

# Foresight Study on the Adoption of Quantum Technology for Enhancing Supply Chain Efficiency in the Manufacturing Industry

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## Abstract

Supply Chain Optimization (SCO) is key to making manufacturing more efficient, cost-effective, and sustainable. By leveraging advancements in Quantum Technology (QT), including quantum computing, quantum sensing, and quantum communication, SCO can achieve new levels of innovation and transform how supply chains operate. Malaysia is still in the initial stages of adopting QT, hindered by challenges such as limited infrastructure, expertise and strategic foresight. This study identifies the issues, challenges and trends of QT adoption for supply chain optimization in the manufacturing sector, which evaluates high-impact and uncertainty factors, and develops future scenarios. A mixed-methods approach was utilized, which incorporating qualitative methodologies such as STEEPV (Social, Technological, Economic, Environmental, Political, and Values) and Impact-Uncertainty analysis, as well as quantitative methods using SPSS for statistical analysis. 384 questionnaires had been distributed with response rate 61.92%. Data collected from the respondent revealed critical factors such as technological advancement and government policy as the most impactful and uncertain. These insights informed the development of four future scenarios: Tech-Driven Growth, Policy Push Without Tech Readiness, Tech-Led Adoption Without Government Support, and Stagnant Growth. Each scenario provides strategic implications for navigating uncertainties in QT adoption. The study concludes with a discussion emphasizing the need for proactive policy-making, collaboration, and investment in technological capabilities to unlock QT's potential for supply chain optimization. This research offers a comprehensive framework for strategic planning and contributes to advancing Malaysia's readiness for the integration of QT in manufacturing.

## 1. Introduction

In today's interconnected global market, the effectiveness of Supply Chain is essential for the success of manufacturing industries (Jenkins, 2024). According to the Jenkins (2024), supply chain encompasses a wide range of activities, including the cost, quality, and sourcing of raw materials, as well as the expenses and scheduling associated with outbound logistics and the delivery of finished products to customers. Supply chains becoming increasingly complex and globalized, businesses are constantly seeking innovative solutions and technologies to optimize operations, enhance resilience, and adapt to shifting market dynamics (Ali, 2024). The word quantum defined as a quantum mechanics, which describes things that behave at the very small scale (CSIRO, 2022). Quantum technology (QT) has become integrated into our daily lives by enabling the control and measurement of single quantum objects such as atoms, ions, electrons, or photons, bridging the fields of physics, computing, and engineering. QT that can open a whole new realm of possibilities. QT plays a crucial role in the supply chain process. Quantum Computing enhances key digitalization initiatives in industrial manufacturing practices, aiding in the prediction of performance optimization, operational excellence, and the identification of use cases for manufacturing excellence within industrial business units (Senapati & Rawal., 2023). QT develops the software tools and understanding to allow quantum computers to tackle real-world problems. Besides that, it could be ensuring computer networks and communication platforms are cybersecure. QT is crucial today as it promises to revolutionize various sectors from computing and cryptography to sensing and communications which offer unprecedented levels of security, speed and precision. The implementation of QT in supply chain helps organisations to optimise scheduling, appointments and improved productivity. Thereby, QT has emerged as a promising tool with transformative potential, offering opportunities to revolutionize various aspects of Supply Chain Optimization (SCO).

According to the Statistics reported by Stimulus, Inc in 2023, only 22% of companies have a proactive supply chain network, while 57% believe that Supply Chain Management (SCM) provides a competitive edge, enabling them to further develop their business (Medium, 2023). Malaysia increasingly emphasizes economic development while maintaining automotive industry and supply chains seeks to balance its economic, environmental, and social performances. SCO is a critical aspect of this management process, which optimizes various elements of supply chain, including production, inventory management, transportation, and distribution. Applications of analytics in SCO and decision-making have been increasing as companies strive to extract insights and generate value to gain a competitive edge (Gardas & Narwane, 2024).

The QT market is projected to be valued at \$1.9 billion by the year 2023 and is expected to increase to \$8 billion by the year 2027 on a global scale (Vernacchia, 2019). While QT is one of the technologies that has been offered transformative capabilities for supply chain optimization, including faster computation, improved data analysis, enhanced security, and dynamic network optimization. These technologies have the potential to revolutionize the creation and delivery of goods, enabling greater efficiency, precision, and flexibility in the manufacturing process (Umbrello, 2024).

Additionally, QT has the capability to address large-scale optimization problems, which have always been a priority issue in the supply chain space. The recent development and project of QT is being explored to solve the placement of shipping containers and truck appointments to optimize container outflow (SavantX, 2022). There will be different aspects of the SCO that will be discovered through this project, namely 'Pier 300 container terminal project' at the Port of Los Angeles, with the innovation of Hyper Optimisation Nodal Efficiency (HONE), which involves the resource efficiency of time, cost, machinery and appropriate staging for rapid on or offload.

Therefore, to achieve the research objectives, the issues, challenges, and trends of quantum technology adoption for supply chain optimization in the manufacturing industry are identified. Furthermore, the key drivers influencing the adoption of quantum technology for supply chain optimization in the manufacturing industry are also determined. Consequently, the future image of quantum technology adoption for supply chain optimization in the manufacturing industry is explored.

