A TOGAF® ADM Perspective on Integrating Quantum Computing in Enterprises

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Abstract

Quantum Computing (QC) has undeniable potential in having a new approach to problem solving at an unrivalled speed compared to classic computers. However, in implementing QC, companies need to carefully plan the changes to its enterprise architecture to minimise the risk of failure in QC investment. In order to realise QC business value through its implementation, it is identified that TOGAF® Architecture Development Method (ADM)would be a suitable enterprise architecture framework due to its completeness and flexibility. Nevertheless, although TOGAF® ADM could provide the baseline framework to guide enterprise architecture development, it needs to be supplemented with further considerations to address the unique challenges presented by QC implementation. Thus, this paper further explores specific aspects in each phase of TOGAF® ADM for enterprises to consider tailored to the unique nature of QC and its current research development. This study identified 20 further considerations corresponding to the 10 phases indicated in TOGAF® ADM, related to specific guidelines that enterprises could directly use while addressing the complexity and generic nature of the framework. Furthermore, the research result will contribute to the evolving knowledge of the enterprise architecture role and its adaption for emerging technology implementation, specifically in QC.

***Keywords**: Quantum Computing (QC), TOGAF® ADM, Enterprise Architecture (EA), Integrating emerging technology.*

1. Introduction

1.1. Background

Industries are gradually adopting Quantum Computing (QC) as applications and use cases in various industries emerge (Bayerstadler et al., 2021; Biondi et al., 2021; Othmani et al., 2022; Yndurain et al., 2019). Boeing, for example, optimised composite design with QC (IBM, 2024)**.** Meanwhile, tech firms like Amazon (AWS, n.d.-a), IBM (IBM, n.d.), and Microsoft (Microsoft Azure, n.d.-a) are starting to commercialise QC services. Moreover, more enterprises are boosting investment in QC (Langione et al., 2023; Zapata, 2021) to tackle complex problems that cannot be solved by classical computers (Awan et al., 2022).

Adopting QC at production-level, however, presents significant hurdles. QC-specialised hardware and software differ greatly from classical ones, necessitating significant shifts in talent, infrastructure, and more (Swayne, 2023). Thus, implementing QC is expected to be costly (The Quant, 2023). Considering how challenging and expensive QC implementation is, organisations need to carefully run the initiatives to ensure a worthwhile investment.

Enterprises can address these challenges with TOGAF®, a popular framework that aligns initiatives with business objectives. Its activity-based approach promotes controlled and efficient execution (The Open Group, 2018). However, as a generic framework, the TOGAF® ADM might not be able to fully capture the unique considerations of integrating emerging technology like quantum computing.

Therefore, this paper proposes additional considerations tailored specifically to QC implementation using the TOGAF® ADM. In the Literature Review section, we will first explore the challenges of adopting QC and explaining the TOGAF® ADM. Then, in the Discussion section, we will delve into each phase of the TOGAF® ADM, highlighting some of the crucial considerations of QC adoption at every step. Finally, in the Conclusion section, we will summarise our recommendations and propose areas for further research.

1.2. Literature Review

Quantum Computing

Quantum Computing (QC) is a new computing technology that is based on the principles of quantum mechanics (Marella & Parisa, 2020). Feynman (1982) first proposed the use of quantum computers to solve physics and chemistry problems. As these problems required intense computational power, a quantum computer that works on quantum bits (qubit) was the solution for such problems, allowing the performing of most calculations simultaneously based on the use of superposition and entanglement of qubit (Pandey et al., 2023).

Such computational power opens up new opportunities in solving complex problem domains, such as prediction of Molecular Quantum Chemical reactivity, complex chemistry calculation for electric vehicle battery research, supply chain planning and drug development (Bayerstadler et al., 2021). Boeing has also utilised QC technology to design better aircraft composites (Letzter, 2023). QC can also be used to crack complex encryption, such as RSA-2048 bit encryption within 10 seconds, which would have taken a classical computer 300 trillion years to break the exact encryption key (QuintessenceLabs, 2019).

Despite the promises that QC ought to bring, there are several barriers holding back the large-scale commercialisation of QC technology. Firstly, qubit is unstable and susceptible to disturbance whereby temperature variance, movement of mechanics or stray electromagnetics will affect the operation accuracy. (Pandey et al., 2023) Hence, quantum computers have to be built to be isolated from external disturbance and be cooled down to -273°C (CSIRO, 2022) to reduce movement of atoms and molecules.

