INTERNATIONAL JOURNAL OF eBUSINESS AND eGOVERNMENT STUDIES
Vol: 16 **No:** 2 **Year:** 2024 **ISSN:** 2146-0744 (Online) (**pp.**345-364) **Doi:** 10.34109/ijebeg.2024160217
Received: 11.04.2024 | **Accepted:** 20.10.2024 | **Published Online:** 03.10.2024

-RESEARCH ARTICLE-

THE PREPARATION TO BE ACCREDITED BY CLEAN ROOM STANDARD (ISO 14644) IN THE ELECTRICAL AND ELECTRONIC INDUSTRY

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─Abstract─

In the current competitive marketing landscape, particularly within the electrical and electronics industry, the adoption of cleanroom standards, including those outlined in ISO 14644, is essential for gaining valuable insights and fostering industry growth. This study aims to investigate the factors influencing the adoption and implementation of cleanroom standards in Thailand's electrical and electronics sector. A mixed-methods approach was employed to explore the motivations, challenges, and impacts of cleanroom certification across 500 companies. The study identified four primary constructs influencing the adoption of cleanroom standards: Regulatory Insights, Resource Arrangement, Stakeholder Collaboration, and Learning and Growth. The

Citation (APA): Janchaichanakun, P., Techakana, J., Silpcharu, T. (2024). The Preparation to be accredited by Clean Room Standard (ISO 14644) in the Electrical and Electronic Industry. *International Journal of eBusiness and eGovernment Studies, 16*(2), 345-364. doi:10.34109/ijebeg. 2024160217

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structural equation model reveals complex interrelationships among these factors, with Regulatory Insights emerging as the most influential. The key motivation for certification was identified as the enhancement of product quality, while the principal challenge was the substantial costs associated with technology and equipment. Following certification, companies reported significant improvements in product quality, reputation, and customer satisfaction. No notable differences were found in the perceived importance of these factors between small-medium enterprises and large enterprises. These findings suggest that enhancing the understanding of quality management practices within emerging manufacturing sectors can significantly contribute to the development of both theory and practice, as well as inform policy decisions, thereby supporting the growth of high-tech industries.

Keywords: Structural Equation Model, Cleanroom, ISO 14644, Electronics Manufacturing, Regulatory Compliance, Controlling Dust

INTRODUCTION

Background and Significance of the Problem

The electrical and electronics industry is pivotal to Thailand's economic development, with the government prioritising its growth as part of a broader strategy to establish the country as a hub for "High-Tech" manufacturing in Southeast Asia (Poyyamani Sunddararaj et al., 2021). The sector has experienced substantial expansion, with the number of businesses increasing by 14.41% between 2018 and 2022. However, this growth has been hindered by significant environmental challenges, particularly air pollution, which poses a threat to both public health and industrial operations (Cabral et al., 2020). Airborne particulates are of particular concern in the manufacturing of sensitive electronic components, where cleanroom environments are essential to ensure product quality and reliability. Despite the critical importance of cleanrooms, Thailand has seen a significant decline in cleanroom certifications within the electrical and electronics sector, dropping from 769 in 2018 to 239 in 2022. This trend suggests that many businesses are struggling to meet the necessary standards (Mičko et al., 2022). Factors contributing to this decline include technical complexity, financial constraints, and inadequate training, particularly within small and medium-sized enterprises (SMEs). This decrease poses a threat to Thailand's aspirations to become a leader in high-tech manufacturing and to fully participate in global value chains.

Moreover, the broader implications of cleanroom certification extend to public health and environmental management, highlighting the need for a holistic approach to industrial hygiene (Annamalai, 2015). Current literature predominantly focuses on the technical aspects of cleanroom technologies, with insufficient attention given to the practical challenges faced by businesses in developing economies, particularly SMEs (Kiani et al., 2022; Rizwan et al., 2022). Furthermore, there is a gap in understanding

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the role of organisational culture and human factors in the successful operation of cleanrooms (Manjunatheshwara & Vinodh, 2021). Additionally, the economic impacts of cleanroom certification in developing economies remain underexplored, with research limitations concerning "Long-Term Benefits", such as enhanced competitiveness and improved market access. This study aims to address the declining certification rates in Thailand's electrical and electronics sector by investigating the factors influencing businesses' readiness for cleanroom certification. By examining the technical, organisational, and cultural factors involved, the study seeks to identify practical strategies to improve certification rates, thereby contributing to Thailand's broader economic and industrial development objectives.

Objectives of the Research

To examine the general structure, organisational frameworks, and operational processes that contribute to the successful attainment of cleanroom certification (ISO 14644) by organisations in Thailand's electrical and electronics industry.

