Navigating Smart Quality Adoption: Challenges and Success Factors for Taiwan's Manufacturing SMEs

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***Abstract* – In the face of global competition, SMEs (Small and Medium Enterprises) in the manufacturing industry must implement creative strategies to ensure product quality. The transition from traditional to smart manufacturing is critical for optimizing processes, improving quality, and enhancing efficiency and competitiveness. However, SMEs face numerous obstacles in this transition due to the complexity of industrial structures and the involvement of various stakeholders. To address these challenges, this study investigates the current state and key dimensions necessary for the effective adoption of smart quality practices among Taiwan's SMEs. The research identifies both the motivations and barriers to adopting Smart Quality, as well as the impact of Smart Quality on organizational performance, providing managers with insights to guide their implementation efforts. Using a hybrid approach of the Analytical Hierarchy Process, Delphi method, and SWOT analysis, the study evaluates eight key dimensions critical to smart manufacturing implementation.**

The findings reveal that financial resources, a skilled and competent workforce, and strategic tactics are the primary determinants of the successfull smart manufacturing in Taiwan's SMEs. This study offers detailed insights into the practical application of Smart Manufacturing and Smart Quality frameworks, offering valuable guidance for managers and practitioners to prioritize efforts and maximize the benefits of Smart Quality in their organizations.

***Keywords* – Smart quality, manufacturing, Taiwan's SMEs.**

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1. Introduction

Industry 4.0, which began in Germany in 2011, has been widely promoted by advanced economies, leading to the introduction of "smart manufacturing." As an innovative strategy for the manufacturing sector, smart manufacturing has garnered significant attention in both academic and practical fields [1], [2]. However, the substantial investments required by individual enterprises and their varying approaches have created a considerable gap between policy promotion and practical application, resulting in limited progress in smart manufacturing [3], [4]. The integration of multiple technologies—such as the Artificial Intelligence (AI), Machine Learning, Internet of Things (IoT), cybersecurity, mixed reality, autonomous robots, cognitive computing, augmented reality, cyber-physical systems, quantum computing, cloud computing, blockchain, nanotechnology, 3D printing, and genetic engineering—has significantly impacted industrial systems in recent years [5], [6]. These technologies, that are grouped together under the term Fourth Industrial Revolution (Industry 4.0), have transformed design, manufacturing, quality, and delivery processes, and are often referred to as smart manufacturing or integrated industry [7], [8].

Modern organizations have experienced dramatic shifts in engineering, manufacturing practices, and technologies with the advent of Industry 4.0 [9], [10]. This revolution, built on massive digitization, robotics, big data analytics, advanced manufacturing and engineering technologies, adaptive automation, and nanotechnology, has fundamentally changed the way industries operate [11].

In Taiwan, as in many other countries, Small and Medium-Sized Enterprises (SMEs) are categorized based on by the staff count or annual revenue. For example, Taiwan's Ministry of Economic Affairs (MOEA) defines SMEs as those employing fewer than 250 employees, with small enterprises having fewer than 100 employees. Conventional manufacturing encompasses subtractive techniques and time-honored methods, ensuring quality and application within the commercial sector [12].

Taiwan's traditional manufacturing industries need to focus on design and innovation to enhance value-added production and international competitiveness, leading to sustainable development [13], [14]. Traditional manufacturing, which is characterized by long-established subtractive methods, is evolving towards high-value-added production, driven by new technologies that improve resource utilization and reduce carbon emissions [13]. However, a key challenge remains: How effectively have traditional quality management practices adapted to the evolving demands of product development, shortened production cycles, and increasing customer expectations [15].

Digitization creates new opportunities for industries to leverage technological advancements and achieve operational excellence, improved performance, and innovation [16]. Technologies such as IoT and cloud computing are being applied to meet the stringent demands of design, conformance, and performance quality [17], [18].

The significance of quality has emerged as a pivotal aspect for products and services within international markets [19]. Companies that effectively implement quality management can gain a competitive advantage internationally [3]. With the onset of Industry 4.0, quality management (QM) has evolved, incorporating modern technologies [20]. While Quality 4.0 extends the principles of Industry 4.0 into broader areas, Smart Quality concentrates on the technological advancement of quality in smart manufacturing [21]. Smart Quality links all systems within manufacturing, creating an integrated, real-time network that enhances quality control and performance. Smart Quality emphasizes the application of technology to connect all components of the manufacturing system, thereby creating an integrated and real-time framework [22].