Furthermore, the implementation of QC is cost intensive, whereby it requires the procurement of not only QC hardware, but also cooling systems and software development (QuantumExplainer, 2024). Organisations should also consider the higher energy consumption and maintenance costs associated with the adoption of QC (QuantumExplainer, 2024). Despite that, providers such as IBM and Amazon are offering pay-per-use quantum cloud computing services, allowing organisations to explore QC technology at lower upfront investments (QuantumExplainer, 2024).

The Open Group Architecture Framework (TOGAF®)

Enterprise Architecture methodologies such as TOGAF® ADM offer a structured approach that addresses both the technological and business needs of implementing QC in enterprises. TOGAF® is an established framework for developing, deploying and maintaining enterprise architecture in organisations (Wijaya et al., 2022). The TOGAF® ADM in particular focuses on describing the method to develop and manage the lifecycle of an enterprise architecture to address business requirements (Vasconcelos & Sousa, 2022), as seen in *Figure 1.0*.

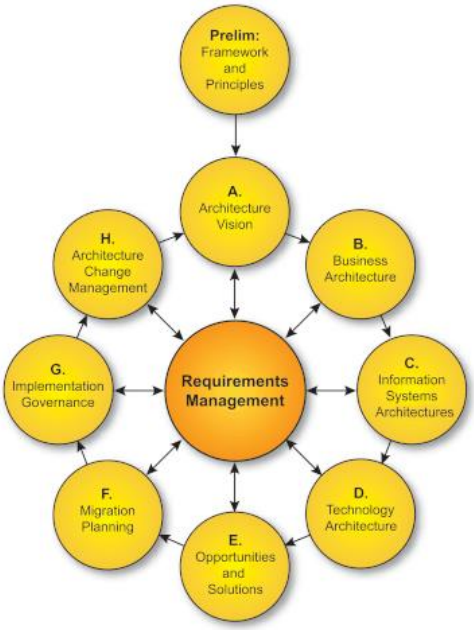

Figure 1.0: Structure of TOGAF® ADM (The Open Group, 2018)

TOGAF® ADM classified the methodology to manage enterprise architecture into the following phases (The Open Group, 2018):

1) Preliminary

Establish a baseline to kick-start the architecture development initiative, such as to identify the governance structure of this initiative and establish a desired enterprise architecture maturity level for this initiative.

2) Architecture Vision

Define business goals and vision to be achieved from the proposed Enterprise Architecture and establish guiding principles for shaping the architecture. This stage is crucial in getting stakeholder buy-in and support for the initiative.

3) Business Architecture

Establish a blueprint of current business processes to evaluate existing value chains and identify areas that require improvements to develop a target business architecture in supporting the organisation to overcome the existing gaps and achieve business goals.

4) Information Systems Architectures

Build an understanding of the existing information system landscape and identify data and application components required to support the organisation in achieving target information systems architecture for supporting the business architecture.

5) Technology Architecture

Identify the technology infrastructure required and define its standards in implementing the desired architecture.

6) Opportunities and Solutions

Produce an initial Architecture Roadmap with a few solutions, understand the constraints, and determine the best solution and implementation approach to meet the defined requirements in the previous stages.

7) Migration Planning

Develop a strategy to move the current state of the architecture to the future state, ensuring the potential risks associated with the migration are identified, communicated with the relevant stakeholders and are mitigated.

8) Implementation Governance

Establish a governance process to ensure that the project implementation is monitored and implemented as planned.

9) Architecture Change Management

Define a change management framework that helps organisations to ensure that existing enterprise architecture aligns with technology advancement and business needs.

10) Requirements Management

Ensure that stakeholder needs are properly captured, prioritised and implemented in the final architecture by integrating all phases of the TOGAF® ADM.

Research Gap

Although QC is still in the development stage, its potential is expected to be realised in the coming decade. Therefore, many attempts have been made to guide the implementation of QC. Studies by Soller (2023) and Aljaafari (2023) discussed the potential use of QC along with the business considerations that follow. Meanwhile, Khan et al. (2023), Haghparast et al. (2023), and Grossi et al. (2021) focused on addressing the challenges in QC software engineering. No existing research has discussed a comprehensive framework that considers both business aspects and technological aspects.

On the other hand, TOGAF® ADM offers a structured approach that addresses both technological and business needs of enterprises. This framework has been widely used by enterprises to solve the challenges of IT-business alignment (Goepp & Petit, 2017; Riwanto & Andry, 2019; Puspitasari, 2019). It can also be used for different technology implementations, such as artificial intelligence (Dilnutt et al., 2023) and cloud computing (Alghamdi et al., 2017).

