amplitude values of Qubits. This enhances *Performance* and supports *Scalability* by reducing the number of Qubits required for large datasets. Yet, it often results in high *Implementation Complexity*.



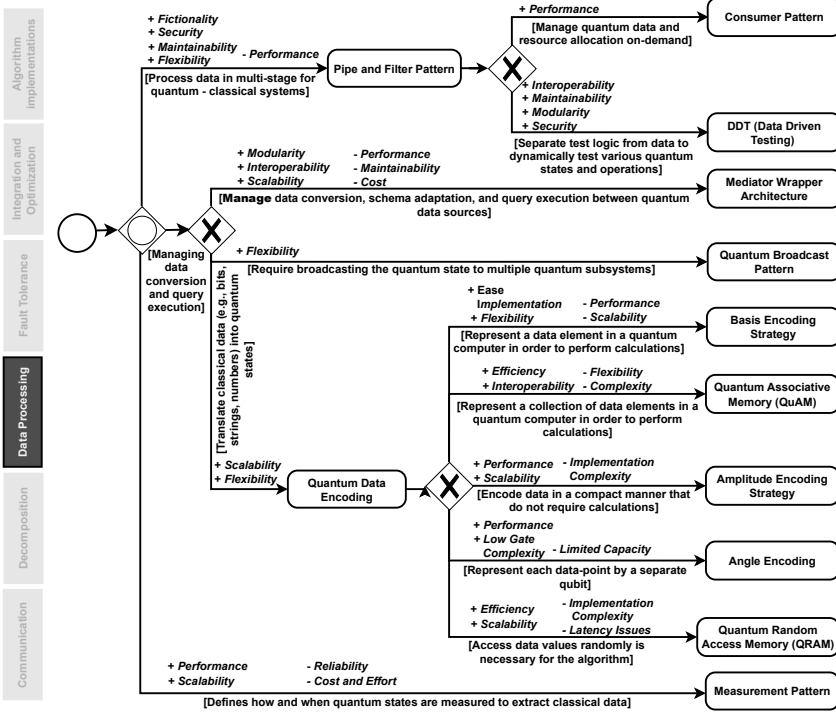


Fig. 5. Decision model for selecting architecture patterns and strategies for data processing

due to precision control during state preparation, and increased *Error* rates due to susceptibility to noise. When representing data via rotational angles is desired, **Angle Encoding** is chosen. It enables high *Performance* through minimal gate usage and contributes to *Low Gate Complexity*, but struggles with *Limited Capacity*, as representing high-dimensional data with a limited number of angles is challenging. Lastly, **Quantum Random Access Memory (QRAM)** is selected when fast, non-sequential access to quantum-stored data is required. It improves *Efficiency* by enabling parallel data access in superposition and aids *Scalability* for large datasets. However, it introduces significant *Implementation Complexity* due to the need for specialized quantum hardware and suffers from potential *Latency Issues* during quantum-classical transitions.

Finally, for tracking and interpreting quantum state collapse during execution, **Measurement** is selected. It improves *Performance* by providing clear data at defined checkpoints and supports *Scalability* by enabling concurrent state evaluation. However, it increases *Cost and Effort* due to repeated measurements and introduces risk to *Reliability* by collapsing the quantum state prematurely if not timed correctly.

The Data Processing Decision Model guides practitioners in selecting suitable architecture patterns and encoding strategies based on system-specific data needs and QA trade-offs, offering a structured decision flow that balances modularity, performance, scalability, and implementation complexity in quantum software systems.

#### 4.4 Fault Tolerance Decision Model

The Fault Tolerance Decision Model is designed to assist in selecting appropriate architectural patterns that enhance fault detection, correction, and tolerance in quantum systems. This decision

model begins with an **Inclusive Gateway**, allowing evaluation of multiple fault tolerance requirements simultaneously. Table 12 lists the patterns and strategies covered by the Fault Tolerance Decision Model (see Figure 7).

Table 12. Architecture patterns and strategies for fault tolerance

Pattern Name	Summary
Sparing Pattern	Introduce redundant components that can take over in case of a component failure, ensuring continuity during faults.
Comparison Pattern	Execute two quantum channels simultaneously and compare their outputs to identify discrepancies or inconsistencies, which can indicate potential faults in the system
Voting Pattern	Use a majority decision mechanism to detect and handle faults by comparing outputs from multiple components.
Error Correction Pattern	Dynamically detect and correct errors during the execution of quantum circuits.
Readout Error Mitigation Pattern	Reduce the impact of measurement errors on quantum computations to improve accuracy.
Gate Error Mitigation Pattern	Mitigate errors arising from noisy gate operations in quantum circuits.
Decorator Design Pattern	Dynamically integrate error mitigation into quantum algorithms to allow real-time adaptability during execution.
Quantum Patterns of Behavior (qPoB)	Provide high-level abstraction by encapsulating quantum operations mathematically, supporting complex quantum behaviors and error mitigation strategies.

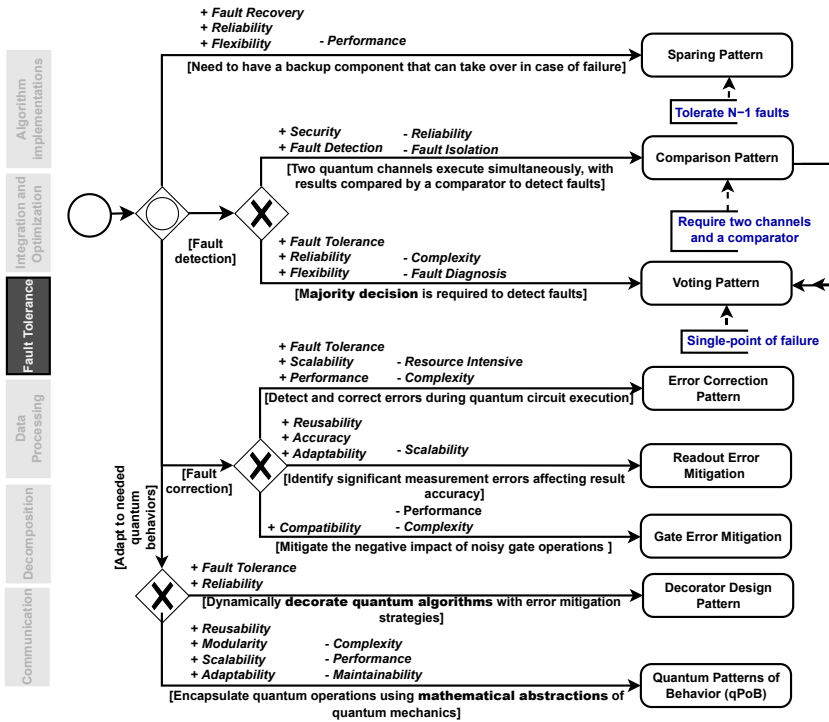


Fig. 6. Decision model for selecting architecture patterns and strategies for fault tolerance

For ensuring operational continuity during component failures, **Sparing** is selected. It introduces standby components that automatically take over when a failure occurs, thereby improving *Fault Recovery* by providing immediate redundancy, *Reliability* by reducing downtime risk, and *Flexibility* through seamless switchover. However, it may slightly reduce *Performance* due to synchronization overhead and increase *Cost* from added hardware requirements.

For fault detection, the decision model follows an **Inclusive Gateway** to explore detection mechanisms. When simultaneous execution and comparison of two quantum channels are required, **Comparison** is selected. It strengthens *Security* by identifying mismatches between channels and supports *Fault Detection* through real-time output comparison. However, synchronized operations may reduce overall *Reliability* and hinder *Fault Isolation*, as errors can propagate across dependent processes. If a system benefits from redundancy through collective decision-making, **Voting** is selected. It improves *Fault Tolerance* by using a majority rule to mask faulty results, supports *Reliability* by minimizing single-point failures, and offers *Flexibility* to adapt to various fault scenarios. Yet, maintaining multiple replicas increases *Complexity*, and tracking faults becomes harder, reducing the effectiveness of *Fault Diagnosis*. If localized backups are preferred to ensure continued operation, **Sparing** is selected. It improves *Fault Recovery* by enabling seamless switching to standby components, enhances *Reliability* through redundancy, and offers *Flexibility* in component management. However, constant monitoring and switching overhead may slightly degrade *Performance*.