Smart Quality provides methods and strategies to streamline regulatory practices; nonetheless, its complete potential regarding the influence on industrial quality remains unexamined [14], [15]. To fully leverage Smart Quality, industries need to automate digital processes and link them to other operations, allowing high-value employees and managers to focus on innovation and improvement. Support from senior management is essential for advancing promoting quality initiatives and cultivating a culture of continuous improvement [14], [23]. This study seeks to establish a transition framework for SMEs in the manufacturing sector, facilitating their shift from conventional quality methodologies, including quality assurance, quality control, and total quality management (TQM), to Smart Quality, a contemporary approach consistent with the Fourth Industrial Revolution.

2. Methodology

Figure 1 shows the research methodology and research stages in more detail in this study. The research methodology commences with the identification of the research problem and a literature review, which informs the formulation of research objectives and hypotheses. A study instrument was created to assess the threats, opportunities, weaknesses, and strengths associated with Smart Quality applications in Taiwan's manufacturing sector. The instrument of this research utilized is a questionnaire designed to assess the dimensions of Smart Quality applications. In the contemporary perpectives of Industry 4.0, digitalization and the adoption of intelligent methodologies are central to the advancement of autonomous systems aimed at achieving an optimal balance between quality and productivity [19].

Industries require advanced tools and technologies to effectively respond to the evolving landscape of quality management. A thorough literature research has been performed to evaluate progress and deficiencies in the industry concerning the application of contemporary quality management system requirements. The implementation of total quality management (TQM) philosophy across organizations resulted from extensive debate, yielding benefits such as increased revenues, reduced waste, and strategic advancements. Researchers primarily concentrated on the reengineering of processes and standardization, as well as the strategic alignment of organizations with the satisfaction of the customers. The primary result of the research involved a framework that was verified through applications in both the service and manufacturing sectors [24], [25]. Digitalization and real-time data management systems were made necessary for industries to integrate with enterprise resource planning [16], [26], [27].