However, as a generic framework (Kornyshova & Barrios, 2021), application of the TOGAF® ADM may cause confusion due to lack of specific guidance in implementing a new technology solution. Many attempts have been made to adapt TOGAF® for different applications to ensure the strategic objectives of each initiative are achieved (Fitriani et al., 2023; Gebayew & Arman, 2019). Nonetheless, there is no prior adaptation discussed for QC implementation.

1.3. Research Question

Building on the gap mentioned above, this research will investigate: *"What are the considerations when integrating QC into enterprises' architecture based on the TOGAF® ADM framework?"*

2. Discussion

This discussion will follow the structure of TOGAF® ADM methodology, addressing each phase in detail: Preliminary Phase, Architecture Vision, Business Architecture, Information Systems Architectures, Technology Architecture, Opportunities and Solutions, Migration Planning, Implementation Governance, and Architecture Change Management.

2.1. Preliminary Phase

A thorough review of the organisational context in the preliminary phase of QC integration is essential for understanding the scope and elements influenced by the Architecture Capability. This process entails assessing the organisational landscape, considering factors such as existing IT infrastructure, skill sets, and strategic goals regarding QC implementation. This assessment can be complex, as challenges may arise in managing change, adapting to new development environments, and addressing skill set limitations (Akbar et al., 2022).

Dependencies Evaluation

Understanding the organisational context requires an evaluation of dependencies among various entities, processes, and communication channels within the organisation. Moreover, comprehending operational aspects such as business objectives, policies, and compliance requirements is crucial for effectively evaluating and managing

dependencies (Hasan et al., 2024). In addition, employing frameworks such as SWOT (Strength, Weakness, Opportunities, Threats), PESTLE (Political, Economic, Sociological, Technological, Legal and Environmental), Porter's Five Forces, and ISO (International Organization for Standardization) standards can further enhance the understanding of the organisational context.

Adoption Strategic Alignment

Enterprises should understand the alignment between their business strategy and the goals of QC adoptation. This understanding ensures that QC adoptation can effectively support and enhance existing business objectives and strategic initiatives. Failing to comprehend this aspect may lead to misguided investments that do not add value to the organisation.

2.2. Architecture Vision

With QC implementation being resource-intensive, enterprises must prioritise the business segment that will get the most impact from this project and determine the best investment timing. This approach will enable enterprises not only to maximise the Return On Investment (ROI), but also justify the investment and secure management buy-in.

Business Segment Prioritisation

Similar to any IT investment, enterprises need to strategically align QC implementation to its business to obtain maximum benefit and financial return (Oh et al., 2007). Enterprises need to effectively manage resource allocation by identifying business segments that will benefit the most from QC integration. This can vary as it depends on the enterprise's specific goals in implementing QC. For instance, an enterprise prioritising innovation can integrate QC into its R&D work to accelerate new product development. Meanwhile, a company seeking to maximise manufacturing efficiency can leverage QC to optimise production workflows and reduce costs.

Capability-based Project Timeline

The timing of QC adoption is crucial in determining the scale of first-mover advantages and the associated risks (Sodhi & Tayur, 2022). Organisations must evaluate their internal capabilities and the size of the problem they aim to solve.

As a rule of thumb, if an organisation has confidence in its in-house team's ability to leverage the benefits of QC and manage potential risks, and if the problem size is substantial enough to yield significant improvements (Tyrrell, 2023), early adoption of QC is advantageous to maximise first-mover advantage. Conversely, if these conditions are not met, it is prudent for the organisation to delay adoption until off-the-shelf QC services are stable and mature, thereby minimising risk.

2.3. Business Architecture

Enterprises seeking to adopt QC face several significant hurdles that can hinder their readiness and competency. To bridge this gap and foster a QC-ready environment, enterprises need to adapt their organisational structure and management strategies.

Management Strategy

Bhasin & Tripathi (2023) highlights lack of management support as one of the challenges in QC adoption. QC research requires long-term commitment before the benefit realises, while management may want to prioritise short-term investments. To overcome this barrier, management needs to have basic knowledge about QC and its technology. This knowledge will empower them to be more supportive and make informed decisions regarding QC initiatives (Mohr et al., 2022). Enterprises can consider partnership with universities or leading research institutions to facilitate the management training.

Team Building Strategy

Building a new QC team can present a challenge to enterprises due to the limited availability of QC talents in the current market. This requires enterprises to have a flexible approach to talent acquisition. An external talent pipeline can be developed by establishing partnerships with universities and research institutions. In addition, enterprises should explore the potential within their existing workforce. Recruiting and upskilling experienced professionals to

the QC team can benefit enterprises as they have domain and organisational knowledge (Pfaendler et al., 2024). With these strategies, enterprises will be able to address the talent scarcity and build a robust QC team with qualified skills and institutional knowledge.