To identify and analyse the key components of preparedness strategies essential for achieving cleanroom certification (ISO 14644), along with the critical factors and strategies that organisations within the electrical and electronics industry need to implement effectively.

To develop and assess a structural equation model that represents the preparedness strategies, their interrelationships, and their effectiveness in facilitating successful cleanroom certification (ISO 14644) within the electrical and electronics industry.

Scope of the Research

The study was conducted in three main phases as follows:

Phase 1: A qualitative approach involving in-depth interviews with industry experts and successful cleanroom operators to gain a comprehensive understanding of the certification process and organisational characteristics.

Phase 2: A quantitative phase consisting of a large-scale survey conducted across businesses in the electrical and electronics industry to collect data on preparedness factors, organisational characteristics, and certification outcomes.

Phase 3: A qualitative phase involving focus group discussions with industry stakeholders to evaluate the findings from the quantitative phase and ensure the practical relevance and applicability of the research outcomes.

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Population and Sampling

Phase 1: A qualitative approach involving experts in cleanroom technology, certification processes, and Thailand's electrical and electronics industry. Nine experts were selected based on criteria established by the Doctoral Program Committee in Industrial Business Administration, Faculty of Business Administration, King Mongkut's University of Technology North Bangkok.

Phase 2: A quantitative phase targeting business operators or quality management executives in Thailand's electrical and electronics industry. A sample of 500 respondents was selected using cluster sampling, followed by the lottery method, to ensure representativeness across different business sizes and sub-sectors within the industry.

Phase 3: A qualitative phase involving a focus group of 11 qualified experts, chosen for their expertise and involvement in the industry and certification processes. This multi-layered sampling approach ensures that the study captures perspectives from a diverse range of stakeholders, including individual businesses, industry experts, and policymakers.

Variables of Study

1) Independent Variable: Refers to the characteristics of businesses in Thailand's electrical and electronics industry, such as size, sub-sector, and years of operation.

2) Dependent Variables: Refers to preparedness for cleanroom certification (ISO 14644), measured through a checklist of readiness indicators, and components of preparedness strategies, assessed on a rating scale. These variables are categorised into:

1) Observed Variables: Directly measured indicators of cleanroom certification preparedness.

2) Latent Variables: Exogenous Latent Variable: Regulation Insights

Endogenous Latent Variables: Resources Arrangement, Stakeholder Collaboration, and Learning and Growth

LITERATURE REVIEW

Related Theory

The crucial theories that form the foundation of this study include: 1) System Theory, 2) SWOT Analysis, 3) McKinsey's 7S Framework, and 4) IFE and EFE Matrices (Wang et al., 2022). Each of these theories contributes to a comprehensive understanding of

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the structural, strategic, and operational elements critical to the success of modern businesses, particularly in environments where technology and innovation are central (Liu et al., 2022).

1) System Theory focuses on the interconnection of various components within an organisation, emphasising that for optimal performance, each subsystem must function effectively. In this study, System Theory offers a perspective for understanding the complex relationships between Regulation Insights, Stakeholder Collaboration, and Learning and Growth. The theory aligns with the research, providing a framework for analysing how these elements interact and influence the overall performance of a system, particularly in the context of businesses adapting to digitalisation.
2) SWOT Analysis involves the internal recognition of an organisation's Strengths and Weaknesses, as well as external Opportunities and Threats. This is pertinent to the study as it provides a framework to assess the strategic position of businesses adopting new technologies, enabling an evaluation of their potential for success and identifying areas for improvement (Junga et al., 2023).
3) McKinsey's 7S Framework focuses on seven critical elements of organisational success and offers insights into understanding organisational dynamics (Habibollahi Najaf Abadi et al., 2023). It is particularly relevant to this research as it explains how organisations align their strategy, structure, and systems with the skills, leadership style, staff, and shared values necessary to foster innovation and adaptation in a rapidly changing environment (Dobrowolski, 2021).
4) The IFE and EFE Matrices Grigorescu et al. (2019) provide quantitative methods for evaluating both internal and external factors influencing organisational success. These matrices are crucial for assessing the elements that affect the effectiveness of digital transformation and circular economy strategies within the manufacturing sector. By using these tools, the researchers can identify business areas that are performing well or require improvement, thus supporting the development of targeted strategies to enhance overall performance.

Related Variables

The independent variables in this study include Regulation Insights, Resources Arrangement, Stakeholder Collaboration, and Learning and Growth. These variables have been extensively explored in the literature, with their influence on various aspects of business performance being well-documented. The dependent variable in this study is organisational performance, which is measured using metrics such as efficiency, profitability, and sustainability.