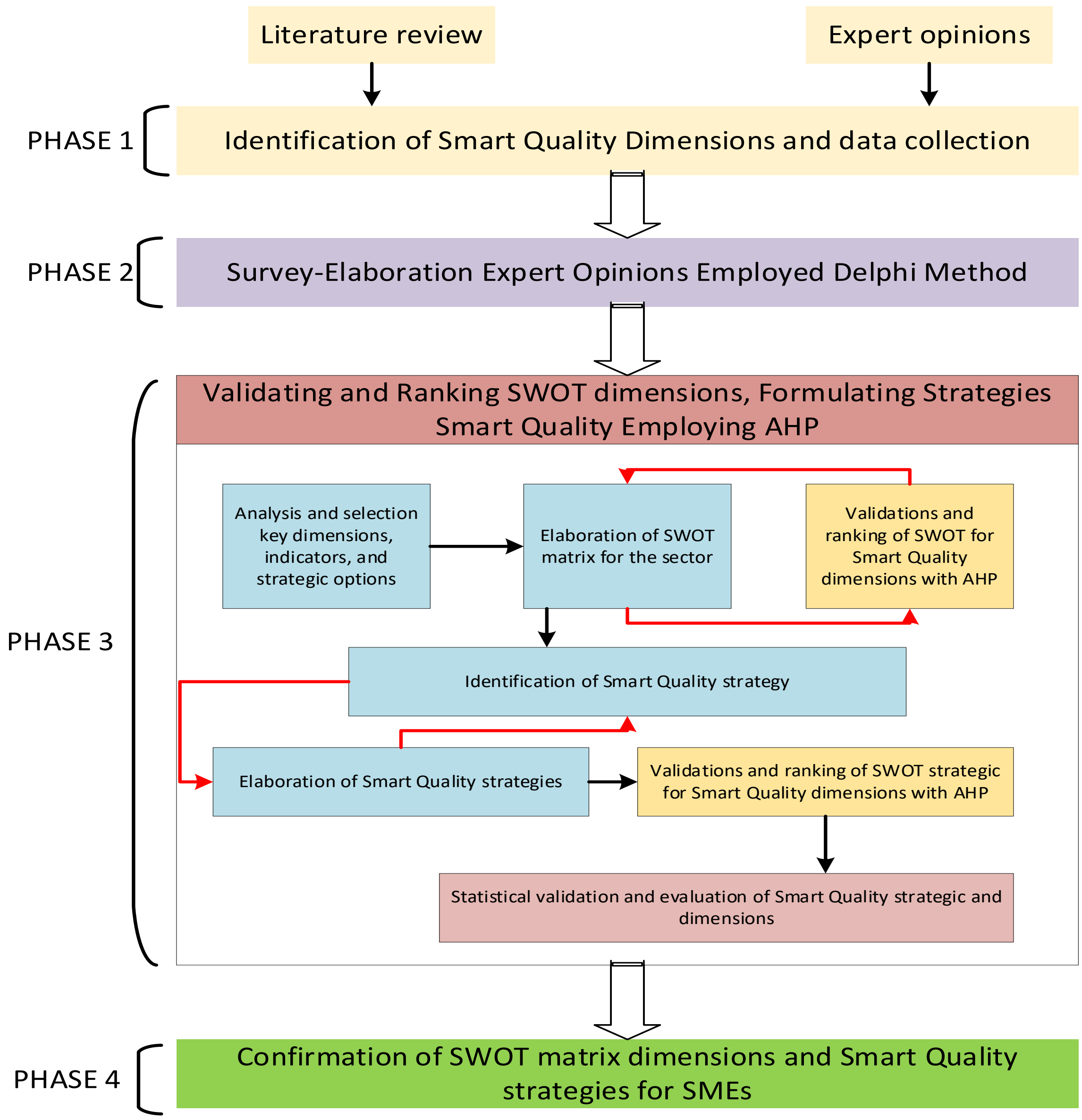

Figure 1. Research framework

2.1. Delphi Method

The Delphi method iteratively processes expert opinions on a specific problem until the experts reach a consensus. Delphi efficiently gathers and refines expert judgment through a continuous data collection method and subsequent brainstorming on the subject under investigation.

2.2. AHP Methods

The analytical hierarchy process (AHP) is a pairwise comparison measuring method that establishes priority scales based on expert opinions. The AHP addresses the assessment of the relative significance of a set of acts in a multi-criteria decision-making context. As shown in Table 1, the AHP employs a standardized nine-level scale to perform multiple pairwise comparisons.

Table 1. Likert scale

Scale rating	Meaning
1	'Equally' important
3	'Moderately' important
5	Important
7	'Very' important
9	'Extremely' important
2,4,6,8	There are values amid binary neighboring decisions.

These variables are also validated by counting the consistency ratio on the AHP stage. The consistency index (CI) must first be computed using the following formula:

$$\mathrm{CI} = \frac{\lambda_{max} - n}{n - 1} \quad (1)$$

Where λ_{max} This means the maximum value of Eigenvalue and n is several matrix order. To obtain the consistency ratio (CR), divide the consistency index by the random consistency index using the following formula:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \quad (2)$$

An CR value of 0.1 is the upper limit. When the total consistency ratio is higher than what is wanted, it is necessary to repeat the review technique in order to get a better consistency level.

The overall hierarchy and the consistency of decision-makers can be examined through consistency evaluation. Figure 2 is a hierarchical model of smart quality consisting of 8 categories and 21 factors.

2.3. Statistical Analysis

At this stage, statistical tests are conducted to test the correlation between categories and the hypotheses that are proposed. Table 3 presents the proposed hypotheses. For each dimension, the t-value, significance (p-value), mean difference, and standard deviation will be presented. Any response that fits inside the 95% confidence interval has a p-value of less than 0.05 for each dimension. The value exceeds the stated threshold of 2.5, considered minor to normal.

2.4. SWOT Analysis

SWOT is a crucial analysis tool within decision-making frameworks. It helps evaluate system characteristics, potential, and competitive standing.

This tool can also serve as a strategic asset during planning stages to achieve specific objectives.

By identifying SWOT parameters within a decision matrix, known as the SWOT matrix, organizations can engage in strategic planning. Moreover, the SWOT technique is valuable for initiating smart quality processes by assessing strategies to uphold organizational positions. This study's initial phase involved conducting a SWOT analysis to understand the landscape of smart quality processes in SMEs.