For fault correction, the decision model proceeds through an **Exclusive Gateway** to explore correction mechanisms. If the system requires dynamic detection and correction of errors during quantum circuit execution, **Error Correction** is implemented. It improves *Fault Tolerance* by actively identifying and correcting errors at runtime, supports *Scalability* by ensuring the system remains reliable even as it grows in size or complexity, and boosts *Performance* by preventing failures from propagating. However, the need for additional ancilla Qubits and control logic adds significant *Complexity* to circuit design and resource management. If substantial measurement errors are detected that compromise output accuracy, **Readout Error Mitigation** is applied. It enhances *Reusability* by calibrating corrections across multiple experiments, improves *Accuracy* through statistical post-processing of erroneous measurements, and increases *Adaptability* by optimizing correction techniques for specific hardware. However, as the system size increases, the *Scalability* of the chosen error mitigation strategy may be limited due to the growing complexity of error modeling and correction matrices. Alternatively, if noisy gate operations present a major challenge, **Gate Error Mitigation** is selected. It supports *Compatibility* by aligning correction techniques with diverse quantum hardware and gate sets. Yet, it may negatively affect *Performance* because it involves repeated circuit executions or calibration, and it increases *Complexity* due to the extra layers of error modeling and compensation logic.

For dynamic adaptation to quantum behaviors, the decision model process navigates to an **Inclusive Gateway**. When the system benefits from seamlessly integrating error correction into quantum algorithms, **Decorator Design** is chosen. **Decorator Design** is chosen. It enhances *Fault Tolerance* by allowing additional behaviors (e.g., correction or validation) to be layered onto core operations without altering the algorithm itself. It also improves *Reliability* by making the system more responsive to changing fault conditions at runtime. However, using nested decorators can make execution harder to trace, increasing *Complexity* and potentially affecting debugging and testing processes. If the system requires a higher level of abstraction by encapsulating quantum operations within structured mathematical constructs, **Quantum Patterns of Behavior (qPoB)** is selected. It supports *Reusability* by enabling standardized quantum behaviors across different contexts, and enhances *Modularity* by separating high-level behavior from low-level operations. It facilitates *Scalability* by abstracting complexities and supports *Adaptability* through interchangeable

behavior compositions. On the downside, its layered abstraction can increase *Complexity*, reduce *Performance* due to interpretative overhead, and pose challenges for *Maintainability*, especially for developers unfamiliar with abstract models of quantum operations or system behaviors, which are generalized, high-level representations used to design and understand quantum systems but may lack the detail necessary for direct implementation.

The Fault Tolerance Decision Model systematically addresses fault tolerance requirements and balances QAs to recommend suitable architectural patterns and strategies for quantum software systems.

#### 4.5 Integration and Optimization Decision Model

The Integration and Optimization Decision Model for quantum software systems follows a structured decision-making process using **Gateways** to guide the selection of appropriate patterns and strategies based on specific conditions. Table 13 lists the patterns and strategies covered by the Integration and Optimization Decision Model (see Figure 7).

Table 13. Architecture patterns and strategies for integration and optimization

Pattern Name	Summary
Integration Pattern	Enable the combination of diverse quantum programming approaches into a unified software workflow.
Prototype Design Pattern	Support creating new quantum software objects by cloning existing prototypes, enabling faster development and reuse.
Quantum Broadcast Pattern	Facilitate applying the same quantum operations uniformly across multiple Qubits for synchronized execution.
Decorator Design Pattern	Allow adding new functionalities to quantum operations dynamically without altering their core structure.
Transformer Design Pattern	Convert sequences of quantum operations into batch processes to support parallel execution strategies.
Quantum Service-Oriented Architecture Pattern	Structure quantum tasks as independent services with defined interfaces, promoting modular and service-based integration.
Quantum Service Registry	Centralize the cataloging and discovery of quantum services, resources, and algorithms to simplify integration.
Bring Your Own Container (BYOC) Pattern	Allow packaging quantum services and custom libraries into isolated, reusable containers for flexible deployment.
Quantum Load Balancing Pattern	Distribute quantum computational tasks dynamically across multiple providers or systems to optimize resource usage.

For selecting patterns and strategies that address the integration of diverse quantum programming models, this decision model begins with an **Inclusive Gateway** that offers parallel paths for addressing different concerns. If seamless coordination of hybrid components is required, **Integration** is selected. It enhances *Performance* by reducing overhead in inter-component communication and supports *Testability* by establishing well-defined interface boundaries between classical and quantum parts.

For selecting patterns and strategies when quantum process optimization is the focus, the decision flow proceeds through an **Exclusive Gateway** that activates a specific strategy based on optimization needs. If creating new configurations by replicating existing templates is beneficial, **Prototype Design** is applied. It supports *Extensibility* by allowing reuse of established structures, improves *Scalability* through quick duplication of logic, and enhances *Testability* by enabling controlled variation of object states. However, it may reduce *Compatibility* when reused prototypes do not align with hardware constraints, and compromise *Security* if sensitive logic is copied without isolation. If uniform execution of quantum operations across multiple Qubits is required, **Quantum**

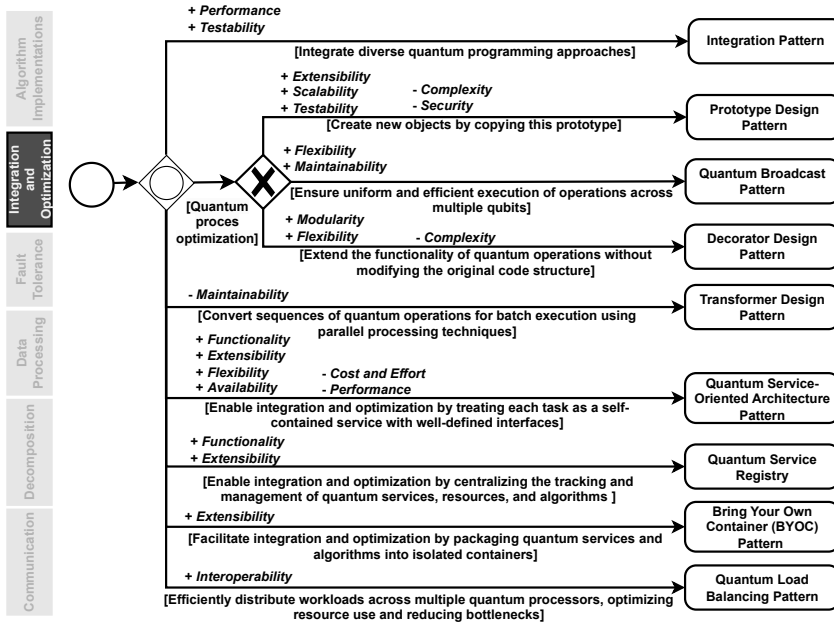


Fig. 7. Decision model for selecting architecture patterns and strategies for integration and optimization

**Broadcast** is chosen. It improves *Flexibility* by enabling synchronized updates across Qubits and supports *Maintainability* by simplifying change propagation. Yet, applying identical operations can limit precision in systems where individual Qubits need specialized handling. Alternatively, if extending functionality without altering core components is necessary, **Decorator Design** is used. It promotes *Modularity* by attaching features dynamically and enhances *Flexibility* by allowing layered behavior changes. However, it increases *Complexity* because tracking layered decorators can complicate debugging and logic tracing.