Conceptual Framework

The conceptual framework for this research integrates the theories and variables

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discussed earlier, providing a structured approach to explore the relationships between Regulation Insights, Resources Arrangement, Stakeholder Collaboration, and Learning and Growth. The framework suggests that effective Regulation Insights, supported by a consistent arrangement of resources, stakeholder collaboration, and a focus on learning and growth, enhances organisational performance. The quality of Regulation Insights mediates this relationship, ensuring that the necessary inputs are available and utilised efficiently to achieve the desired outcomes (Brand et al., 2013; Ghulam & Abushammala, 2023).

Research Hypothesis

H1: *Regulation Insights positively influences resources arrangement in the manufacturing sector.*
H2: *Well-consistent learning and growth increases the effectiveness of strategic planning in achieving regulation Insights.*
H3: *Strategic planning positively moderates the relationship between regulation insights and stakeholder collaboration.*
H4: *Effective management mediates the relationship between learning and growth and resources arrangement.*
H5: *Influence the relationship between learning and growth and stakeholder collaboration.*

METHODOLOGY

This study employed a mixed-methods approach, combining both qualitative and quantitative techniques, to explore the various factors influencing organisational readiness for achieving cleanroom standards (ISO 14644) in the electrical and electronics industry.

The construction of this study incorporates three key methodological techniques, ensuring robustness and depth in the findings:

The qualitative phase involved in-depth interviews and focus group discussions.

The quantitative phase was conducted through survey research.

The survey was designed to assess various organisational characteristics and their relationship with successful certification outcomes.

The combination of qualitative and quantitative data allowed for a comprehensive analysis, where qualitative insights informed the creation of survey methods, and the quantitative results were statistically significant in relation to the hypotheses set (Mata et al., 2022).

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The population and sample for this study comprised business operators in the electrical and electronics industry who sought cleanroom certification between 2018 and 2023. This group was selected based on the relevance of the research objectives, ensuring a representative sample of organisations in the certification process. The study included both large enterprises with fixed assets exceeding 200 million Thai Baht and small to medium-sized enterprises (SMEs) with assets below this threshold.

In the qualitative phase, a purposive sampling method was used to select 9 experts from three key groups: government officials, business executives, and academic scholars, each offering unique perspectives on the study. To ensure a diverse range of opinions, 11 industry experts were chosen for focus group discussions, distinct from those interviewed in the earlier phase.

The quantitative phase employed a multi-stage sampling technique, beginning with the development of a sampling frame based on industry size and geographical location. A total of 500 respondents were selected using Cluster Sampling, further enhanced by probability sampling methods, such as Lottery Selection. This approach ensured a robust and diverse sample, allowing the generalisation of results to the broader population.

The tools used in the quantitative phase were organised into four sections to collect comprehensive information on organisations preparing for cleanroom certification, as follows:

Section 1: Collecting demographic data related to the organizations.

Section 2: Examining resources arrangements and their operations applicable to the cleanroom certification.

Section 3: Evaluating the readiness for certification using a Likert Scale, where respondents rated the significance of various preparation techniques on a scale from the least important (1) to the most important (5).

Section 4: Conducting open-ended questionnaires designed to gather additional deeper information and key suggestions from respondents.

The tools used in the study were extensively tested for validity and reliability. Expert reviews confirmed the content validity of the qualitative tools, ensuring alignment with the research objectives. For the quantitative questionnaire, a pilot test was conducted with a sample of 30 respondents, which facilitated the calculation of bias indicators and the use of Cronbach's alpha to assess reliability. The trial test revealed high reliability, with Cronbach's alpha values at 0.92, indicating that the tool was both consistent and reliable.

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The data collection process was structured into both qualitative and quantitative phases.

1) The qualitative phase involved conducting in-depth interviews, where participants were invited via formal letters and scheduled at convenient times. The interviews were conducted face-to-face, audio-recorded, and later transcribed verbatim for analysis. Additionally, focus group discussions were organized, with participants provided discussion topics in advance to encourage informed and constructive conversations.

2) In the quantitative phase, a survey questionnaire was distributed to the selected sample, with respondents contacted via email and postal mail. Reminders were sent to non-respondents to encourage a higher response rate. The completed questionnaires were collected, coded, and entered into statistical software for analysis. Ethical guidelines were strictly adhered to throughout the data collection process, ensuring confidentiality, voluntary participation, and informed consent from all participants.

Data Analysis

The qualitative data from interviews and focus groups were analyzed using "Content Analysis," which identified and coded concepts related to the research objectives. This analysis revealed the main factors influencing readiness, which were then used to inform the quantitative analysis. The quantitative phase involved descriptive statistics, such as frequencies, percentages, means, and standard deviations, to summarize the data. Inferential statistics, including t-tests, Pearson chi-square tests, and structural equation modeling (SEM), were employed to test hypotheses and explore relationships between variables. The SEM analysis, conducted using AMOS software, adhered to guidelines for model evaluation and adjustments based on indicators like CMIN/DF, GFI, and RMSEA. The combination of qualitative and quantitative results provided insights for developing a robust model, contributing to both theoretical and practical knowledge in the field.