A comprehensive SWOT analysis and formulated strategies were undertaken to achieve effective quality implementation objectives. This comprehensive approach, incorporating SWOT analysis, corporate strategies, and public policies, was validated using Delphi and AHP methods.

3. Results

In this research, the first stage was to identify dimensions that influence smart quality in Taiwan SMEs. Dimensions were obtained based on literature reviews and expert opinions regarding smart quality. There are 8 dimensions of smart quality which are shown in Table 2.

Next, these dimensions are analyzed for validity and reliability. The purpose of reliability analysis is to measure how consistently a measurement instrument or research method produces the same or similar results when repeated. This helps determine whether the instrument is reliable in measuring what it is intended to. The aim of validity analysis is to assess the degree to which a measurement instrument or research method accurately assess what it is intended to measure. This ensures that the method measures the variable or concept intended in the research.

Table 2. Smart quality dimensions

Dimensions	Descriptions	References
Financial side (FS)	This refers to the financial aspects involved in maintaining and improving smart quality. It includes budgeting, cost analysis, return on investment (ROI), and financial planning to ensure that smart quality initiatives are financially sustainable and beneficial to the organization.	[28], [36]
Tactics (TC)	Tactics in the context of smart quality involve the specific actions and plans implemented to achieve quality goals efficiently.	[29], [30], [36]
Technology	Technology plays a crucial role in smart quality by enabling automation, data analysis, and real-time monitoring. It includes tools such as sensors, data analytics software, quality management systems (QMS), and other digital solutions that help optimize processes, detect defects, and ensure consistency in quality.	[31], [32], [36]
Infrastructure (INF)	Infrastructure refers to the physical and organizational framework necessary to support smart quality initiatives. This includes facilities, equipment, IT systems, communication networks, and logistical support needed to implement quality processes effectively and efficiently.	[28], [36]
Leadership (LD)	Leadership is essential for driving smart quality initiatives throughout an organization. Effective leaders provide vision, direction, and support for quality improvement efforts. They also foster a culture of continuous improvement, empower employees, and allocate resources strategically to achieve quality objectives.	[33], [34], [36]
Organizational Culture (OC)	When people in an organization talk about their "culture," they're referring to their commonalities in terms of values, beliefs, conventions, and actions toward excellence.	[34], [35], [36]
Skilled & Competent Worker (SC)	Skilled and competent workers are essential for maintaining smart quality standards. They possess the necessary knowledge, skills, and expertise to perform tasks accurately, identify quality issues, and contribute to continuous improvement efforts.	[14], [30], [36]
Strategy	A well-defined strategy provides a roadmap for prioritizing resources, implementing improvement initiatives, and measuring success in terms of quality outcomes.	[34], [36], [37]

Table 3. Evaluation of the hypothesis testing

No.	Hypothesis	Test
H1	The Smart Quality framework is implemented in the industry.	t-test (Target value = 2.5)
H2	All dimensions of the Smart Quality framework are implemented in the industry.	t-test (Target value = 2.5)
H3	All dimensions of Smart Quality have a relationship with each other	Sig. Pearson (Correlation Coefficient)
H4	The existence of Quality Management professionals enables an organization to implement the Smart Quality framework.	ANOVA (F-value)