For selecting patterns and strategies that support integration and optimization in quantum software systems, the decision model returns to an **Inclusive Gateway** to evaluate system-wide needs such as modularity, service orchestration, and performance tuning. If the objective is to convert sequences of quantum operations for batch execution using parallel processing techniques, **Transformer Design Pattern** is adopted. It enables optimized transformation of gate sequences into efficient execution blocks, improving *Performance* by minimizing idle qubit cycles and circuit depth. However, the transformation logic introduces additional abstraction layers that make debugging and code adaptation harder, thereby reducing *Maintainability*. To integrate diverse quantum tasks as independently managed services, **Quantum Service-Oriented Architecture** is considered. It improves *Functionality* by allowing services to encapsulate specific logic, supports *Extensibility* through service reuse, increases *Flexibility* by enabling reconfiguration of components, and boosts *Availability* through service redundancy. However, the need for service interface definitions, orchestration, and infrastructure setup increases *Cost and Effort* and can degrade *Performance* due to communication overhead between services. To manage and orchestrate these services more efficiently, **Quantum Service Registry** is selected. It improves *Functionality* by maintaining a centralized catalog of available services, endpoints, and metadata. It also supports *Extensibility* by allowing new services to be registered and discovered dynamically, promoting modular growth of the system. If packaging services and algorithms into isolated environments is necessary for

deployment flexibility, **Bring Your Own Container (BYOC)** is adopted. It enhances *Extensibility* by allowing developers to use custom runtime environments and dependencies without system-wide conflicts. However, containerization requires additional orchestration and resource isolation mechanisms, increasing deployment *Complexity*. To distribute the computational load across multiple quantum processors, **Quantum Load Balancing** is selected. It improves *Interoperability* by enabling smooth coordination between different hardware backends and execution queues.

The Integration and Optimization Decision Model offers a structured approach for selecting architectural patterns and strategies in quantum software systems, aligning integration and optimization needs with trade-offs among key QAs, including performance, scalability, flexibility, and testability.

#### 4.6 Algorithm Implementation Decision Model

The Algorithm Implementation Decision Model is designed to guide practitioners through systematically selecting patterns and strategies for implementing quantum algorithms, ensuring that solutions align with specific project requirements and QAs. The decision model initiates with an **Inclusive Gateway**, allowing multiple paths to be explored simultaneously. Table 14 lists the patterns and strategies covered by the Algorithm Implementation Decision Model (see Figure 8).

Table 14. Architecture patterns and strategies for algorithm implementation

Pattern Name	Summary
Hybrid Module Pattern	Package both quantum and classical parts of an algorithm into a single module with control flow to manage their orchestration.
Quantum-Classic Split Pattern	Separate the execution of classical and quantum tasks into distinct components to support hybrid computation.
Classical-Quantum Interface	Provide a standardized interface that conceals quantum implementation details and converts problem-specific inputs for quantum processing.
Quantum Module Pattern	Encapsulate reusable quantum code that generates quantum circuits based on provided inputs to promote modularity.
Quantum Module Template	Define generic templates for quantum algorithm components that can be instantiated with varying inputs or submodules.
Qubit Gate Pattern	Specify the design and selection of quantum gate operations necessary for building and optimizing quantum circuits.
Brickwork Pattern	Arrange quantum operations in a grid-like structure supporting measurement-based quantum computing (MBQC).
Template-Matching Pattern	Use predefined templates to match and construct quantum algorithm components based on input patterns.
Quantum Circuit Translator	Convert quantum circuits into target programming languages and transpiles them to supported hardware instruction sets.

For selecting patterns and strategies that support seamless coordination between classical and quantum components, the decision model starts with **Hybrid Module**. It improves *Reusability* by encapsulating classical-quantum interactions in shared modules that can be reused across different applications. It supports *Scalability* by allowing independent extension of classical or quantum parts without restructuring the entire system. It also enhances *Maintainability* by separating concerns between classical and quantum components. However, managing dependencies across dual components increases *Complexity*, especially when synchronizing their execution flows. Next, an **Exclusive Gateway** directs the decision flow based on integration needs. If the goal is to distinctly divide classical and quantum responsibilities, **Quantum-Classic Split** is selected. It enhances *Modularity* by separating the logic into discrete parts, which aids in focused development. It improves *Reusability* by allowing each component to be applied independently in other contexts.



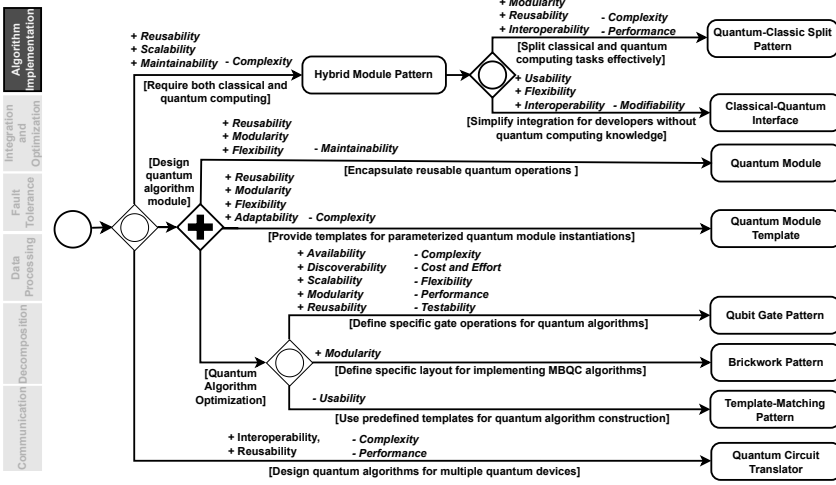


Fig. 8. Decision model for selecting architecture patterns and strategies for algorithm implementation

It also strengthens *Interoperability* by enabling integration with other systems that interact with either the quantum or classical part. However, managing communication between two isolated parts introduces *Complexity* and may reduce *Performance* due to data transfer overhead. Alternatively, if simplifying integration for developers with limited quantum expertise is a priority, **Classical-Quantum Interface** is selected. It improves *Modularity* by offering defined boundaries between classical and quantum logic. It supports *Reusability* by allowing interface components to be reused across projects with similar interaction needs. It enhances *Interoperability* by providing standard access points to quantum resources. Yet, the abstraction layers and conversion logic add *Complexity* and reduce *Performance* because of translation and coordination delays.

For selecting patterns and strategies to design quantum algorithm modules, an **Inclusive Gateway** leads to parallel optimization approaches through a **Parallel Gateway**. One path encapsulates reusable quantum operations using **Quantum Module**, which improves *Reusability* by packaging operations into isolated modules, supports *Modularity* by separating concerns across well-defined units, and promotes *Flexibility* by allowing easy substitution of operations. However, managing these modules over time may pose *Maintainability* challenges as dependencies and updates grow more complex. In parallel, **Quantum Module Template** provides parameterized blueprints for module instantiations. This improves *Reusability* by enabling consistent reuse of parameter-driven modules, enhances *Modularity* through structured construction, increases *Flexibility* by supporting variation in instantiation, and boosts *Adaptability* by allowing dynamic binding to specific use cases. Still, defining and maintaining these templates may add *Complexity* due to template hierarchies and configuration overhead. In optimizing quantum algorithms, another **Inclusive Gateway** activates additional paths. If defining fine-grained gate-level behavior is critical, **Qubit Gate** is selected. It improves *Availability* by enabling low-level customization, enhances *Discoverability* through explicit operation definitions, supports *Scalability* by aligning with fine-grained control in large systems, and benefits *Modularity* and *Reusability* through composable gate blocks. However, it introduces *Complexity* in design, increases *Cost and Effort* due to manual configuration, limits *Flexibility* in abstraction, reduces *Performance* through control overhead, and complicates *Testability* due to low-level verification needs. Alternatively, when targeting Measurement-Based Quantum Computing (MBQC), **Brickwork** is adopted. Its structured grid layout improves *Modularity* by

mapping quantum logic to a fixed computational structure that supports predictable configuration. When reusable construction is a priority, **Template-Matching** is employed. It offers predefined algorithm templates that simplify development but may reduce *Usability* due to rigid structures that limit developer control and customization.