RESULTS

The Quantitative Research Results

The findings highlight the significance of understanding the demographic and organizational characteristics of the 500 companies surveyed, which provide crucial context for interpreting the results. The sample was evenly split between SMEs and large enterprises, with 50% of respondents from each group, enabling a robust comparative analysis of their cleanroom strategies. Most companies (69%) had been operating for 10-20 years, suggesting an established sector with experienced personnel in electrical and electronics manufacturing, while 18.8% had operated for less than 10 years and 12.2% for over 20 years, indicating a mix of both new and long-standing companies. The majority (87.2%) were structured as limited companies, reflecting

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typical ownership and governance in Thailand's manufacturing sector, while 5% were public companies. Additionally, 60.8% of the companies were located within industrial estates, emphasizing the advantages these areas offer in supporting manufacturing operations, particularly in the electronics sector. Regarding ownership, 75.4% of the companies were Thai-owned, while 10.6% were foreign-owned, indicating a strong domestic presence alongside foreign investment, reflecting the global nature of the electronics manufacturing industry, as shown in Table 1.

Table 1: The Demographic and Organizational Characteristics of the 500 Companies that Participated in the Survey

Characteristic	Frequency	Percentage
Company Size		
Small and Medium	250	50%
Large	250	50%
Years in Operation		
<10 years	94	18.80%
10-20 years	345	69%
>20 years	61	12.20%
Company Type		
Public Limited Company	39	7.80%
Limited Company	436	87.20%
Public Company	25	5%
Location		
Industrial Estate	304	60.80%
Outside Industrial Estate	196	39.20%
Ownership		
Thai-owned	377	75.40%
Foreign-owned	53	10.60%
Joint Venture	70	14.00%

Implementing cleanroom standards is crucial in the electronics manufacturing industry, as environmental control directly impacts product quality. Among the surveyed companies, 73.2% obtained ISO 14644 certification within the last 5-15 years, indicating a to maintaining high standards. However, the certification process is time-consuming, with 47.8% of companies taking over two years to prepare. The data reveals that 54.2% of companies focus on household appliances, positioning Thailand as a leader in producing white goods, followed by industrial electronics (15%) and consumer electronics (30.8%). Market orientation is nearly balanced, with 51.8% of companies serving domestic markets, 9% exporting, and 39.2% catering to both. Furthermore, 57.4% operate as Original Equipment Manufacturers (OEMs), highlighting Thailand's role in global supply chains, while 31.6% produce goods under their own brands and 11% operate as Original Design Manufacturers (ODM), as presented in Table 2.

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Table 2: Summarizes the Key Characteristics Related to Clean Room Implementation among the Surveyed Companies

Characteristic	Frequency	Percentage
Years Since ISO 14644 Certification		
- <5 Years	61	12.20%
- 5-15 Years	366	73.20%
- >15 Years	73	14.60%
Time Required for Certification Preparation		
- <1 Year	49	9.80%
- 1-2 Years	212	42.40%
- >2 Years	239	47.80%
Primary Product Category		
- Household Appliances	271	54.20%
- Industrial Electronics	75	15%
- Consumer Electronics	154	30.80%
Primary Market		
- Domestic	259	51.8%
- Export	45	9%
- Both Domestic and Export	196	39.20%
Business Model		
- Original Equipment Manufacturer (OEM)	287	57.40%
- Own Brand Manufacturer(OBM)	158	31.60%
- Original Design Manufacturer (ODM)	55	11%

Understanding the motivations for cleanroom implementation and the challenges faced by companies is vital for improving compliance and efficiency. Table 3 reveals that 72.20% of companies primarily pursued ISO 14644 certification to improve product quality, highlighting its importance in the competitive electronics industry. Corporate image was the second most common reason (5.20%), indicating external pressures for compliance. Manufacturing quality and cost reduction (22.60%) also influenced some companies. The manufacturing and procurement departments were the main drivers of certification (79.40%), while financial departments played a lesser role (14.40%). Most companies developed cleanroom expertise internally (68%), with 14.60% relying on external consultants and 7.40% using industry associations for knowledge. The most time-consuming aspects of cleanroom certification preparation were facility design and layout, identified by 62.80% of companies as the biggest challenge, reflecting the complex physical demands of creating a cleanroom environment. Staff training (21%) and documentation procedures (16.2%) were also significant, highlighting the importance of training and accurate record-keeping. The most substantial challenge, however, was the cost of technology and equipment, cited by 80.2% of respondents, representing a major financial strain due to the need for advanced technology and ongoing investment to meet stringent standards.