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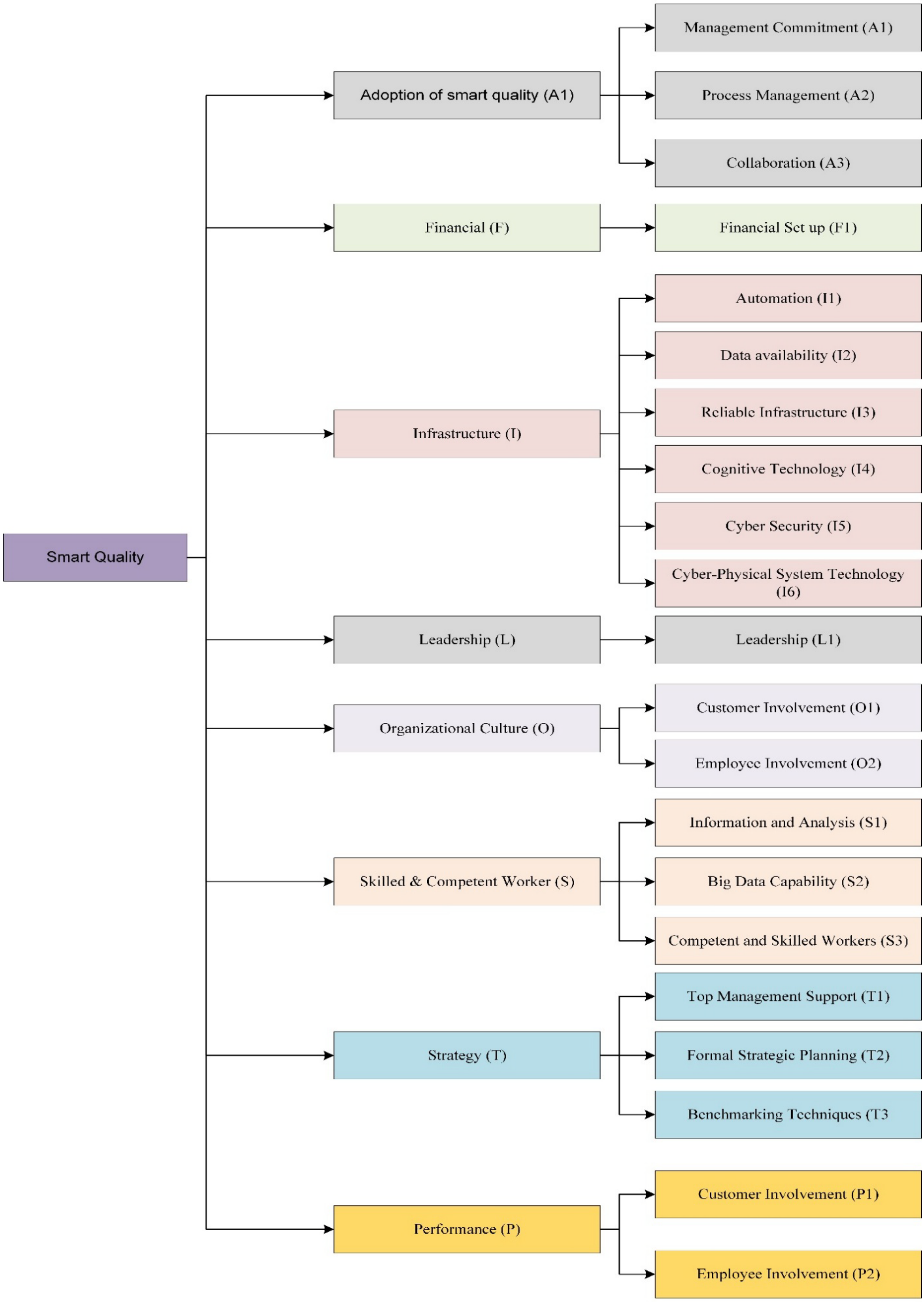

Figure 2. Decision hierarchy for ranking variable to smart quality adoption

3.1. Statistical Analysis

It is evident from the F hypothesis test table that the eight factors pertaining to smart quality dimension have a substantial influence on smart quality, with a concurrently significant value of less than 0.05 or 5%. This means that simultaneously all variables influence smart quality (Table 4).

As shown Table 5 in this study, the model has a value of 0.976. This proves that the model in this research is considered adequate, reliable, and consistent. The value of Cronbach's Alpha can vary between 0 and 1, with higher values indicating greater internal reliability of the instrument [37].

Table 4. F smart quality test results

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	1365.436	8	170.680	.	.00
Residual	.000	21	.000		
Total	1365.436	29			

Table 5. Reliability statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
0.975	0.976	8

The results for H1 and H2 for the eleven Quality 4.0 dimensions were checked by comparing the means of the replies for each variable with 2.5 (a target value - low to normal implementation). For each dimension, it gives the t-value, p-value, mean, standard deviation, and mean difference. The response falls within the 95% confidence interval and is considerably greater than the 2.5 (set value - minor to normal implementation) if the significance (p-value) of any dimension is less than 0.05 in this table. Results for each of the eleven dimensions are displayed in Table 6, along with a t-value of 8.467 that is statistically significant at a level higher than 0.05.