For selecting implementation patterns and strategies when algorithms must be compatible with multiple quantum devices, the decision flow proceeds to **Quantum Circuit Translator**. This improves *Reusability* by allowing circuits to adapt across diverse backends and enhances *Interoperability* by translating device-specific representations. However, it increases *Complexity* due to the need for dynamic translation layers and reduces *Performance* through additional compilation and transformation overhead.

Through this structured decision flow of **Inclusive**, **Exclusive**, and **Parallel Gateways**, the Algorithm Implementation Decision Model systematically supports algorithm implementation by evaluating context-specific requirements and balancing key QAs — such as reusability, interoperability, modularity, and performance — to recommend suitable architectural patterns and strategies for quantum software systems.

## 5 EVALUATION

To evaluate the proposed decision models, we conducted semi-structured interviews with 16 practitioners using a standardized interview questionnaire<sup>14</sup>. The results of this evaluation are organized into two parts: (1) participant demographic and professional background, and (2) evaluation of the decision models with respect to familiarity, understandability, and correctness.

### 5.1 Participant Demographics and Professional Background

We present an overview of the demographics and professional experience of the 16 interview participants in Table 15, which provides essential context for interpreting the feedback provided on the decision models.

**Geographic Distribution:** The participants represent a geographically diverse group across three continents: Asia, Africa, and Europe. The majority are from Bangladesh 37.5% (6 participants), followed by China with 31.3% (5 participants). Other countries represented include one participant each from France, Germany, Pakistan, Saudi Arabia, and Senegal (see Figure 9 (a)).

**Experience in Software Development:** Most of the respondents (15 out of 16, 93.8%) reported having between 2-5 years (8 participants) or 6-10 years (7 participants) of experience in software development. Meanwhile, a smaller portion, representing 6.3% (1 participant), indicated having more than 10 years of software development experience. This distribution illustrates a balanced representation between early-career and mid-level professionals, with limited participation from those with long-term industry experience (see Figure 9 (b)).

**Experience in Quantum Software Development:** The majority of participants, 75.0% (12 out of 16), reported having 2 to 5 years of experience in quantum software development. This is followed by 18.8% (3 participants) who have less than one year of experience, and 6.3% (1 participant) who has over 6 years of experience. This distribution highlights a strong representation of early-career professionals actively contributing to the field of quantum software development, with a few participants bringing emerging or more advanced experience (see Figure 9 (c)).

**Professional Roles:** During the interviews, participants reported holding a variety of professional roles within their organizations, reflecting the interdisciplinary nature of the quantum software field. The most frequently mentioned role is *Researcher*, mentioned by 87.5% (14 participants). This is followed by *Developer* 25.0% (4 participants), *Physicist* 12.5% (2 participants), and

<sup>14</sup><https://tinyurl.com/bdcvzjib>

Table 15. Demographic information of the interview participants

#	Country	Software Dev. Exp	Quantum Software Dev. Exp	Professional Role	Organization Domain
P1	Bangladesh	2–5 Years	Less than 1 Year	Researcher	Quantum cryptography
P2	Bangladesh	2–5 Years	2–5 Years	Developer & Researcher	Quantum cryptography, Optimization and simulation, Education
P3	Senegal	2–5 Years	2–5 Years	Researcher	Optimization and simulation
P4	Bangladesh	2–5 Years	2–5 Years	Researcher	Quantum Software framework
P5	China	2–5 Years	Less than 1 Year	Developer	Quantum cryptography, ML/AI, Data processing
P6	Saudi Arabia	More than 10 Years	2–5 Years	Researcher	Quantum Foster generic
P7	Germany	6–10 Years	6–10 Years	Researcher	Data processing
P8	Bangladesh	2–5 Years	2–5 Years	Researcher, Project Manager	Quantum cryptography, Optimization and simulation, ML/AI
P9	China	6–10 Years	2–5 Years	Researcher	Scientific software
P10	France	6–10 Years	2–5 Years	Researcher/Developer	Scientific software
P11	Bangladesh	6–10 Years	2–5 Years	Physicist/Researcher	Scientific software
P12	Pakistan	2–5 Years	2–5 Years	Researcher	Quantum optics
P13	China	2–5 Years	2–5 Years	Researcher	Manufacturing, ML/AI
P14	Bangladesh	6–10 Years	Less than 1 Year	Physicist	Education
P15	China	6–10 Years	2–5 Years	Researcher	Education
P16	China	6–10 Years	2–5 Years	Developer, Architect and Researcher	Data processing, ML/AI, Quantum cryptography

6.3% (1 participant) each as *Project Manager* and *Architect*. Given that some participants reported involvement in multiple roles, the total percentage exceeds 100% (see Figure 9 (d)).

**Domains of Quantum Software Projects:** The participants reported involvement in various domains of quantum software projects. *Quantum Cryptography* is the most frequently mentioned area, with 31.3% (5 participants), followed by *AI/ML*, *Education*, *Optimization and Simulation*, and *Scientific Software* each mentioned by 18.8% (3 participants). Domains such as *Quantum Software Frameworks*, *Quantum Foster Generic*, *Quantum Optics*, and *Manufacturing* each mentioned 6.3% (1 participant). Given that some participants reported involvement in multiple domains, the total percentage exceeds 100% (see Figure 9 (e)).

## 5.2 Practitioner Feedback on Decision Models

We discuss below practitioners' assessments of the proposed decision models. This includes their familiarity with the patterns and strategies, the perceived understandability and ease of use, the correctness and sufficiency of the decision models in supporting architectural decisions, and suggestions for improvement. The results reflect both the strengths and areas for potential refinement across the six decision models presented in Section 4.

**Familiarity with Patterns and Strategies:** During the interviews, we asked participants whether they were familiar with the patterns and strategies used in the respective six decision models, “*Are you familiar with the patterns and strategies used in the six decision models?*”. The majority of participants reported a high level of familiarity with the architectural patterns and strategies across most of the decision models (see Figure 10). The Fault Tolerance and Communication Decision Models received the highest familiarity ratings, with 100.0% and 93.8% of participants, respectively, reporting familiarity with most or all patterns and strategies. The Algorithm Implementation