## 2. Research Methodology

### 2.1 Research Design

There are two main approaches in research methodology: quantitative and qualitative. However, these methods can also be combined and used concurrently (Beutlich, 2020). The quantitative method involves the collection and analysis of numerical data. It enables researchers to identify patterns, calculate averages, make predictions, and generalize results to larger populations (Bhandari, 2020). On the other hand, mixed methods research is a study design that incorporates both qualitative and quantitative methodologies. Considering the need for a larger number of respondents and the exploration of future possibilities, this research has opted to employ a mixed-method approach. Both qualitative and quantitative data will be analysed to gain a comprehensive understanding. The research aims to identify the STEEPV factors that lead to QT adoption for SCO in manufacturing industry

through a mixed-method foresight process. This foresight process utilizes a combination of qualitative and quantitative methods to explore the future trend of QT adoption for SCO in manufacturing industry.

The research scope outlines the boundaries and objectives of the study on the adoption of QT for SCO within the manufacturing industry. This study is focused on identifying the STEEPV factors that lead to QT adoption for SCO in manufacturing industry. It emphasizes a focused inquiry restricted to the manufacturing sector, specifically examining how QT is integrated into supply chain processes. The study's timeframe is set between 2024 and 2039, a decade preceding the present. The scope of this study was limited to the Manufacturing Industry that has a supply chain process. The targeted respondents are individuals such as all employees involved in supply chain within the manufacturing industry. Questionnaires will be prepared by the researcher to assess the STEEPV factors that lead to QT adoption for SCO in manufacturing industry. Additionally, various sources including news, blogs, books, journals, articles, and relevant video that applicable to the subject matter were analysed and evaluated.

## 2.2 Research Flow Chart

Fig. 1 is a flowchart that shows the visual display flow of the activities in a process. The researcher will have a better understanding of the processes and the work at all levels with the aid of this visual review process, which serves as a framework. This research flowchart will also help the researcher ensure that the research was carried out properly and successfully.

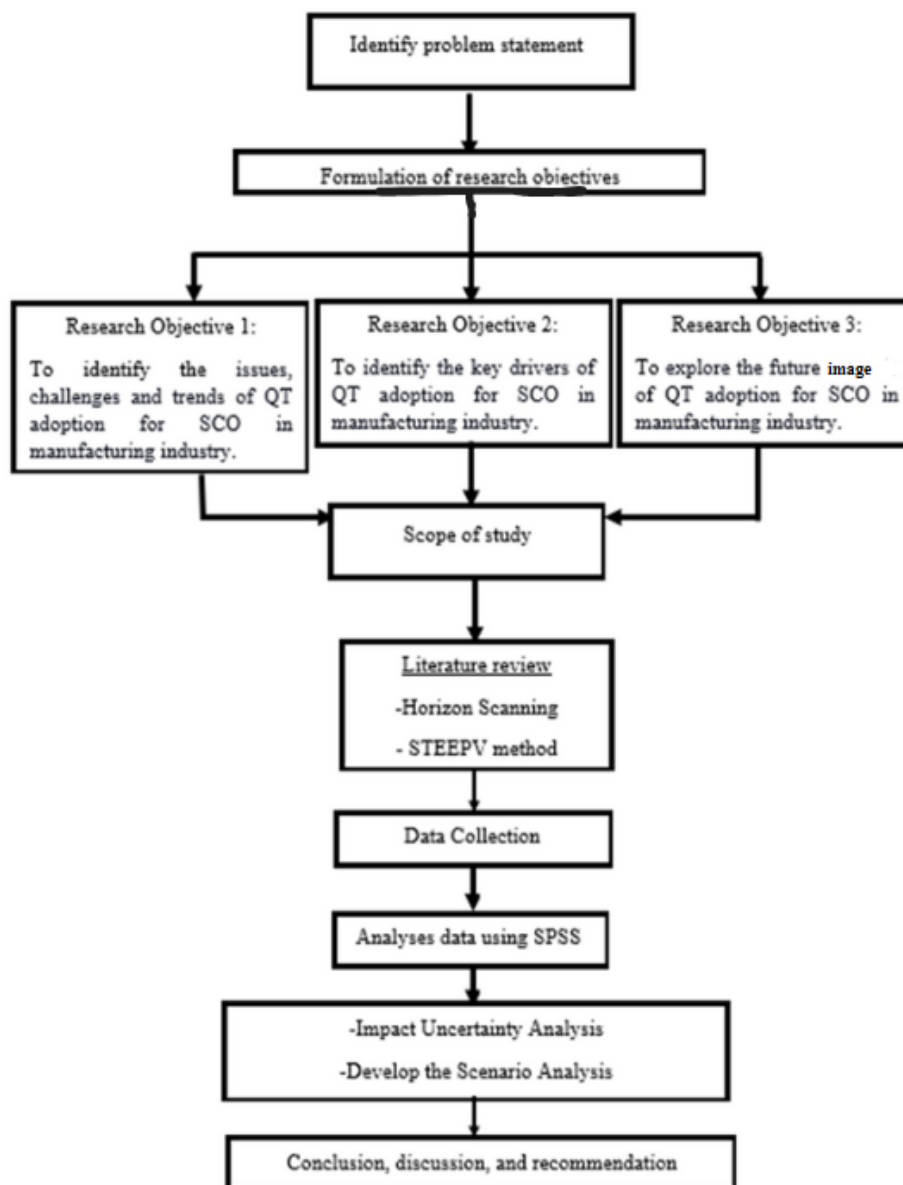


Fig. 1 Research flow chart

## 2.3 Population and Sampling

This research concentrates on QT adoption for SCO in manufacturing industry. Therefore, the target audience consisted of organization users of SCM in manufacturing industry. Consequently, this research was targeted to collect data from the users of SCM in manufacturing industry in Malaysia. Purposive sampling was used as a sampling technique for this study.