This proves that H1 is correct, as mentioned before, since the average rating across all eleven dimensions (3.007) is much greater than the cutoff grade of 2.5. Displays statistically significant results for the following dimensions: analytics, data collection, leadership, competency, connection, and cooperation (p-value greater than 0.05). Culture, scalability, and app development did not show statistical significance, suggesting limited industry application (p-value less than 0.05), although the study participants stated that these characteristics are significantly applied in their industries. In addition, they prove that H2 is false, since the Quality 4.0 framework's eleven dimensions have not been widely adopted by the industry.

Table 6. Summary of independent samples t-Test examining differences of factors in smart quality

Parameters	DOF	Mean	Std. Deviation	Std. Error Mean	t-test	Sig (2-tailed)
LD	29	4.370	1.036	0.192	0.319	0.376
TC	29	4.213	0.977	0.181	-0.523	0.698
OC	29	4.292	1.044	0.191	-0.086	0.534
SC	29	4.269	0.827	0.151	-0.257	0.600
WQ	29	4.264	1.045	0.194	-0.227	0.589
INF	29	4.517	0.895	0.166	1.256	0.109
FS	29	4.258	0.935	0.171	-0.288	0.612
IP	29	4.300	1.100	0.201	-0.041	0.516

Note : LD: leadership, TC: tactics, OC: organization culture, SC: skill and competent, INF: infrastructure, FS: financial side, IP: integrated performance

3.2. SWOT Analysis

According to the results of statistical tests, the reliability and validity of the proposed model have been obtained.

Next, a SWOT analysis was carried out to identify existing smart quality conditions in Taiwanese SMEs.

Table 7 presents the findings of the SWOT analysis, highlighting the internal and external elements that affect smart quality.

Table 7. SWOT analysis result

Internal Factors	
Strength	**Weakness**
Personalized learning experiences: Tailored content and resources based on individual student needs and preferences (S1) Streamlined administrative processes: Automation of tasks and optimized resource allocation leading to increased efficiency (S2) Strong leadership support: Essential for successful implementation and alignment with institutional goals (S3) Robust technology infrastructure: Enabling the integration of advanced solutions for quality management (S4)	Cost of implementation: Expenses associated with technology investments, training, and maintenance (W1) Resistance to change: Faculty and staff may be hesitant to adopt new processes or technologies (W2) Skill gaps: Lack of necessary skills and training among faculty and staff (W3)
External factors	
Opportunities	**Threats**
Expansion of online course offerings: Greater flexibility and accessibility for remote learning (O1) Agile curriculum development: Staying responsive to changing industry needs and emerging trends (O2)	Competing priorities: Potential diversion of resources away from smart quality initiatives (T1) Technological complexities: Integration challenges with existing institutional systems (T2) Cultural barriers: Resistance to new attitudes, practices, and cultures (T3) Speed of technological upgrading: Keeping pace with rapid advancements in technology (T4)

Alternatives; According to the analysis in the previous stage, the strategic alternatives have been determined to support smart quality in SMEs in Taiwan shown in Table 8.

Table 8. The strategic alternative of smart quality

Code	Alternative
A1	Personalized Learning Expansion: Leverage your personalized learning experiences (S-1)
A2	Develop a roadmap for scaling personalized learning initiatives to accommodate the increased demand for online education.
A3	Invest in adaptive learning technologies to enhance the flexibility and accessibility of online courses.
A4	Skill Enhancement Program: Address skill gaps (W-3) by capitalizing on the opportunity for agile curriculum development (O-2).
A5	Development programs focused on emerging trends and industry needs.
A6	Partner with industry experts to provide hands-on training and mentorship opportunities for faculty.
A7	Technology Security Enhancement: Utilize your robust technology infrastructure (S-4) to mitigate data security and privacy concerns (T-4).
A8	Allocate resources to strengthen cybersecurity measures and ensure compliance with data protection regulations.
A9	Implement regular audits and assessments to identify vulnerabilities and proactively address security threats.
A10	Change Management and Risk Mitigation: Address resistance to change (W-2) while managing the speed of technological upgrading (T-4).
A11	Develop a comprehensive change management strategy that emphasizes the importance of adapting to technological advancements.
A12	Implement risk management protocols to identify potential challenges and formulate contingency plans to reduce their impact.