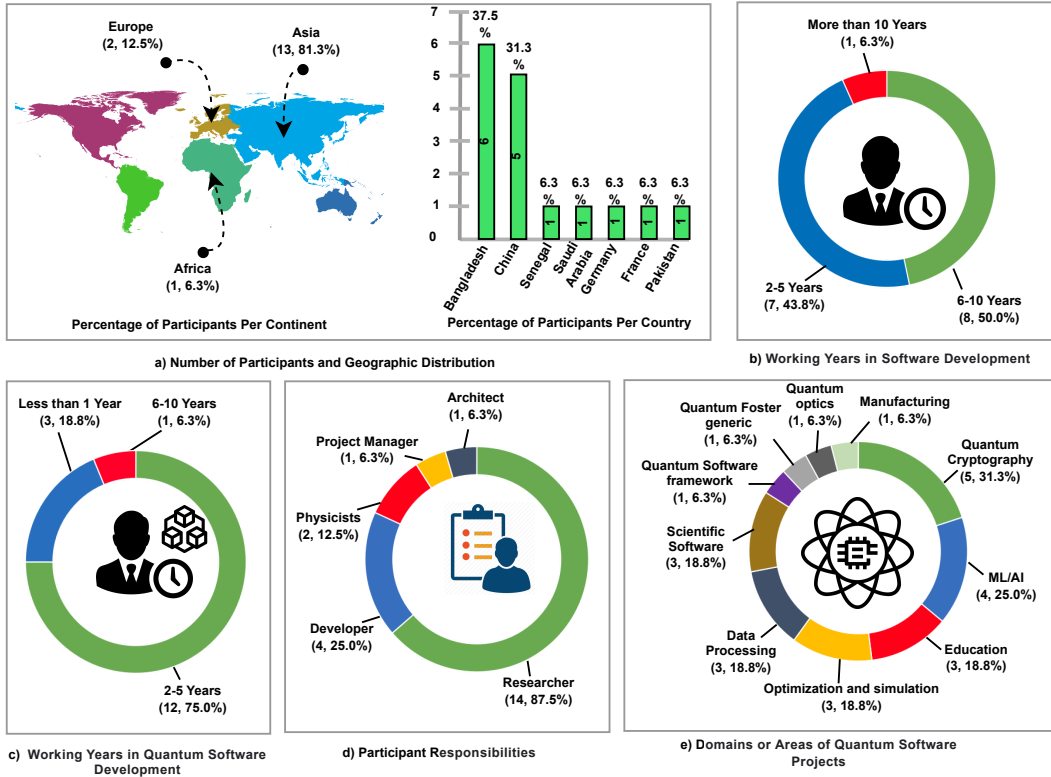


Fig. 9. Demographic details of the interview participants

Decision Model also scores highly, with 87.8% of participants reporting their familiarity with most or all patterns and strategies. For the Decomposition and Data Processing Decision Model, 81.3% of the participants were familiar with most or all patterns and strategies, while 18.7% were familiar with only a few. Similarly, for the Integration and Optimization Decision Model, 75.0% were familiar with most or all patterns and strategies, while 25.0% were familiar with only a few patterns and strategies.

**Understandability of Decision Models:** To assess the understandability of each decision model, interviewees were asked whether the decision model was easy to understand and use, “*To what extent are the six decision models easy to understand and use?*”. Overall, the majority of participants rated the decision models as either *Easy* or *Very easy*, indicating that the proposed decision models exhibit a clear and intuitive structure (see Figure 10). The Data Processing, Fault Tolerance, and Algorithm Implementation decision models received the most favorable feedback, with 100.0% of participants rating those decision models as either *Easy* or *Very easy*. Similarly, the Communication, Decomposition, and Integration and Optimization decision models also received positive feedback, with 93.7% of participants rating those decision models as either *Easy* or *Very easy*. In general, all decision models were well-received, with the majority of participants finding them either *Easy* or *Very easy* to understand.

**Correctness of Decision Models:** To assess the sufficiency of the proposed decision models, we asked participants whether each decision model sufficiently supports architecture decision-making,

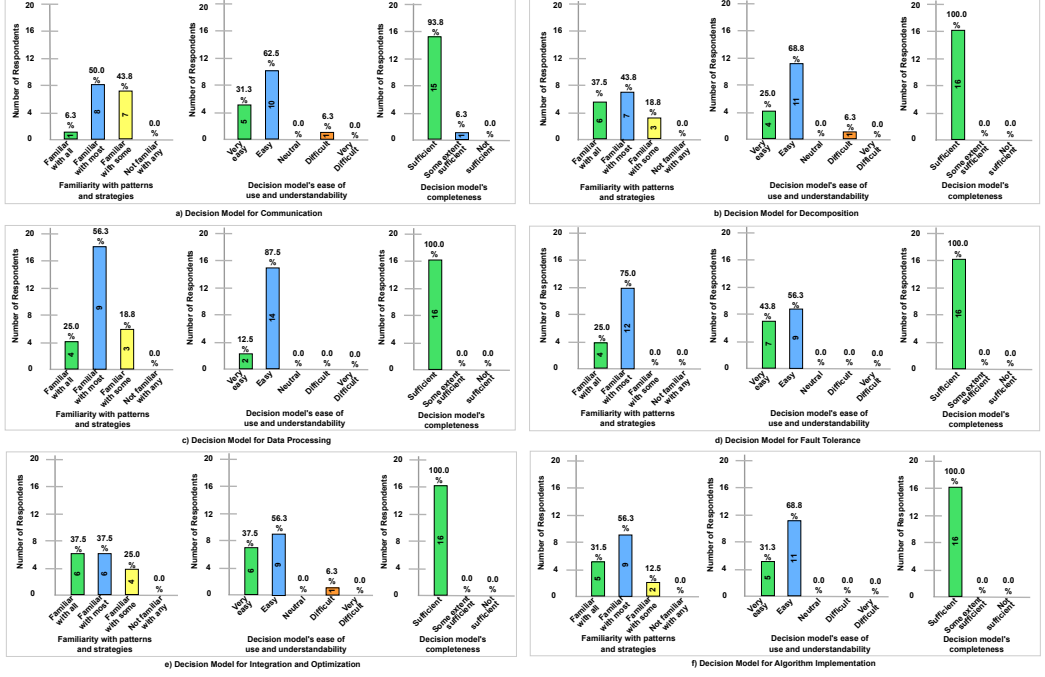


Fig. 10. Overview of practitioners' responses for familiarity, understandability, and completeness of the decision models

"Does the information in the decision models (e.g., Communication, Decomposition, Data Processing, Fault Tolerance, Integration and Optimization, and Algorithm Implementation) sufficiently support making architecture decisions about quantum software systems?" The responses indicate that all six models were perceived mainly as sufficient by the interviewees (see Figure 10). For instance, in the case of the communication decision model, 15 participants (93.8%) reported that the decision model sufficiently supports decision-making, while 1 participant (6.3%) stated that it is sufficient to some extent. For the decomposition, data processing, fault tolerance, integration, optimization, and algorithm implementation decision models, all 16 participants agreed that the models are sufficient for guiding architecture decisions. This strong consensus across all models suggests that the proposed decision models are generally perceived as correct and reliable in supporting architectural choices within quantum software systems.

**Suggestions for Improving Decision Models:** We asked the participants to offer suggestions for improving the decision models, "What are your suggestions to improve the decision models?". Most participants believed that the decision models are sufficient for guiding the architecture design of quantum software systems, particularly in selecting appropriate architectural patterns and strategies. They attributed this effectiveness to several factors: the presence of constraints on patterns, the necessary conditions that these patterns must fulfill, the trade-offs concerning QAs, and the influence of both patterns and strategies on these QAs. For instance, P13 mentioned that "Yes, I believe all the models are very effective — especially for guiding optimization. These models will be highly useful in practical quantum computing projects". Finally, participants also provided several suggestions. These include presenting patterns with code, measuring quantitative values for QAs, and using decision models in industrial quantum software projects. These suggestions

address issues such as missing conditions, unclear *complement* relations, duplicate patterns and strategies, bidirectional influence, and incorrect impact of patterns on QAs. We fixed these issues in the updated version of the decision models. For instance, one participant (P2) suggested that *“Providing a more detailed breakdown of potential trade-offs for each pattern could help users better understand their impact on performance, system stability, and resource utilization”*.

Practitioners generally found the decision models useful, with the Communication and Fault Tolerance models receiving the highest ratings for *clarity* and *ease of use*. However, decision models like Decomposition, Integration, and Optimization were seen as needing refinement, particularly in adapting to hardware constraints. Suggestions for improvement include clearer trade-off analysis and AI-based optimizations. These insights highlight the need for future research to enhance the adaptability and context-awareness of decision models, ensuring that they better support evolving quantum systems.

## 6 DISCUSSION

**Decisions related to communication design must account for hardware constraints and evolving protocols:** The evaluation of the Communication Decision Model reveals its strong applicability in supporting architecture-level decisions in quantum software systems, particularly by providing structured guidance through reusable patterns such as Entanglement-Assisted Channels, Quantum API Gateways, and Workflow Orchestration. The majority of practitioners agreed that this decision model enhances modularity and scalability in quantum software design. One interviewee (P11) explained that the model *“provides a structured framework for selecting communication patterns, making architectural decisions more informed, consistent, and optimized”*. Another participant (P6) stated that *“it clearly outlines trade-offs — performance, scalability, security, and complexity — helping balance system constraints”*. These observations suggest that this decision model has practical value in guiding early design decisions. However, despite these strengths, several practitioners pointed out a crucial limitation: the current decision model does not fully account for the variability and constraints of quantum hardware. For instance, a participant (P13) emphasized that *“as hardware implementations vary, the communication model must evolve or adapt to meet the specific requirements and constraints of each platform”*. Practitioners also raised concerns about the absence of universally applicable communication protocols, particularly in hybrid quantum–classical systems, where coherence and fidelity can be compromised. This highlights a significant challenge: *quantum communication patterns are not one-size-fits-all*. As systems become increasingly complex and distributed, the need for context-aware communication strategies that take into account the underlying hardware becomes critical. This presents an important opportunity for future research, which can focus on extending communication decision models with adaptive logic that incorporates quantum hardware specifications (e.g., topology, qubit fidelity, decoherence rate). Future research could explore how to formalize such context-awareness through constraint-based decision models or learning-enhanced decision support. For practitioners, the takeaway is that applying communication strategies without considering hardware-specific factors can lead to inefficiencies or incompatibilities in system performance. Therefore, practitioners are encouraged to view communication patterns as flexible blueprints rather than fixed recipes, customizing them in light of e.g., system characteristics, hardware constraints, and evolving demands for quantum–classical integration.