Selected sample size adheres to the standards established by Krejcie and Morgan (1970), ensuring an accurate representation of the known population. The sample size for this study will be 384 respondents, derived from a population of 2.35 million employees (Department of Statistics Malaysia Official Portal, n.d.). This sample size is adequate to ensure a comprehensive representation of the diverse perspectives within the manufacturing industries in Malaysia. The purposive sampling technique will be used to identify and select individuals whose input is most relevant and valuable to the study's objectives, thereby enhancing the depth and quality of the findings.

## 2.4 Research Instrument

The researcher must select a dependable instrument for the current research. This research decided to conduct a questionnaire as the research instrument. This research utilized a questionnaire because the data collected from the questionnaire was efficient and simple to comprehend. The questionnaire was used in this research because it can help to identify the issues, challenges, and trends of QT adoption for SCO in manufacturing industry in Malaysia in the future. The questionnaire was distributed to the advocates of SCM in manufacturing industry in Malaysia. This research questionnaire was classified into four sections: Section A (Respondents' demographic information), Section B (Importance of QT adoption), Section C (Impact of QT adoption), and Section D (Uncertainty of QT adoption).

## 2.5 Data Collection

This research has used primary and secondary data collection for data collection. Primary data refers to a variety of data that has been collected for the first time. For example, a questionnaire was used to capture most primary data, which was distributed to the supply chain management employees in the manufacturing industry in Malaysia. Secondary data collection was commonly used in many research reports because secondary data can be a support resource to support the data that is derived from primary sources. The collection of secondary data from sources such as journals, articles, newspapers, books, websites, and others.

## 2.6 Data Analysis

All collected data is organized systematically and presented clearly for ease of understanding. Data analysis is conducted to identify research findings and assess whether the research objectives are met. Descriptive analysis and correlation analysis methods are used to analyse the data gathered from primary sources, specifically through a questionnaire.

### 2.2.1 Descriptive Analysis

In this study, data was collected using a questionnaire, and the collected data was analysed using the SPSS. The SPSS system aids in generating statistical results in numerical form. Additionally, SPSS presents the gathered data in percentages, means, and standard deviations. As a result, SPSS was made more accessible to researchers because it facilitates the analysis of large quantities of data and displays the results of data collection straightforwardly.

### 2.2.2 Impact Uncertainty Analysis

The list of drivers was used to develop an Impact Uncertainty analysis. The drivers were ranked according to their importance, impact, and uncertainty. Based on the list, the top two variables with a higher level of impact and uncertainty have been selected to develop a scenario analysis. Following the impact-uncertainty analysis, which was conducted based on the calculated mean values from the data analysis, the scenario analysis development commenced.

### 2.2.3 Reliability Analysis

Reliability Analysis is a measurement scale employed to assess the reliability of the research questions and provide researchers with information regarding the consistency of individual items (IBM, n.d.). In this study, Cronbach's Alpha value will be utilized to examine the consistency and reliability of the data. The Cronbach's Alpha value produces a numerical result ranging from 0 to 1. A Cronbach's Alpha value above 0.8 can be categorized as better, while a value below 0.5 means that the data was inappropriate.

### 3. Literature Review

#### 3.1 Quantum Technology

QT represents an emerging field at the intersection of physics and engineering, leveraging quantum mechanical properties such as quantum entanglement, quantum superposition, and quantum tunnelling. These principles are applied to individual quantum systems to enable practical applications across various domains (Michal Krelina, 2023). According to Raymer (2019), QT is defined by leveraging the distinctive quantum characteristics of superposition, entanglement, and fundamental metrology metrics to unlock new opportunities in secure communication, high-precision sensing, and revolutionary computing. It is anticipated that QT could potentially lay the groundwork for an entirely new technological infrastructure, akin to how the semiconductor revolution reshaped the landscape in the latter half of the 20th century. Therefore, QT is an advanced field that applies principles of quantum mechanics, including entanglement, superposition, and tunnelling, to practical applications. It aims to harness these unique quantum properties to innovate in areas such as secure communications, precise sensing, and powerful computing.

According to Johanna Sepúlveda (2022), QT harnesses quantum physics properties to offer disruptive solutions for processing information, exchanging data, and interacting with the surrounding environment. One of the key pillars of QT, namely 'Quantum computing,' introduces a novel approach to encoding and processing information using quantum states. Quantum computers have the capability to solve highly complex problems in record time, which are often challenging or even unsolvable with traditional computers. Another significant aspect is 'Quantum sensing,' which has profound implications across various industries. It utilizes quantum states to measure a wide range of properties, including acceleration, rotation, electromagnetic radiation, magnetic fields, time, and frequencies. Additionally, 'Quantum communications' encode information as quantum states, ensuring security by leveraging two key quantum properties: the inability to clone quantum information and the detection of any attempted eavesdropping. Presently, quantum communication is employed for distributing cryptographic keys.