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Table 3: Motivations and Challenges in Clean Room Implementation

Characteristic	Frequency	Percentage
Primary Motivation for Certification		
- Product Quality Improvement	361	72.20%
- Corporate Image	26	5.20%
- Manufacturing Quality and Cost Reduction	113	22.60%
Key Department Driving Certification		
- Manufacturing & Procurement	397	79.40%
- Financial Department	72	14.40%
- Human Resource and Communications	31	6.20%
Main Source of Clean Room Knowledge		
- Internal Team	340	68%
- External Consultants	73	14.60%
- Industry Associations	50	7.40%
Most Time-Consuming Aspect of Preparation		
- Facility Design and Layout	126	62.8%
- Staff Training	42	21%
- Documentation and Procedures	32	16.2%
Biggest Challenge in Implementation		
- Technology and Equipment Costs	401	80.20%
- Maintaining Consistent Practices	5	1%
- Consultant, Design, Training	94	18.80%

Clean Room Management Practices

Effective management practices are crucial in maintaining cleanroom standards and ensuring their sustained adherence. Table 4 outlines the management practices associated with cleanroom operations among the surveyed companies. A majority (66.6%) employed a centralized control strategy, reflecting a preference for standardized procedures and centralized decision-making, which helps ensure uniformity across departments and locations in applying cleanroom protocols. However, a notable minority (18%) opted for a decentralized approach, and 15.4% used a hybrid model, suggesting some companies prefer delegating control to individual units for greater flexibility and responsiveness to local conditions. Regarding team composition, 50.2% of companies relied solely on internal teams for cleanroom operations, while 20.4% utilized a mix of internal and external experts, balancing in-house knowledge with external expertise. A smaller group (10.2%) depended mainly on external consultants, either due to a lack of internal expertise or a preference for outsourcing specialized tasks. To manage cleanroom protocols, most companies (74.6%) used posted guidelines, a simple and effective method for keeping employees informed, while 9.6% conducted regular training sessions, and 15.8% implemented automated monitoring systems, signalling a shift toward more interactive and

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technologically advanced approaches.

Table 4: Clean Room Management Practices

Practice	Frequency	Percentage
Management Approach		
Centralized Control	333	66.60%
Decentralized Control	90	18%
Hybrid	77	15.40
Clean Room Team Composition		
Internal Team Only	251	50.20%
Mixed Internal and External Experts	102	20.40%
Primarily External Consultants	51	10.20%
Method of Enforcing Clean Room Protocols		
Posted Guidelines	373	74.60%
Regular Training Sessions	48	9.60%
Automated Monitoring Systems	79	15.80%
Budget Allocation vs. Initial Estimate		
On Budget	370	74%
Over Budget	100	20%
Under Budget	30	6%
Funding Source for Clean Room Project		
Bank Loan	392	78.40%
Internal Funds	27	5.40%
Government Grants	81	11.40%
Maintenance Responsibility		
Dedicated Internal Team	378	75.60%
Outsourced to Specialists	37	7.40%
Shared Responsibility Across Departments	85	17%

Budget management is crucial in cleanroom projects, with 74% of companies completing them within budget, reflecting effective cost estimation and project management. However, 18% exceeded their budgets, indicating underestimated or unforeseen expenses. Bank loans were the primary funding source for 78.40% of companies, highlighting the capital-intensive nature of cleanroom projects. Maintenance was primarily handled by internal teams (75.60%) for better operational control, although it requires ongoing investment in staff training. Fewer companies outsourced maintenance (7.40%) or shared it across departments (17%), with most preferring to keep it under internal control.

Factors Influencing Clean Room Standard Adoption

The adoption of cleanroom standards is influenced by four key factors: Regulation

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Insights, Resources Arrangement, Stakeholder Collaboration, and Learning and Growth. Regulation Insights was the most important factor (M = 4.50, SD = 0.27), with items such as designing cleanrooms according to ISO 14644, creating costume protocols, and setting clear usage guidelines receiving high ratings (M = 4.56, SD = 0.54), emphasising the importance of adhering to detailed regulatory strategies. Resources Arrangement was also highly rated (M = 4.42, SD = 0.37), with the maintenance of cleanliness in office and factory environments receiving the highest score (M = 4.51, SD = 0.57), indicating a broad strategy for cleanliness across the entire production facility. Stakeholder Collaboration was similarly important (M = 4.45, SD = 0.31), with regular reporting of cleanroom progress to stakeholders rated highly (M = 4.53, SD = 0.30), reflecting the need for transparent communication and stakeholder support. Learning and Growth had a slightly lower rating (M = 4.36, SD = 0.42), suggesting that companies prioritise regulatory compliance and resource management over continuous learning during initial cleanroom implementation. However, the development of cleanroom manuals and updating training curricula received strong ratings (M = 4.50, SD = 0.59), highlighting a focus on education and knowledge sharing, as shown in Table 5.