**Decomposition patterns must enable hardware-awareness and scalable modularity in hybrid quantum systems:** The Decomposition Decision Model was widely perceived as useful for guiding architectural decisions in quantum software systems, particularly in scenarios where hybrid quantum–classical integration is prevalent. Many practitioners emphasized that while decomposition is a well-known concept in classical software engineering, quantum decomposition requires



unique considerations due to the nascent and hardware-sensitive nature of quantum systems. For example, one participant (P1) noted, “*quantum computing is highly sophisticated and complex, which makes a one-size-fits-all decomposition approach insufficient ... We need to tailor decomposition techniques to specific tasks such as algorithm implementation or fault tolerance*”. Others highlighted that, just as classical systems evolve from monolithic to microservices-based architectures, quantum software will inevitably require structured decomposition to ensure scalability, flexibility, and maintainability. Interestingly, several participants emphasized that decomposition patterns, such as Quantum-Classical Split and Quantum Microservices, already facilitate modular development and smoother interaction between classical and quantum layers — an essential requirement for current hybrid architectures. A participant (P10) explained that “*since most quantum applications today still rely on classical-quantum hybrid systems, decomposition is essential to ensure smooth interaction between components*”. This aligns with a common theme across interviews: decomposition decisions must be hardware-aware. As one participant (P4) pointed out, “*If any type of hardware has any kind of issue with the decomposition process, that will create problems when implementing algorithms on that hardware*”. This suggests that decomposition in quantum systems is not only about logical separation, but also about compatibility with physical constraints — e.g., connectivity, qubit coherence, and gate fidelity. While the decision model was largely rated as sufficient and easy to understand by most participants (68.8% *Easy*; 25.0% *Very easy*), several suggestions were raised to enhance its applicability. Participants suggested various approaches, including a cost-benefit analysis framework to weigh trade-offs between system complexity, resource consumption, and latency. Others recommended integrating an evaluation module with the Decomposition Decision Model that assesses the compatibility of decomposition patterns and strategies with available hardware resources and performance capabilities, including factors such as resource allocation, hardware availability, and operational efficiency. Additional suggestions include incorporating adaptive decomposition capabilities or using AI-based optimization to dynamically refine decomposition strategies. For researchers, this signals an opportunity to refine decomposition decision models by introducing context-awareness, specifically adapting the models to quantum hardware constraints (e.g., qubit connectivity, coherence times) and system performance conditions (e.g., real-time computational resource usage, latency) that vary depending on the quantum environment. Future work can also explore formal validation frameworks or AI-assisted architecture search techniques to automate the decomposition planning process. For practitioners, the decision model encourages a more structured approach to modularizing quantum systems, moving away from ad hoc, hardware-agnostic decisions. Practitioners are advised to tailor decomposition strategies to their specific quantum hardware capabilities and operational goals, particularly as system scale, error rates, and algorithmic complexity increase. Finally, while the Decomposition Decision Model provides a valuable framework for modular architecture design, its future evolution hinges on its ability to adapt to quantum-specific constraints. Making it hardware-aware, cost-sensitive, and dynamically tunable will significantly improve its utility for both researchers and practitioners building the next generation of quantum software systems.

**Quantum data processing requires structured and scalable handling of classical-quantum transitions:** The evaluation of the Data Processing Decision Model highlights its effectiveness in supporting architectural decision-making for managing the transition between classical and quantum data, a task fundamental to quantum software design. With 100.0% of the participants rating the Data Processing Decision Model as *Easy* or *Very easy* to understand and all 16 participants confirming its sufficiency in guiding architecture decisions, this decision model demonstrates a clear advantage in clarity and practical applicability. Participants particularly appreciated the structured flow and the inclusion of well-established patterns such as the Pipe-and-Filter Pattern, Quantum Data Encoding, and the Consumer Pattern, which enable the construction of scalable data pipelines

and reduce computational load. As one participant (P5) explained in detail: “*The Quantum Data Processing Decision Model is highly useful. It supports decision-making by incorporating patterns like the Pipe and Filter Pattern and the Quantum Data Encoding Pattern, which enhance scalability and flexibility — enabling quantum software to adapt to growing data processing demands*”. Likewise, another participant (P10) explained: “*The model provides a clear structural flow for handling quantum data. The processing steps are well-defined and systematic. For example, the use of the Consumer Pattern allows for on-demand quantum data management, which helps optimize resource allocation and improve overall system performance*”. These insights confirm the model’s practical relevance in guiding pattern selection during architectural design. However, several interviewees also highlighted opportunities for improvement, particularly in supporting real-world applicability and adaptability. One participant (P2) suggested that the decision model should include “*more examples — specifically, for each pattern, demonstrating how it performs or fails in real-world applications*”. Another participant (P8) proposed that “*I suggest adding a benchmarking framework to compare data processing patterns based on their efficiency*”, which would assist practitioners in selecting the most effective strategy according to their context. Additionally, a participant (P12) noted that “*I would suggest integrating artificial intelligence. In my view, quantum computing and AI are the leading technologies of this era, and combining them will be very impactful*” and another participant (P16) recommended “*to enhance the (decision) model, it could be designed to accommodate multi-bit architectures and distributed quantum computing systems*”. For researchers, these insights emphasize the need for adaptive and empirically validated extensions to data processing decision models that reflect evolving hardware and software contexts. For practitioners, the takeaway is that while the current Data Processing Decision Model offers valuable scaffolding for architectural thinking, future enhancements should incorporate operational metrics and context-aware data processing recommendations. The ultimate goal is to ensure the decision model remains relevant, usable, and impactful as quantum data processing challenges grow in scale and complexity.

**Researchers should advance multi-level fault correction techniques, while practitioners need layered, runtime-aware mechanisms for resilient quantum software systems:** The Fault Tolerance Decision Model plays a central role in guiding quantum software engineers to mitigate quantum-specific risks such as decoherence, error propagation, and gate instability. Practitioners widely endorsed the clarity and relevance of the decision model, with 100.0% of interviewees finding it sufficient to support architectural decisions. One participant (P5) emphasized that “*the Decorator Design Pattern enables real-time error handling by allowing quantum algorithms to dynamically adapt fault-tolerant strategies based on runtime conditions*”. Likewise, another participant (P8) highlighted the model’s contribution to resilient quantum architectures by stating that “*it promotes best practices by evaluating fault governance against performance and resource utilization*”. Yet, the interviews also revealed evolving demands for layered decision-making that reflect the operational complexity of quantum systems. Several participants, such as P9, recommended hierarchical fault abstraction, “*One suggestion would be to enhance the model by categorizing fault tolerance into multiple levels (e.g., hardware level, gate level, circuit level, and algorithm level). This layered classification could make the model more comprehensive and easier to apply in different contexts*”. This suggestion aligns with the unique error models in quantum computing, where fault propagation dynamics differ significantly from those in classical systems. For researchers, these findings highlight a pressing need to develop adaptive and modular fault tolerance frameworks that evolve in tandem with quantum hardware. This includes defining a taxonomy of fault categories, embedding predictive analytics into decision models, and exploring automated reasoning tools that can recommend suitable patterns for emerging error types. Researchers should also investigate cross-layer coordination techniques to ensure that fault mitigation is consistent from the hardware abstraction layer up to algorithm execution. For practitioners, fault tolerance must be treated as a

first-class architectural concern. The adoption of layered, runtime-aware fault handling, such as using Sparing, Voting, and Gate Replacement patterns, should be grounded in the specific operational conditions of the target platform. Moreover, practitioners are encouraged to establish validation pipelines that include error injection, resilience testing, and resource profiling to ensure that fault tolerance is not only designed but empirically verified throughout the lifecycle of quantum software. The Fault Tolerance Decision Model provides a structured approach for using and combining fault tolerance patterns and strategies. This approach ensures that error handling is effectively designed and integrated into quantum software systems. However, as quantum systems grow in complexity, both research innovation and practitioner discipline will be necessary to ensure resilient, scalable, and high-performing quantum software systems.