#### 3.2 The Advantages of Quantum Technology

QT's pillar, quantum computing, holds the potential to safeguard data from real-time hacking attempts, thereby providing defences against approaches such as 'download now, decrypt later,' where criminals capture encrypted information for decryption at a later time (Vernacchia, 2019). This heightened security is possible if cyberterrorism and cybercrime prevention teams have access to quantum computing capabilities before malicious actors, bolstering the fight against next-generation cyber-warfare. Quantum computers, operating akin to the human brain with the assistance of neural networks like deep learning and machine learning, possess remarkable speed and can tackle unresolved classical computing problems (Balamurugan *et al.*, 2024). Umbrello (2024) suggests that the application of QT in Industry 4.0 holds immense transformative potential, revolutionizing the manufacturing process and significantly enhancing productivity and competitiveness. Additionally, Quantum AI demonstrates superior capabilities in identifying patterns in large datasets, handling corrupt data more effectively, and expediting the training of large neural networks (Erp & Gladysz, 2022). Organizations stand to benefit from quantum technology by improving efficiency, optimizing scheduling, and fortifying against data theft by competitors. Fraunhofer's ongoing development of quantum algorithms aimed at solving combinatorial optimization problems fundamental to Machine Learning and AI further underscores the potential of quantum technology in organizational enhancement.

#### 3.3 The Challenges of Quantum Technology

The quantum supply chain is still in its early stages, marked by a growing demand for cutting-edge products that require extensive research and development, resulting in prolonged lead times that hinder progress (Doug Finke, 2024). Traditional industries are now venturing into the quantum realm by investing in quantum computing, sensing, and communications technologies. Their entry is reshaping the quantum supply chain by merging conventional manufacturing expertise with quantum innovation. However, there's a pressing need for policymakers, investors, and vendors to gain a deeper understanding of the intricate quantum supply chain. Policymakers must make strategic decisions to drive progress, investors seek the next breakthrough, and vendors must grasp customer needs, competition, and other factors to streamline the chaos of innovation into clear solutions. Additionally, the occurrence of errors in qubit states poses a significant challenge (Balamurugan *et al.*, 2024). These errors, stemming from environmental disturbances, complicate quantum computations and necessitate meticulous care for qubits during computation. As a result, progress in quantum computation is hindered, thwarting the realization of quantum computers' full potential, which holds vast applications in fields like cryptography, communication, and medicine. Addressing these challenges is pivotal for the advancement of quantum technology. Furthermore, scalability emerges as a critical challenge for software companies, particularly those with a vested interest in the development of larger, more reliable quantum computers (Tarraf, 2023). In a

quantum computer, each qubit must interact with every other qubit to maximize computational power. However, meeting this requirement becomes increasingly challenging as the number of qubits grows. With more qubits, the likelihood of errors also increases, stemming from factors ranging from environmental noise to imperfections in the qubits themselves.

### 3.4 STEEPV Analysis

STEEPV analysis is a foresight tool used to anticipate future developments across six broad categories. STEEPV stands for Social, Technological, Environmental, Economic, Political, and Values. It is an internationally recognized method for brainstorming commonly employed in Technology Foresight initiatives worldwide (Minhax, 2011). Thus, STEEPV analysis allows appropriate boundaries to be derived and broad trends that influence the objectives to be identified by asking which drivers are important (Loveridge, 2002). Thus, this method also could help to gain insight into developments of the external environment. The STEEPV analysis is also used to identify drivers of QT adoption in Malaysia. Firstly, social factors focus on social development includes many factors, for instance lifestyle, values, demographics and religion. Secondly, technological factors focus on the technological progress, pace of diffusion of innovations, problems and risks. Thirdly, environmental factors focus on the sustainability of the environment and climate change while implementing that involves the ecosystem factors which include water, soil, wind and energy. Moreover, economic factors focus on the level distribution of economic growth, industrial structure, competition and competitiveness, markets and financial issues. Additionally, political factors focus on political development that may highly influence individuals and organisations for example government's involvement and acceptance. Lastly, values factor will focus on positive elements instilled for instance attitudes to working life and culture. Through the identification of STEEPV factors may help in explore the future trend of QT adoption for SCO in manufacturing industry in Malaysia.

### 3.5 Merging Issues and Drivers

Based on the Table 1, the major factors from STEEPV analysis are technological which recorded as 16 times of issues and drivers from the previous studies. The STEEPV analysis reveals that while QT holds substantial promise for SCO in the manufacturing industry, several key drivers and issues across social, technological, environmental, economic, political, and value dimensions need to be addressed. The analysis underscores the potential benefits of QT, such as enhanced data security, operational efficiency, and sustainability, but also highlights challenges like high implementation costs, technological uncertainty, and the need for robust regulatory frameworks.

**Table 1** Table of key drivers related to merged issues, challenges and trends

No.	Drivers
1	Technology advancement
2	Resources efficiency
3	Safety and health
4	Environment impact
5	Reduced energy consumption
6	Security
7	Government policies
8	Economic growth
9	Production Cost
10	Advance in living standard

## 4. Data Analysis and Findings

### 4.1 Reliability Test

A reliability test in research refers to the process of assessing the consistency and stability of a measurement instrument, such as a survey or questionnaire, over time. Reliability is crucial in research because it ensures the accuracy and dependability of the results. Researchers often report reliability coefficients (like Cronbach's Alpha) to provide evidence of the reliability of their measurement tools. Improper use of alpha can lead to situations in which either a test or scale is wrongly discarded, or the test is criticised for not generating trustworthy results (Tavakol & Dennick, 2011).