Table 5: Factors Influencing Clean Room Standard Adoption

Construct/Item	Mean	SD
Regulation Insights	4.50	0.27
Design clean room construction in line with ISO 14644 standards	4.56	0.54
Establish appropriate clean room attire regulations	4.56	0.54
Set clear guidelines for clean room and dust-free zone usage	4.56	0.54
Resources Arrangement	4.42	0.37
Maintain cleanliness in office and factory environments	4.51	0.57
Design or renovate buildings to minimize dust infiltration	4.47	0.57
Allocate appropriate budget for clean room investment	4.45	0.57
Stakeholder Collaboration	4.45	0.31
Regularly report clean room project progress to shareholders	4.53	0.53
Seek input from clean room technology suppliers	4.52	0.56
Participate in industry associations for knowledge-sharing	4.51	0.54
Learning and Growth	4.36	0.42
Develop online and offline clean room usage manuals	4.50	0.59
Regularly update training curricula to reflect new technologies	4.50	0.61
Encourage knowledge sharing among employees	4.47	0.58

Comparison of Construct Scores between SMEs and Large Companies

To explore potential differences in cleanroom standard operations between SMEs and large enterprises, independent t-tests were performed on the four main constructs. Table 6 presents the results, which show no statistically significant differences between SMEs

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and large enterprises across all constructs ($p > 0.05$). These findings suggest that enterprise size does not significantly impact the perceived importance of factors related to cleanroom standard implementation in Thailand's electrical and electronics industry. Although large enterprises tended to report slightly higher mean scores across all constructs, the differences were minimal and not statistically significant. The similarity in scores between SMEs and large enterprises can be attributed to factors such as the precise requirements of cleanroom standards, the need for substantial commitment, and effective resource management, which are important for all companies regardless of their size. The mature state of the Thai electrical and electronics industry, as indicated by the long operational histories of most surveyed companies, has led to a convergence of practices and perceptions across enterprises of various sizes. This suggests that the challenges and considerations in adhering to cleanroom standards are similar across the industry, with both SMEs and large enterprises equally prioritizing regulatory compliance, resource management, stakeholder collaboration, and continuous learning.

Table 6: Comparison of Construct Scores between SMEs and Large Companies

Construct	SMEs (n=250)	Large Companies (n=250)	t-value	p-value
Regulation Insights	4.45 (0.25)	4.41 (0.33)	1.48	0.25
Resources Arrangement	4.44 (0.34)	4.41 (0.39)	1.02	0.31
Stakeholder Collaboration	4.47 (0.26)	4.44 (0.34)	1.10	0.27
Learning and Growth	4.40 (0.35)	4.33 (0.48)	1.71	0.09

Hypothesis Testing

The study examined the relationships between key constructs and their impact on cleanroom standard operations, with the hypotheses being largely supported. Table 7 presents the results, highlighting significant relationships between the constructs. The strongest relationship was found between Regulation Insights and Resource Arrangement ($\beta = 0.71$, $p < 0.001$), indicating that a deep understanding of cleanroom regulations strongly influences companies' allocation and management of resources to meet cleanroom standards. This underscores the critical role of regulatory knowledge in effectively mobilizing resources. Additionally, Regulation Insights significantly positively influenced Learning and Growth ($\beta = 0.52$, $p < 0.001$) and Stakeholder Collaboration ($\beta = 0.44$, $p < 0.001$), suggesting that companies with better regulatory knowledge are more likely to invest in continuous learning and engage effectively with stakeholders. Learning and Growth also had moderate positive effects on Resource Arrangement ($\beta = 0.42$, $p < 0.001$) and Stakeholder Collaboration ($\beta = 0.57$, $p < 0.001$). These findings emphasize the importance of fostering a learning culture within organizations, as it enhances both resource management and stakeholder engagement—key factors for the successful implementation and ongoing adherence to cleanroom standards.