**Researchers should refine integration methods and modularize optimization strategies, while practitioners should adopt adaptable, service-oriented patterns to build scalable quantum systems:** The Integration and Optimization Decision Model was broadly regarded by practitioners as a highly valuable resource for guiding both design and architectural evaluation in quantum software systems. Across the 16 interviews, practitioners consistently praised the model's structured approach in supporting the selection of suitable patterns, such as Quantum Load Balancing Pattern, Quantum Transformer, Prototype Design Pattern, and Quantum Service Registry, for ensuring system adaptability, resource efficiency, and interoperability across hybrid infrastructures. One participant (P5), for example, highlighted that *"the Quantum Load Balancing Pattern ensures efficient workload distribution, preventing bottlenecks and optimizing computational resources across multiple quantum processors"*. Similarly, another participant (P9) emphasized the model's utility in *"optimizing execution time and resource allocation, ultimately leading to better performance"*. However, some interviewees noted that the decision model could further improve its practical applicability by offering clearer guidance on pattern prioritization and trade-off analysis. Specifically, one participant (P6) pointed out, *"The model could be improved by providing more explanation for different problem types — particularly optimization problems. For instance, how constraints are handled should be clearly defined"*. This indicates a need for the decision model to address not just pattern selection, but also the evaluation of trade-offs in integration and optimization decisions, especially as quantum applications scale and face increasingly complex operational environments. For researchers, this opens a significant opportunity to advance the current decision model by incorporating quantitative trade-off evaluation frameworks, constraint-handling techniques, and architecture decision-support mechanisms. Future studies could formalize integration strategies using performance models, sensitivity analysis, and hybrid AI-optimization methods to recommend context-specific patterns based on system goals, such as latency, scalability, and energy usage. In addition, modular representations of integration-optimization pipelines — especially for multi-qubit orchestration and classical-quantum bridging — could increase generalizability across evolving quantum software ecosystems. For practitioners, the findings reinforce the importance of modularity and service-oriented integration in QSE. As one participant (P8) noted, *"the Quantum Service Registry supports centralized tracking and management of quantum services, enhancing interoperability across platforms"*. Practitioners should prioritize patterns that support scalable integration, composability, and ease of future extension. Leveraging well-structured patterns such as Integration Pattern, Service-Oriented Architecture, and BYOC (Bring Your Own Container) can help teams avoid ad hoc architecture decisions, mitigate integration risk, and better prepare for evolving hardware and software toolchains. Moreover, adopting modular, loosely coupled architectures supports the deployment of optimized workflows, especially in distributed quantum environments. While the Integration and Optimization Decision Model is already perceived as sufficient and beneficial, it could evolve into a more powerful tool with enhancements that support trade-off awareness and dynamic adaptability. Researchers should focus on embedding system-level intelligence into the

decision model, while practitioners are encouraged to adopt modular, service-driven approaches that align with the rapid evolution of quantum technologies and standards.

**Researchers should explore algorithm adaptation and modular integration techniques, while practitioners need reusable components for scalable quantum development:** The Algorithm Implementation Decision Model was widely acknowledged by practitioners as essential for navigating architectural complexity in quantum software systems. It supports a range of architectural patterns such as Quantum Module Templates, Qubit Gate Patterns, and Classical–Quantum Interface Patterns — each aimed at facilitating efficient algorithm design and deployment. All participants (100.0%) found the decision model either *Easy* or *Very easy* to understand, and all agreed on its correctness and sufficiency to guide implementation decisions. One participant (P5) noted that “*the model facilitates performance-based decision-making through the use of Qubit Gate Patterns and Brickwork Patterns, allowing developers to balance efficiency, flexibility, and cost*”. This reflects a strong alignment between the decision model and real-world demands for performance optimization, hardware abstraction, and architectural flexibility. In particular, many practitioners emphasized the role of the decision model in promoting modularity and reusability, which are critical for building scalable quantum applications. As another participant (P10) observed: “*Patterns such as the Quantum Module and Quantum Module Template promote reusability, modularity, and maintainability. They help make quantum software more adaptable and efficient*”. Other participants, such as P9, pointed out that “*the Quantum Circuit Translator ensures that algorithms can be adapted for cross-device compatibility, allowing architectures to remain flexible across different quantum hardware platforms*”. For instance, the inclusion of the Quantum Circuit Translator pattern was seen as vital for achieving cross-device portability and reducing hardware lock-in, a key concern in a rapidly evolving ecosystem. Despite the strengths of this decision model, participants provided valuable insights into areas for improvement. One commonly cited suggestion was the need to provide clearer trade-off analysis for each implementation pattern. As a participant (P2) proposed, “*providing a more detailed breakdown of potential trade-offs for each pattern could help users better understand their impact on performance, system stability, and resource utilization*”. Furthermore, as quantum systems increasingly involve hybrid architectures, practitioners highlighted the importance of expanding support for classical-quantum coordination patterns. One participant (P6) emphasized, “*In our case, we’ve used the Classical–Quantum Interface pattern, particularly in quantum machine learning. This model supports hybrid algorithm implementation effectively*”. For researchers, these insights suggest the need to further formalize and empirically validate trade-off considerations in algorithm implementation decisions. This includes developing tooling or model extensions that integrate cost-performance metrics, usability constraints, and system fidelity considerations. Additionally, researchers should investigate how adaptive implementation strategies, such as AI-assisted selection of algorithmic patterns, can support runtime flexibility in emerging quantum-classical hybrid systems. For practitioners, the key takeaway is the value of implementing modular, reusable algorithm components that can evolve with system complexity and hardware transitions. Practitioners are encouraged to adopt the decision model not as a static guide, but as a living framework — flexible enough to support experimentation, benchmarking, and the layering of advanced strategies such as template matching, circuit translation, and hybrid orchestration. In summary, the Algorithm Implementation Decision Model provides a robust foundation for guiding architectural choices; however, its long-term effectiveness depends on continued adaptation to algorithmic complexity, cross-platform compatibility, and the emergence of hybrid quantum-classical computing workflows.