To determine the relative importance of each subcategory strategy, experts compared each strategy against others and suggested priorities for them. Additionally, a comparison matrix was generated using the comparative data from the questionnaire. The weight of each subcategory strategy for every expert was then normalized. Subsequently, the average of the ideal weights for each barrier, as determined by multiple experts, was calculated.

The resulting relative weights were used to rank the subcategory strategies, with the highest-weighted strategy ranked first and the lowest-ranked last. Furthermore, the relative weights of the subcategory strategies and the optimal weights of the corresponding main category strategies were multiplied to obtain the global weights of the subcategory strategies. Figure 3 shows the priority weight of each category of the dimensions of smart quality. While Figure 4 shows the weight of the factors of smart quality.

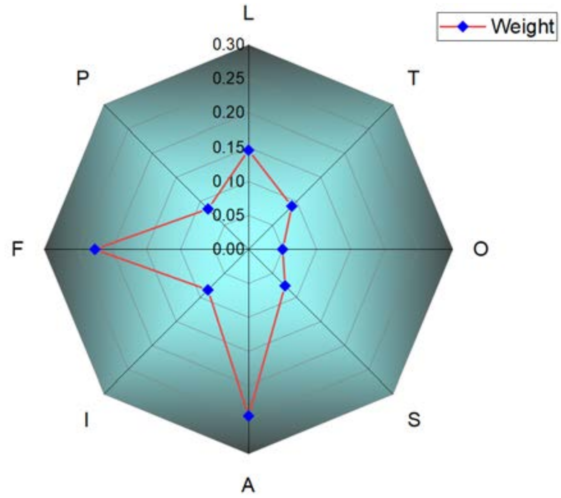

Figure 3. Final weight of categories of smart quality

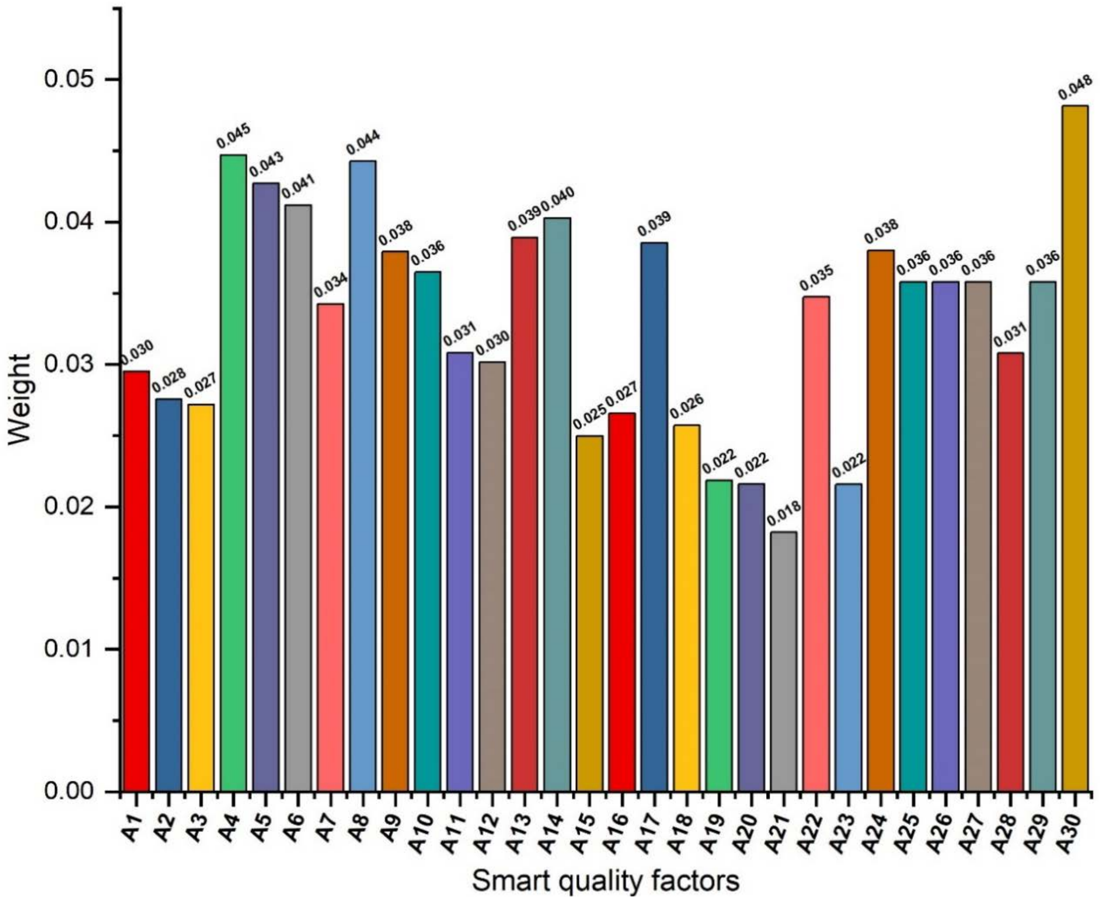

Figure 4. Final weight of smart quality factors

4. Discussion

The role of the financial side or financial aspects is very important in the context of smart quality because it has a direct influence on the effectiveness, efficiency, and sustainability of the adoption of smart quality strategies. The success of smart quality depends on the efficiency and effectiveness of operational processes. Good financial management allows the appropriate allocation of funds to optimize production processes, reduce costs, and improve product or service quality. Overall, finance plays an vital role in facilitating and supporting the adoption of smart quality, helping organizations to achieve higher quality goals in an efficient and financially sustainable manner. The right tactics in implementing smart quality methods and techniques can help organizations achieve the desired results more efficiently. This includes the use of tools such as Six Sigma, Lean Manufacturing, or TQM. Workers who have the skills to apply these tactics can optimize production processes, reduce waste, and improve product or service quality. Overall, the tactics used by the organization and the skills of individual workers play a major role in realizing smart quality. By implementing the right tactics and developing appropriate skills, organizations can achieve higher levels of quality in their operations, create competitive advantages, and better meet customer needs.

Table 8 shows that the A1 strategy is the main strategic priority in moving towards smart quality for Taiwan SMEs. By leveraging personalized learning experiences, companies can improve the overall quality of learning, thereby increasing customer satisfaction and their ability to achieve better learning outcomes for the company. This strategy encourages companies to develop a roadmap to scale personalized learning initiatives. This not only allows organizations to accommodate