2.4. IS Architecture

The architecture of QC-integrated information systems must consider both data architecture and application architecture. These two components are essential for ensuring the effective integration and operation of QC within existing information systems.

Data Management Architecture

One of the primary challenges in utilising QC lies in encoding classical data, which exists in various structures and models, into a suitable format for quantum computers (Zajac, 2023). Unlike classical computers that store data in bits, quantum computers store data in qubits (Sood & Chauhan, 2024), making direct access from database systems impractical.

Hybrid data management architecture enables classical database systems to serve as data sources for quantum algorithms, addressing this challenge effectively. This approach involves using a tree structure-tailored first-encoding method (Zajac, 2023), possibly supplemented by reversible quantum logic circuits with quantum gates (Kundu et al., 2023).

Application Architecture

Differences between QC and classical computing mechanisms clearly diverge in recording, storage, and access methods (Gill et al., 2022). Consequently, quantum computers typically operate within their own system, isolated from classical systems, but work together as a system of systems.

To the best of our knowledge, there is no standardised communication system between classical and quantum applications, requiring the implementation of customised connectors between systems. This gap highlights an opportunity for further research in application architecture to develop effective solutions for this integration challenge. Therefore, organisations need to consider how they wish to address this issue.

2.5. Technology Architecture

Two key considerations for QC technological architecture discussed below will ensure a future-proof architecture is established, taking into account financial viability and strategic alignment of QC.

Deployment Model

Before deploying QC, enterprises should determine whether to use on-premises or cloud-based managed services. While on-premises services offer dedicated access and queue-free processing (Sutor, 2024), it requires high upfront investment and ongoing maintenance resources for specialised hardware, cooling systems, and physical space (Choi et al., 2023).

Cloud-based services, as recommended by McKinsey (2023), offer a solution to this problem. These services provide immediate access to state-of-the-art QC environment, minimising upfront investment and expediting development. A cloud platform's inherent scalability and adaptability provide a future-proof architecture that accommodates future advancement without significant overhaul.

Vendor Selection

The current state of QC introduces a unique challenge in vendor selection, especially for cloud-based solutions. The lack of standardised protocols and interoperability between all vendors (Swayne, 2023) leads to "vendor lock-in" where an enterprise becomes dependent on a specific vendor's ecosystem due to the incompatibility between vendors. For instance, IBM and AWS utilise Python-based Qiskit (AWS, n.d.-b; IBM Cloud, n.d.), while Microsoft has its own proprietary language, Q# (Microsoft Azure, n.d.-b).

To navigate challenge, enterprises should prioritise vendors that are involved in open-source and standard development initiatives to mitigate lock-in risk in the long run.

2.6. Opportunities and Solution

The focus of this phase in adopting QC as a new technology is to understand the implementation feasibility associated with risks, constraints, and its solutions to successfully deliver the targeted architecture (The Open Group, 2018). Thus, it is crucial for enterprises to consider the following aspects:

Implementation Strategic Approach

Identifying the appropriate strategic approach to implement QC is crucial in exploiting its unrivalled agility. For instance, given the emerging maturity of QC, enterprises may consider a Evolutionary Strategic Approach that explores the new technology implementation in a number of phases (Gschwendtner, et al, 2024). It is crucial that this approach is considered upfront while planning QC implementation as a technology solution for the companies, for it may have a risk of failure when being applied using a Big Bang approach that dramatically changes the existing systems and processes.

Architectural Roadmap

Enterprises should identify the Solution Building Blocks (SBBs), which are the potential component options that represent the implementation of QC capabilities or functions, as consolidation of requirements of QC developments (The Open Group, 2008). Additionally, enterprises need to develop the required activities' timeline to realise the adoption efficiently. This is particularly important in planning for QC adoption as involves significant changes and migration, signifying a high level of risks to business operations during the migration if not planned thoroughly.

2.7. Migration Planning

The complex and revolutionary nature of QC technology demands a systematic development approach in facilitating its implementation and migration (Akbar et al., 2022). Hence, it is vital for the enterprise architect to have a clear idea of the resources required and risks associated to ensure that the outcome of the implementation is aligned with the business value that the organisation desires to achieve (The Open Group, 2018).