## 7 THREATS TO VALIDITY

### 7.1 Construct Validity

In the context of our research on decision models for selecting architecture patterns and strategies in quantum software systems, construct validity refers to the degree to which the study accurately captures and operationalizes its intended theoretical concepts, namely quantum software architecture patterns, decision-making strategies, and their influence on QAs. Ensuring strong construct validity is essential, as it underpins the credibility, generalizability, and real-world applicability of our findings. To enhance construct validity, we adopted multiple methodological safeguards:

- 1) *Pilot Search for Terminological Precision*: Before initiating formal data collection, we conducted a pilot search to assess the relevance and appropriateness of the search terms associated with quantum software architecture patterns strategies. This preliminary step allowed us to refine the search strings, ensuring that the terms used aligned with the key theoretical concepts of the study. Specifically, the architecture patterns and decision-making strategies used in quantum software systems. As a result, we maximized the retrieval of conceptually relevant studies and minimized the noise in the dataset.
- 2) *Methodological Triangulation*: To mitigate bias that may arise from relying on a single data source or method, we employed a mixed-methods approach. Quantitative insights were derived from semi-structured interviews with 16 quantum software practitioners across 7 countries and 3 continents, focusing on the perceived familiarity, understandability, completeness, and usefulness of the decision models. In parallel, qualitative data were systematically mined and thematically analyzed from community-driven repositories such as GitHub and Stack Exchange. To mitigate bias that may arise from relying on a single data source or method, we employed a mixed-methods approach. Quantitative insights were derived from semi-structured interviews with 16 quantum software practitioners across 7 countries and 3 continents, focusing on the perceived familiarity, understandability, completeness, and usefulness of the decision models. In parallel, qualitative data were systematically mined and thematically analyzed from community-driven repositories such as GitHub and Stack Exchange. This methodological triangulation strengthened the internal consistency of the concepts (i.e., the architecture patterns, decision-making strategies, and their associated quality attributes) and allowed us to validate emergent themes across independent sources. By combining rigorous terminological refinement with diverse data sources and analytical techniques, our study ensures that the concepts—which represent the key elements we aim to measure, such as patterns, strategies, and their impact on quality attributes—are not only theoretically sound but also empirically grounded. This contributes to the robustness of our conclusions and supports the applicability of the proposed decision models in real-world quantum software engineering practices. This methodological triangulation strengthened the internal consistency of the constructs — specifically, the key theoretical concepts related to the selection of architecture patterns, strategies, and their associated QAs in quantum software systems. This contributes to the robustness of our conclusions and supports the applicability of the proposed decision models in real-world QSE practices.
- 3) *Selection Bias*: A potential threat to construct validity stems from the bias in selecting and interpreting data used to build the decision models. Our decision models were derived from a combination of mining publicly available repositories (i.e., GitHub and Stack Exchange) and an SLR. Although these sources offer both practical insights into real-world use and academic research on the patterns and strategies, they may not reflect the full spectrum of quantum software development practices. To mitigate this threat, we explicitly asked practitioners during the interviews to comment on whether any important patterns or strategies had been missed. Their feedback helped validate the comprehensiveness of our collected patterns and strategies.

## 7.2 Internal Validity

Ensuring the internal validity of our research is critical, particularly when developing decision models that support the selection of architecture patterns and strategies in quantum software systems. We identified the following potential threats to internal validity: *Correctness of Decision Models*: A potential threat lies in the correctness and accuracy of the developed decision models. To address this, we adopted a collaborative approach among the authors and incorporated practitioner feedback. Specifically, the first four authors conducted the initial identification of architecture patterns, strategies, and their associated QAs (Stage 1), while others focused on modeling and cross-validating the decision models to ensure internal consistency and alignment with the extracted data (Stage 2) (see Figure 1). We also included illustrative examples and constraints to clarify usage contexts and minimize misinterpretation. Moreover, the decision models were refined and validated based on the feedback obtained from the semi-structured interviews with practitioners to ensure practical relevance and clarity. *Evaluation Effect*: Another potential threat involves misinterpretation of the decision models or evaluation criteria by interview participants. Misunderstandings regarding the study's purpose, the terminology used, or the models' structure could affect the quality of the feedback. To mitigate this threat, we provided participants with detailed explanations of the research objectives, terminology, model structure, and rationale, as well as clear instructions for the interview process. This helped ensure that their feedback was informed, accurate, and contextually grounded.

## 7.3 External Validity

The external validity of this study, which focuses on the decision models for quantum software systems, may be influenced by the degree to which the findings can be generalized beyond the specific contexts and participants involved. A primary concern lies in the limited scope of practitioner validation. While the proposed decision models were evaluated through semi-structured interviews with 16 quantum software practitioners from 7 countries across 3 continents, the relatively small sample size may constrain the generalizability of the results. To mitigate this limitation, we intentionally sought diversity across geographic regions, years of professional experience, organizational roles, and application domains (see Figure 9). Despite the modest number of participants, their qualitative feedback played a crucial role in refining the decision models, ensuring that these models addressed practical concerns in real-world QSE. Despite the modest number of participants, their qualitative feedback played a crucial role in refining the decision models and ensuring that these decision models addressed practical concerns in real-world QSE. Practitioners assessed the decision models based on their familiarity, understandability, completeness, and usefulness in realistic quantum software development scenarios. However, the reliance on subjective evaluations introduces potential bias, particularly if the participants' experiences, while diverse, do not fully represent all possible contexts in which the decision models may be applied. To strengthen the external validity and general applicability of the proposed models, it is necessary to further validate them across a broader range of real-world scenarios in quantum software systems.

## 7.4 Conclusion Validity

Conclusion validity concerns the extent to which the conclusions drawn from the analysis are credible and accurately reflect the collected data. To strengthen the validity of our study's conclusions, we employed a rigorous multi-stage research methodology grounded in established empirical software engineering practices (e.g., [33], [22], [58]). Our decision models were developed using data derived from a systematic literature review and a mining study of real-world quantum software projects and discussions. To evaluate the reliability and practical relevance of these decision models,

we conducted semi-structured interviews with 16 quantum software practitioners from seven countries, spanning diverse roles and domains. These interviews assessed the decision models in terms of familiarity, understandability, completeness, and usefulness. Finally, to support transparency, reproducibility, and future research, we provided a publicly available replication package [6] that includes all the datasets, analysis artifacts, and interview materials of this study.

## 8 CONCLUSIONS

This study proposes a set of six decision models that integrate architectural patterns, strategies, and Quality Attributes (QAs) to guide quantum software architects and developers in the architecture design of quantum systems. These decision models are constructed based on the data collected from both a mining study of GitHub and Stack Exchange and an SLR, addressing key design challenges in six vital areas: Communication, Decomposition, Data Processing, Fault Tolerance, Integration and Optimization, and Algorithm Implementation. To validate their practical relevance, we conducted semi-structured interviews with 16 practitioners on quantum software development. The proposed decision models demonstrate strong applicability in guiding architecture-centric development for quantum software systems and provide a structured approach to select reusable patterns and strategies based on quality criteria (e.g., maintainability, performance, and modularity), addressing the complexity and abstraction inherent in quantum-classical hybrid environments. To evaluate the practicality and usability of these decision models, we assessed them across three key dimensions: practitioner familiarity, understandability, and perceived correctness. The findings suggest that the decision models offer substantial practical value and can effectively support both novice and experienced practitioners in architecting and evolving quantum software systems. For researchers, the high ratings in familiarity with the patterns and strategies and understandability provide a strong foundation for further extending these decision models with formal methods, tooling support, and domain-specific adaptations. For practitioners, the decision models serve as a reliable reference to structure architectural thinking, improve design quality, and ensure consistency when dealing with the complexities of quantum-classical integration.

In the next step, we plan to expand and refine the decision models to further support the architectural design of quantum software systems in both academic and industrial environments. Building upon this groundwork, our future research will focus on several key directions: (1) Expanding the empirical validation by creating an open-access repository, where we will systematically document detailed mappings between the architectural patterns, strategies, QAs, and design constraints, supported by large-scale industrial and longitudinal case studies; (2) Developing a human-centric recommendation system that integrates contextual metadata (e.g., system requirements, performance metrics, and environmental factors) and AI-driven reasoning to provide adaptive, explainable guidance for pattern selection in quantum software system development; (3) Integration with quantum design tools such as Qiskit, PennyLane, and Cirq, embedding architecture decision-making support directly into the developer workflow. This could include leveraging existing tools like the Quantum Architecture Description Language (QADL), which facilitates architecture-driven development of quantum software systems by offering a graphical interface, syntactical parsing, and integration with platforms like IBM Qiskit, as demonstrated by Waseem *et al.* [60]; and (4) Extension to domain-specific applications, including quantum cryptography, machine learning, and simulation, where domain-specific decision-models will address unique architectural challenges like latency sensitivity and data handling.

## DATA AVAILABILITY

The dataset of this work has been made available at [6].



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