Table 2 outlines the general guidelines for interpreting Cronbach's Alpha values to assess the reliability of a measurement instrument. A Cronbach's Alpha value between 0.70 and 0.80 is typically considered acceptable,

indicating a good level of internal consistency. Values ranging from 0.80 to 0.90 are considered excellent, suggesting very high reliability, while values above 0.90 may indicate excessive redundancy in the items. On the other hand, an Alpha value below 0.60 is generally considered unacceptable, signalling insufficient reliability. These benchmarks assist researchers in determining whether their measurement tools are reliable and consistent, ensuring the validity of their findings (Sekaran & Bougie, 2016).

**Table 2** Cronbach's alpha classification

Cronbach's Alpha	Internal Consistency
$\alpha \geq 0.9$	Excellent
$0.8 \leq \alpha < 0.9$	Good
$0.7 \leq \alpha < 0.8$	Acceptable
$0.6 \leq \alpha < 0.7$	Questionable
$0.5 \leq \alpha < 0.6$	Poor
$\alpha \leq 0.5$	Unacceptable

#### 4.1.1 Reliability for Pilot Test

The results of the pilot test conducted for this study are presented in Table 3. The questionnaire was divided into three sections: Part B, Part C, and Part D, each containing 10 items. Part B focused on the importance of factors or drivers influencing the adoption of Quantum Technology (QT) for Supply Chain Optimization (SCO) in the manufacturing industry in Malaysia, with a Cronbach's Alpha value of 0.911, indicating excellent reliability. Part C addressed the impact of these factors, achieving a Cronbach's Alpha value of 0.918, also demonstrating excellent reliability. Part D examined the uncertainty associated with these factors, with a Cronbach's Alpha value of 0.874, reflecting good reliability. As all sections scored above the threshold of 0.70, the questionnaire items are considered consistent and reliable, making them suitable for the main study.

**Table 3** Result for Pilot Test

Section	Drivers	Cronbach's Alpha	No of Items
B	Importance	0.911	10
C	Impact	0.918	10
D	Uncertainty	0.874	10

#### 4.1.2 Reliability for Actual Study

The results of the actual study conducted for this research are shown in Table 4. The questionnaire was divided into three sections: Part B, Part C, and Part D. Part B addressed the importance of factors or drivers influencing the adoption of Quantum Technology (QT) for Supply Chain Optimization (SCO) in the manufacturing industry in Malaysia. It contained 10 items and achieved a Cronbach's Alpha value of 0.888, indicating a high level of reliability. Part C focused on the impact of these factors or drivers on QT adoption, also comprising 10 items, with a Cronbach's Alpha value of 0.874, reflecting a strong reliability level. Part D dealt with the uncertainty associated with these factors, consisting of 10 items, and had a Cronbach's Alpha value of 0.882, indicating excellent reliability. As all sections achieved Cronbach's Alpha values above the acceptable threshold of 0.70, the results confirm that the questionnaire items are consistent, reliable, and suitable for use in the main study.

**Table 4** Result for Actual Test

Section	Drivers	Cronbach's Alpha	No of Items
B	Importance	0.888	10
C	Impact	0.874	10
D	Uncertainty	0.882	10

#### 4.1.3 Descriptive Analysis (Demographic)

The table 5 summarizes demographic and knowledge-related data for a sample of 238 respondents. The gender distribution is relatively balanced, with 52.1% male and 47.9% female participants. In terms of age, the majority fall between 31-35 years (30.3%) and 36-40 years (27.7%), with only 0.4% aged 20 years and below. Regarding race, the sample is predominantly Malay (49.6%), followed by Indian (34.0%) and Chinese (16.4%). Most respondents have less than five years (33.2%) or six to ten years (27.7%) of working experience, indicating a younger professional demographic. Finally, an overwhelming majority (98.3%) reported having knowledge about quantum technology, while only 1.7% did not. This suggests the respondents are highly informed on the subject matter.

**Table 5 Demographic Analysis**

	Frequency (f)	Percentage (%)
<b>Gender</b>		
Male	124	52.1
Female	114	47.9
Total	238	100
<b>Age</b>		
20 years and below	1	0.4
21-25 years	32	13.4
26-30 years	6	2.5
31-35 years	72	30.3
36-40 years	66	27.7
41 years and above	61	25.6
Total	238	100
<b>Race</b>		
Chinese	39	16.4
Indian	81	34.0
Malay	118	49.6
Total	238	100
<b>Working Experience</b>		
Less than 5 years	79	33.2
6 years – 10 years	66	27.7
11 years – 15 years	48	20.2
16 years and above	45	18.9
Total	238	100
<b>Knowledge about Quantum Technology (QT)</b>		
Yes	234	98.3
No	4	1.7
Total	238	100

#### 4.1.4 Analysis of Drivers based on its Importance

From Table 6, it is evident that Quantum Technology (QT) in supply chain optimization leads to a reduction in energy consumption" holds the highest mean value of 4.5084, indicating that respondents consider it the most important driver for QT adoption. On the other hand, Quantum Technology (QT) in supply chain optimization enhanced data security in operations is associated with the lowest mean value of 4.4118, suggesting it is perceived as the least important driver among the listed factors. This ranking underscores the significance of energy efficiency as a key motivator for QT implementation while highlighting that security, though still important, is less prioritized compared to other drivers. These findings provide valuable insights into the priorities of stakeholders and can guide future strategies for promoting QT adoption in Malaysia.