Assess Migration Viability

As QC is not widely implemented in the industry yet, a thorough assessment of implementing the target QC architecture is important (Piattini et al., 2020). Some of the factors that should be evaluated include hardware availability and costs, technical expertise available, development tools selection, security considerations and regulatory landscape. A risk assessment should also be conducted to identify the implications and dependencies of implementing QC on other projects and activities within the organisation and develop a mitigation strategy to address them (The Open Group, 2018). This ensures that it is viable to implement QC and have better risk management.

Implementation and Migration Plan

A work breakdown structure that lists the key milestones and migration timing should also be established, as it provides a structured way of allocating work packages to the implementation team and ensures the QC migration activity is conducted in a timely manner and in the right sequence based on the architecture roadmap (The Open Group, 2018). As a result, a completed implementation and migration strategy shall be produced and documented in the form of an implementation and migration plan, allowing improved QC migration risk management, and controlled migration costs while minimising disruptions to existing systems and operations.

2.8. Implementation Governance

In implementing QC as a new IT solution, enterprises should be aware of the level of compliance with the existing Architecture Governance (The Open Group, 2018) to maximise business value and minimise the risks in the transformation initiatives. Most importantly:

Implementation Monitoring

In governing the implementation, monitoring the progress and objective delivery is the key to successful implementation. Given QC's high error rate which could be detrimental to data protection and business operation systems (Preskill, 2018), it is important to closely govern its implementation. This governance effort should include the adherence to the agreed Architecture Roadmap, Service Level Agreements (SLAs), and Operational Level Agreements (OLAs) (The Open Group, 2018). This measure would ensure cohesive performance management.

Compliance

Additionally, QC adoption should consider existing organisation standards, regulations, IT, and Architecture Governance which allow organisations to manage its technology comprehensively (The Open Group, 2018). It is especially crucial for disrupting technology like QC as its implementation would change the way an organisation works, signifying the need to have a regular compliance assessment to maintain a good and relevant business control.

In QC adoption, its complex algorithms and potential errors may result in transparency and accountability issues due to the difficulties to trace back potential causes of harmful mistakes (Scientific Work Computing, n.d.). It is clear that transparency and accountability issues would result in non-compliance with legal and business consequences that could be costly for organisations. Thus, companies should understand the suitability of QC technology to its ability to manage the technology according to the established standards and regulation.

2.9. Requirement Management

QC's currently-evolving industry landscape necessitates an adaptable requirements management and prioritisation process to ensure enterprise agility.

Impact-based Prioritisation

TOGAF® ADM's phase-based requirements gathering approach (The Open Group, 2018) can result in conflicting requirements. This is problematic for resource-intensive QC integration, which requires maximum return on investment to secure executive buy-in. Rigorous impact-based prioritisation is essential to ensure most value-generating requirements are addressed first.

3. Conclusion

The integration of Quantum Computing (QC) into enterprise architecture through the TOGAF® ADM framework requires adjustment with several crucial considerations. Our research has identified and outlined these considerations in *Table 1.0*.

TOGAF® Phase	**Key Considerations**
Preliminary	1. Evaluate business dependencies 2. Align adoption strategically
Architecture Vision	1. Prioritise business segments 2. Develop capability-based project timeline
Business Architecture	1. Establish management strategy 2. Plan team building strategy
IS Architecture	1. Manage data architecture 2. Manage application architecture
Technology Architecture	1. Determine deployment model 2. Select right vendor
Opportunities and Solution	1. Adopt strategic approach for the implementation 2. Develop architectural roadmap
Migration Planning	1. Assess migration viability

	2. Develop implementation and migration plan
Implementation Governance	1. Monitor implementation 2. Ensure implementation compliance
Requirements Management	1. Prioritise requirements based on impact

As we navigate the evolving landscape of QC, it becomes increasingly clear that thoughtful planning and adaptation are essential for realising its full potential in driving innovation and advancement.

3.1. Limitation

Our considerations are based on best practices and practical implementation in industry according to research theories and industry standards. However, our study did not delve into specific case studies because QC technologies are still in the developmental phase and lack a stable body of knowledge. This limitation highlights the need for further research to explore various implementation scenarios and incorporate real-world case studies for a more comprehensive understanding of QC adoption.

3.2. Further Research

The lack of a standardised communication system between classical and quantum applications requires the development of customised connectors, highlighting an opportunity for further research in application architecture to address this integration challenge. Future research could also investigate the impact of emerging technologies on QC integration and examine cross-industry variations in QC adoption strategies.

Organisations need to consider how they wish to address these issues to facilitate the seamless integration of QC into enterprise architecture.

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