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Table 7: The Results of Hypothesis Testing

Hypothesis	Standardized Coefficient	P-Value	Result
H1: Regulation Insights → Resources Arrangement	0.71	<0.001	Supported
H2: Regulation Insights → Learning and Growth	0.52	<0.001	Supported
H3: Regulation Insights → Stakeholder Collaboration	0.44	<0.001	Supported
H4: Learning and Growth → Resources Arrangement	0.42	<0.001	Supported
H5: Learning and Growth → Stakeholder Collaboration	0.57	<0.001	Supported

Structural Equation Modelling (SEM) Analysis

To further explore the relationships between the constructs and their impact on cleanroom standards and operations, a SEM analysis was conducted. Table 7 presents the model fit indices before and after model improvements, with the final model achieving a good fit across all indicators. The original model showed acceptable CMIN/DF and RMSEA values, but did not meet the criteria for p-value and GFI. After making repeated modifications, guided by modification indicators and theoretical considerations, the model fit well within all required indicators. The SEM analysis confirmed the significant relationships identified through hypothesis testing and revealed some "indirect" effects. The strongest direct influence was found between Regulation Insights and Resource Arrangement ($\beta = 0.71$, $p < 0.001$), highlighting the importance of regulatory understanding in managing resources for cleanroom operations. A significant indirect effect was observed, where Regulation Insights influenced Resource Arrangement through Learning and Growth ($\beta = 0.22$, $p < 0.001$). This indicates that regulatory knowledge not only directly impacts resource arrangement but also fosters a culture of learning and growth, which in turn enhances resource management.

The model also emphasized the critical role of Learning and Growth in mediating the relationships between Regulation Insights and both Resource Arrangement and Stakeholder Collaboration. These findings underscore the importance of cultivating a learning culture within organizations operating cleanroom standards, as it supports resource management and stakeholder engagement. The indirect effects suggest that companies that prioritize learning and development are better equipped to manage resources effectively and collaborate with stakeholders, contributing to more successful cleanroom operations. The refined SEM analysis of readiness preparation for ISO 14644 cleanroom standards in the electrical and electronics industry is illustrated

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through Unstandardized and Standardized Estimates in Figures 1 and 2.

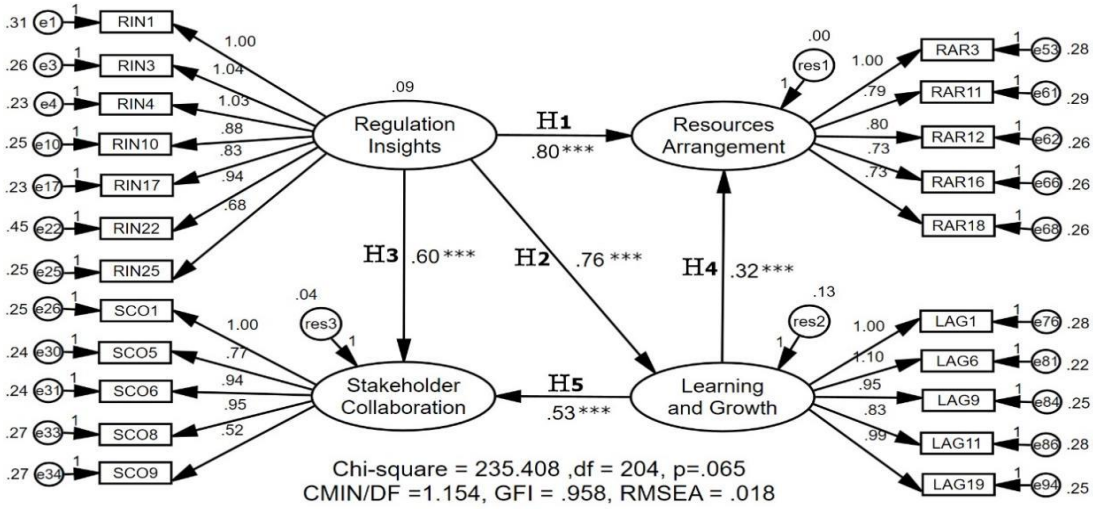

Figure 1: The Structural Equation Model in the Unstandardized Estimate Mode after Model Improvement