**Table 6 Mean of Drivers on Importance**

No.	Drivers	Mean
1	Technology advancement	4.4412
2	Resources efficiency	4.4496
3	Safety and health	4.4790
4	Environment impact	4.4286
5	Reduced energy consumption	4.5084
6	Security	4.4118
7	Government policies	4.4370
8	Economic growth	4.4118
9	Production Cost	4.4916
10	Advance in living standard	4.4118

#### 4.1.5 Analysis of Drivers based on its Impact

From Table 7, Quantum Technology (QT) in supply chain optimization grants users access to advanced technology, which has the highest mean value of 4.5336, indicating that it is considered the most impactful driver. This emphasizes the role of technological progress in influencing QT adoption. Conversely, Quantum Technology (QT) in supply chain optimization reduces the environmental impact" has the lowest mean value of 4.4286, suggesting it is perceived as the least impactful driver compared to the others. These findings underline that while all drivers are important, technology advancement is seen as a critical factor in driving QT adoption, whereas environmental impact is less prioritized in this context. This information provides a basis for stakeholders to focus on key impactful drivers when implementing QT in Malaysia.

**Table 7** Mean of drivers on level of impact

No.	Drivers	Mean
1	Technology advancement	4.5336
2	Resources efficiency	4.4454
3	Safety and health	4.4874
4	Environment impact	4.4286
5	Reduced energy consumption	4.4538
6	Security	4.4580
7	Government policies	4.4496
8	Economic growth	4.4790
9	Production Cost	4.4412
10	Advance in living standard	4.3824

#### 4.1.6 Analysis of Drivers based on its Uncertainty

From Table 8, Supportive government policies are critical in encouraging the adoption of Quantum Technology (QT) for supply chain optimization has the highest mean value of 4.5042, indicating that it is perceived as the driver with the greatest level of uncertainty. This suggests that stakeholders view the improvement in government policies as a key area of unpredictability in the context of QT adoption. On the other hand, both Quantum Technology (QT) in supply chain optimization improves the standard of living and Quantum Technology (QT) in supply chain optimization led to a reduction in energy consumption. share the lowest mean value of 4.4286, implying that these drivers are perceived as having lower uncertainty. These findings highlight that while all drivers exhibit level of uncertainty, those related to government policies are considered more unpredictable, guiding policymakers and industry stakeholders to address this uncertainty in their strategies.

**Table 8** Mean of drivers on level of uncertainty

No.	Drivers	Mean
1	Technology advancement	4.4790
2	Resources efficiency	4.4748
3	Safety and health	4.4538
4	Environment impact	4.3950

5	Reduced energy consumption	4.4286
6	Security	4.4706
7	Government policies	4.5042
8	Economic growth	4.4790
9	Production Cost	4.4370
10	Advance in living standard	4.4286

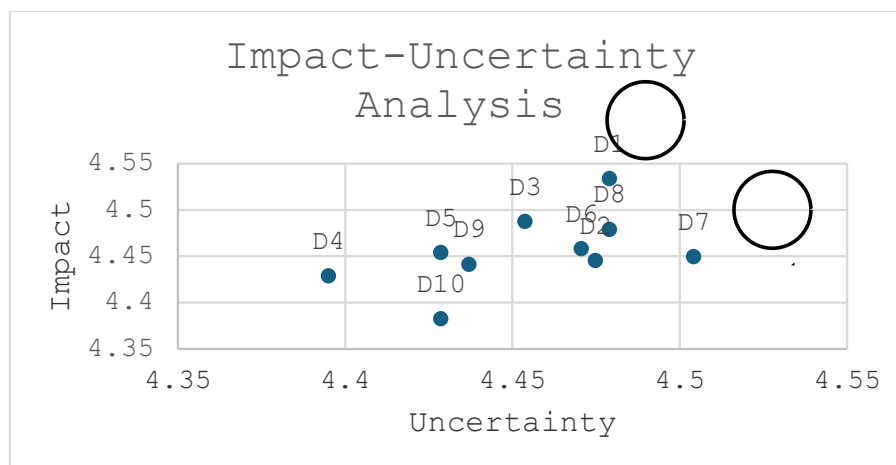
#### 4.1.7 Impact-Uncertainty Analysis

Impact-uncertainty analysis is conducted to identify the top two drivers with high impact and high uncertainty values. These two drivers will then be used to develop the scenario analysis. Table 9 shows the impact-uncertainty results.

**Table 9** Mean of the 10 leading drivers on level of impact and uncertainty

No.	Drivers	Impact Mean	Uncertainty Mean
1	Technology advancement	4.5336	4.4790
2	Resources efficiency	4.4454	4.4748
3	Safety and health	4.4874	4.4538
4	Environment impact	4.4286	4.3950
5	Reduced energy consumption	4.4538	4.4286
6	Security	4.4580	4.4706
7	Government policies	4.4496	4.5042
8	Economic growth	4.4790	4.4790
9	Production Cost	4.4412	4.4370
10	Advance in living standard	4.3824	4.4286

Fig. 2 visually represents the relationship between the levels of impact and uncertainty for the 10 leading drivers influencing the adoption of Quantum Technology (QT) in Malaysia. The data derived from Table 4.9, plots the mean values of each driver, with impact on the x-axis and uncertainty on the y-axis. The analysis identifies Technology Advancement (D1) and Government Policies (D7) as the most significant drivers. D1 has the highest impact score (4.5336), indicating its critical influence on QT adoption, while D7 has the highest uncertainty score (4.5042), reflecting the unpredictability of policy-related factors. The remaining drivers are distributed relatively close to each other, indicating moderate levels of impact and uncertainty for most factors. These findings emphasize the importance of D1 and D7, which will be prioritized in the subsequent scenario analysis to forecast and strategize for the future of QT adoption in Malaysia.