growth but also encourages innovation in the learning approaches, technology, and teaching strategies used, thereby enabling continuous improvement in the quality of learning. Meanwhile, the third strategic priority is A5. By focusing development programs on new trends and developing industry needs, companies can better understand what the market and their customers want. This allows them to design products or services that better meet market demands, increase customer satisfaction, and ensure higher product quality.

Based on the findings of Figure 3 and Figure 4, the most significant variable in implementing Smart Quality is the financial setup, with a value of 0.048.

Globally, as shown in the figure, the top three factors for implementing Smart Quality in SMEs are financial setup, commitment management, and process management.

In the perspectives of Small and Medium Enterprises (SMEs), these three elements—financial setup, management commitment, and process management—are crucial for the successful implementation of technology-driven quality management systems. An effective financial setup enables SMEs to allocate sufficient funds to adopt smart technologies, provide employee training, and maintain the system over time. Proper financial management ensures that smart quality initiatives can be implemented smoothly and sustained in the long term, leading to reduced operational costs through increased automation and efficiency. The benefits of such investments include enhanced operational efficiency and competitive advantage, as smart technologies streamline processes, reduce time and manual labor, and enable SMEs to compete more effectively with larger enterprises.

5. Conclusion

SMEs play an important role in contributing to national GDP and economic growth. By integrating smart manufacturing principles with a focus on quality, this framework represents a strategic shift towards modern technologies that enhance productivity and competitiveness. While smart manufacturing offers significant potential for improving production and consumption efficiency, many SMEs face limitations and obstacles that hinder its full adoption. This research addresses this gap by thoroughly examining the challenges and potential benefits of adopting smart quality practices to improve efficiency and quality. Key dimensions identified as critical for smart quality include financial resources, effective strategies, and a skilled, competent workforce. The synergy between these elements is essential for achieving smart quality targets. By investing in these areas, organizations can build a solid foundation for continuous improvement, innovation, and excellence in quality management. This research elucidates the drivers propelling SMEs' shift from traditional to smart quality. These insights will assist SMEs in developing tailored roadmaps for smart manufacturing adoption, enabling them to stay competitive and foster sustainable growth.

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