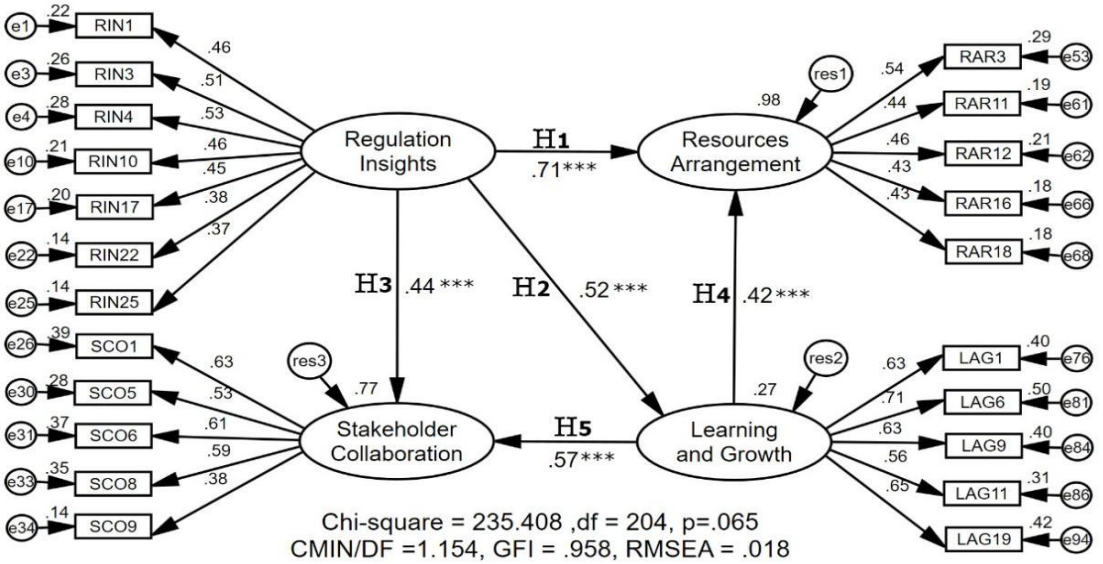

Figure 2: The Structural Equation Model in the Standardized Estimate Mode after Model Improvement

DISCUSSION

This study provides valuable insights into the application and operation of cleanroom standards within the electrical and electronics industry in Thailand, contributing to a broader understanding of quality management practices in emerging economies. The

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widespread adoption of ISO 14644 certification across the surveyed companies reflects global trends, although extended preparation periods were reported (Lin et al., 2019; Yang et al., 2021). The primary motivation for certification was identified as improving product quality, highlighting its strategic role in enhancing global competitiveness (Bhattacharya et al., 2023; Mu & Antwi-Afari, 2024). Knowledge management emerged as a critical factor in the certification process, significantly influencing resource management and stakeholder collaboration. The study also revealed the complexity of the regulatory environment and the need for a comprehensive application strategy (Marinello & Gamberini, 2021). Organizational learning was shown to play a key role in technology operations, challenging assumptions about size-related capabilities by demonstrating no significant differences between SMEs and large enterprises. The results also suggested that while initial operational costs are high, long-term benefits could offset these expenses. Significant positive influences on overall efficiency management were found, underscoring the strategic importance of stakeholder communication and knowledge sharing within cleanroom operations. Given the high costs of technology and equipment, the study emphasizes the need for supportive policies to assist SMEs in adopting these standards. Overall, the findings underline the strategic significance and challenges of cleanroom certification, which is crucial for enhancing competitiveness and supporting high-tech manufacturing in emerging economies.

CONCLUSION

The analysis of this study reveals that most companies recognise the importance of cleanroom standards, with 73.20% obtaining ISO 14644 certification within the last 5-15 years, highlighting the industry's commitment to high-quality standards and international compliance. However, nearly half of the companies reported that achieving certification took over two years, reflecting the complexity and resource intensity of the process. Product quality improvement was the primary motivation for certification, with 72.20% of respondents citing it, underscoring the competitive nature of the global electronics market where precision is crucial. Customer requirements and competitive advantage were also significant motivators, indicating that companies view certification as both a regulatory obligation and a strategic investment. Cleanroom standards also had a broader impact on business operations, leading to improvements in product quality, reputation, and customer satisfaction, emphasising the strategic value of certification beyond compliance. However, the impact on operational costs was mixed, indicating the need for careful financial planning. Key factors for successful cleanroom operation included Regulation Insights, recognised as the most important for regulatory knowledge, alongside Resources Arrangement and Stakeholder Collaboration, which highlighted the need for effective resource management and stakeholder engagement. The study found no significant differences between small, medium-sized, and large enterprises, indicating that cleanroom operation challenges are

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consistent across the industry. Structural equation modelling revealed that Regulation Insights significantly influenced resource management, with Learning and Growth playing a mediating role in enhancing resource management and stakeholder engagement. The study underscores the strategic importance of certification, highlighting its role in improving product quality, reputation, and customer satisfaction, offering valuable insights for companies to boost competitiveness and for policymakers supporting industry development.

SUGGESTIONS

Future research should develop theoretical models that integrate regulatory knowledge, organizational learning, and resource allocation, particularly in emerging economies and various industry sectors. Long-term studies exploring industry-specific factors will provide insights into the impact of quality management practices and regulatory changes on sustainability. Operationally, enhancing expertise and promoting continuous learning are crucial for aligning resources with regulatory requirements. Developing robust stakeholder engagement strategies and detailed operational plans will help address challenges in quality management practices. At the policy level, offering financial incentives for SMEs and improving access to regulatory information can support quality management practices. Encouraging industry collaboration through forums and integrating sustainability with quality management policies will further advance sustainable industrial practices.

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