**Fig. 2** Impact-Uncertainty Analysis

## 5. Conclusion

This study established two research objectives. The first objective is to identify the key drivers influencing the adoption of Quantum Technology (QT) for Supply Chain Optimization (SCO) in manufacturing industry in Malaysia. To achieve this, a STEEPV analysis was conducted. Identifying the challenges and drivers associated with QT adoption is critical, as it can benefit potential users, business, and government. These factors play a pivotal role in shaping the future utilization of QT in Malaysia. The STEEPV analysis revealed that the most significant factor driving QT adoption in Malaysia is the technological element, followed by economic, political, environmental, value, and social factors.

The second objective of this research is to study the future trend of QT adoption in Malaysia. The aim is to discover the trends that will drive future developments, as well as the future environment and market for QT adoption in Malaysia. The trend is accomplished by using the top two drivers from the impact-uncertainty analysis, which are Technological Advancement and Government Policies, to generate scenario analysis for four different alternative scenarios. The selected top two drivers have been discussed in the following section. It is discussed how uncertain future developments will be and what impact this will have on QT adoption in Malaysia. In comparison to the other drivers, these two selected drivers had the greatest impact and uncertainty.

Technological advancements are identified as the most impactful and uncertain driver for QT adoption. This encompasses innovations in quantum computing hardware, quantum communication systems, and quantum algorithms that improve data processing, encryption, and problem-solving capabilities. Technological advancements provide the infrastructure necessary for seamless integration of QT across various sectors, from financial services to healthcare and logistics. However, the rapid pace of technological evolution creates uncertainties about adoption rates, compatibility, and cost implications. Furthermore, the private sector's investment in R&D and the availability of a skilled workforce specializing in quantum technologies will play a critical role in the success of such innovations.

As show in Fig. 3, government policies are also highlighted as a pivotal driver due to their influence on the regulatory landscape and financial incentives for QT adoption. Policies such as funding for quantum research, subsidies for developing quantum-enabled applications, and tax rebates for companies investing in QT infrastructure can accelerate adoption. However, inconsistencies in policy enforcement and shifts in government priorities can introduce significant uncertainties. Establishment of national quantum strategies and adherence to international standards for quantum technology development has the potential to stimulate broader adoption of QT in Malaysia, particularly in industries such as telecommunications, defence, and manufacturing.

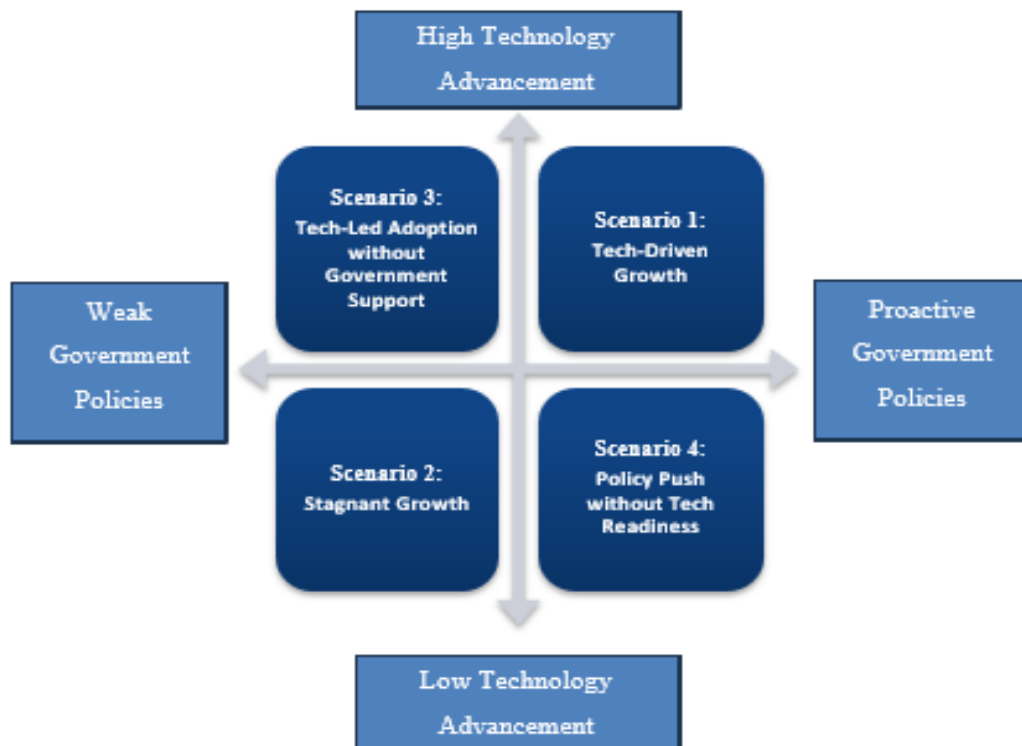


Fig. 3 Four alternative scenarios

The first scenario shows that Malaysia becomes a leader in the adoption of Quantum Technology (QT) for supply chain optimization. Technological advancements in QT are robust, marked by breakthroughs in quantum

computing algorithms and hardware. These advancements enable manufacturers to solve previously intractable supply chain problems, such as dynamic inventory optimization, route planning for logistics, and demand forecasting, with unprecedented precision and speed (Brown *et al.*, 2022). For instance, QT's ability to process vast datasets simultaneously allows manufacturers to anticipate supply chain disruptions, reduce costs, and improve overall operational efficiency. The Malaysian government actively supports this growth by implementing favourable policies, such as subsidies for quantum adoption, tax breaks for industries integrating QT, and substantial investments in R&D. This includes establishing national quantum research centres and fostering collaborations between universities, private industries, and international quantum technology leaders (Smith *et al.*, 2020). These initiatives not only lower the entry barriers for manufacturers but also ensure a steady pipeline of skilled workers equipped with quantum expertise. However, this scenario is not without challenges. High initial costs for implementing QT systems and the need for ongoing workforce training could strain smaller manufacturers. Nevertheless, government support mitigates these challenges, ensuring an inclusive approach to adoption. This scenario showcases the transformative potential of aligning technology and policy to revolutionize supply chain management.

Scenario two is the least favourable scenario, where both technological advancements and government policies fail to support the adoption of QT in supply chain optimization. Technological progress in QT remains slow, with hardware and software advancements failing to meet the needs of the manufacturing sector. Existing quantum systems are plagued by high error rates, limited scalability, and prohibitive costs, making them inaccessible to most manufacturers (Chen & Liu, 2019). The lack of proactive government policies further exacerbates the situation. Without subsidies, tax incentives, or regulatory frameworks, there is little motivation for manufacturers to invest in QT. Additionally, the absence of government-funded research initiatives results in a lack of local expertise and infrastructure, leaving Malaysian manufacturers at a significant disadvantage in the global market (Miller *et al.*, 2020). This scenario underscores the critical importance of coordinated efforts between government and industry to drive QT adoption. Without such efforts, the transformative potential of QT remains unrealized, and the manufacturing sector fails to capitalize on its benefits.

Scenario three is the advancements in QT are driven by private sector initiatives and global market trends rather than domestic government support. Breakthroughs in quantum computing hardware and software result in powerful QT systems that are capable of solving large-scale supply chain optimization problems. For instance, quantum-based systems could enable manufacturers to optimize global logistics networks in real time, reducing transportation costs and delivery times (Brown *et al.*, 2022). Global corporations operating in Malaysia, such as multinational electronics and automotive companies, spearhead the adoption of QT. They invest heavily in integrating quantum systems into their supply chains to remain competitive in global markets. However, the absence of supportive government policies, such as subsidies or regulatory frameworks, creates significant barriers for local manufacturers, particularly SMEs. High implementation costs and a lack of incentives make it difficult for smaller firms to adopt QT solutions, leading to an uneven distribution of technological benefits (Johnson & Wang, 2021). Despite these challenges, this scenario demonstrates the potential of market-driven QT adoption. It highlights the need for governments to play an active role in supporting technological advancements to ensure inclusive and equitable adoption across all sectors.

Scenario 4 is focus on the government efforts to promote QT adoption are ambitious and well-structured, but the technology itself lags in maturity. Policies such as tax incentives, grants, and subsidies encourage manufacturers to explore QT for supply chain optimization. However, the existing quantum systems are not yet advanced enough to handle the complex demands of supply chains effectively. For example, limitations in quantum hardware, such as low qubit stability and high error rates, restrict the scalability of QT solutions (Chen & Liu, 2019). Despite these challenges, the government continues to push for QT adoption by setting targets for industries to integrate quantum-based systems within a specific timeframe. This may include mandating QT adoption in large-scale projects or providing incentives for pilot programs in sectors like automotive, electronics, and consumer goods manufacturing (Miller *et al.*, 2020). While some manufacturers comply to benefit from these incentives, the systems they adopt often fail to deliver the anticipated improvements in efficiency and cost savings. While this scenario highlights the importance of proactive government policies, it also underscores the need for these policies to be aligned with the current state of technology. Bridging this gap requires significant investment in quantum R&D and workforce development to ensure that the technology is ready to meet industry demand.

This study has examined the adoption of quantum technology for supply chain optimization within Malaysia's manufacturing industry, identifying key drivers, challenges, and emerging trends. By leveraging these findings, stakeholders can address barriers to adoption and capitalize on QT's transformative potential. Despite the study's limitations, it lays the groundwork for future research and practical applications that can enhance efficiency, sustainability, and innovation in Malaysia's supply chains. The integration of QT represents a significant opportunity for Malaysia to position itself as a leader in quantum-enabled industries. By implementing the recommendations outlined, including policy support, education initiatives, and infrastructure investment, the country can foster an environment conducive to technological innovation and economic growth. This will not only

improve supply chain efficiency but also contribute to Malaysia's broader goals of becoming a hub for advanced technologies in the global economy.

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## Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

## Author Contribution

The authors confirm contribution to the paper as follows: **study conception and design:** Lim Gou Qing and Siti Aisyah Salim; **data collection:** Lim Gou Qing; **analysis and interpretation of results:** Lim Gou Qing.; **draft manuscript preparation:** Lim Gou Qing and Siti Aisyah Salim. All authors reviewed the results and approved the final version of the manuscript.

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