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ORIGINAL RESEARCH

Bridging the gap: Empowering manufacturing and production small medium enterprises through industrial Internet of Things adoption model

Sajid Shah[1] | **Syed Hamid Hussain Madni**[2] | **Siti Zaitoon Mohd Hashim**[1] | **Muhammad Faheem**[3,4] | **Hafiz Muhammad Faisal Shahzad**[5]

[1]Faculty of Computing, Universiti Teknologi Malaysia, Skudai, Johor, Malaysia

[2]School of Computer Science, University of Southampton Malaysia, Iskandar Puteri, Johor, Malaysia

[3]School of Technology and Innovations, University of Vaasa, Vaasa, Finland

[4]VTT Technical Research Centre of Finland Ltd., Espoo, Finland

[5]Department of Computer Science, University of Sargodha, Sargodha, Pakistan

Correspondence

Muhammad Faheem, School of Technology and Innovations, University of Vaasa, Vaasa, Finland; VTT Technical Research Centre of Finland Ltd., Espoo, Finland.
Email: muhammad.faheem@uwasa.fi

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Abstract

The industrial Internet of Things (IIoT) is revolutionising manufacturing and production of small and medium enterprises (SMEs) by enhancing efficiency and product quality. While developed countries like the USA, UK, Canada, Finland, and Japan have widely adopted IIoT, developing nations such as Bangladesh, India, Pakistan, and Malaysia are still lagging. This study explores IIoT adoption in manufacturing SMEs, emphasising its potential for economic growth despite challenges like budget constraints and skill gaps in developing countries. It presents a novel model based on 17 factors from the TOEI (Technology, Organization, Environment, and Individual) framework to support decision-makers in integrating IIoT technologies. The model's reliability and validity are confirmed through rigorous testing and a survey of three SMEs. This proposed model serves as a roadmap for SMEs, breaking down complex processes into manageable steps, and providing SMEs with a structured approach.

KEYWORDS

computer integrated manufacturing, Internet of things, m2m communication, product customisation, small medium enterprises

1 | INTRODUCTION

The IoT has transformed the way humans interact in the physical world. It refers to a network of physical devices embedded with sensors, actuators, smart systems and advanced technologies that collect, process and exchange data over the Internet [1]. The IoT-based devices can range from simple wearables to complex industrial machineries, all connected to a central network for monitoring and control [2].

Industrial IoT (IIoT) takes the basic concept of IoT a step further by focusing on various applications within industrial sectors. IIoT is specifically focused towards addressing the requirements and challenges of the whole industrial sector [3]. IIoT empowers the machine-to-machine (M2M) communication, connectivity, automation and data-driven decision-making, to optimise industrial operations efficiently [4] as shown in Figure 1.

Figure 1 demonstrates the concept of Industrial IoT (IIoT) within the manufacturing and production SMEs. It particularly represents the integration of different industrial systems and technologies that allow production processes and smart manufacturing. The small icons in the figure highlight the

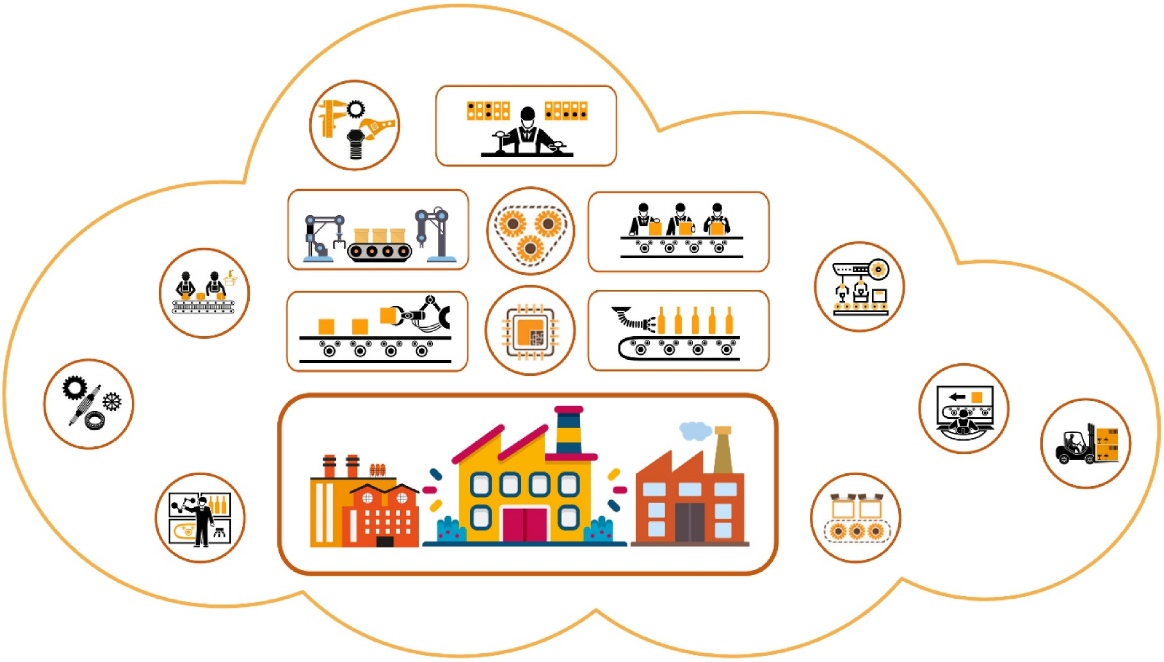

FIGURE 1 Industrial Internet of Things (IIoT).

potential key components and the capabilities of IIoT including automated production lines, sensor networks, robotic systems, data analytics, remote monitoring, supply chain management, workforce collaboration and energy management. The diverse range of applications and technologies that are the main part of the IIoT framework have been shown. Overall, Figure 1 conveys the idea of a data-driven, connected and intelligent industrial landscape, where different systems and smart technologies work together to improve the manufacturing processes, production, quality and overall performance within the manufacturing and production SMEs.

Small medium enterprises (SMEs) are considered as the small businesses as compared to larger corporations and industries that maintain assets, revenues and a number of employees up to a certain level. These SMEs are running independently in various sizes according to the countries. Furthermore, SMEs have employees less than 250 and are playing a significant role in the economy of the country. Small medium enterprises have various types that operate in different sectors, such as agriculture, healthcare, information technology, logistics, manufacturing, production, retail and tourism [5]. Manufacturing SMEs refer to the types of SMEs that produce and provide goods or products from raw materials while production SMEs refer to the types of SMEs that both services and goods.

The comparison of manufacturing and production SMEs based on SMEs' features is demonstrated in Table 1, including focus, processes, tangibility, capital requirement, quality control, regulations, skills, customer interaction, resource management and benefits of IIoT. Furthermore, both the production and manufacturing SMEs need to be focused together as both SMEs are facing the same unique opportunities and challenges when adopting the IIoT technologies within their environment. The adoption of IIoT can benefit both manufacturing and production SMES by enhancing overall operational performance, efficiency and quality.

In the context of manufacturing and production SMEs, the role of IIoT is dominant and transformative, to improve product quality, enhance the efficiency, real-time monitoring, predictive maintenance and optimised production processes, and also play a significant role in economic growth. These SMEs face various unique challenges and complications by adopting IIoT technologies due to several constraints, such as lack of budget, skills, knowledge etc. However, IIoT opens a lot of opportunities for SMEs to improve their competitiveness, by leveraging IIoT solutions for the manufacturing and production SMEs [6].

Industrial IoT (IIoT) serves at the forefront of transforming the manufacturing and production sectors across developed nations, such as Austria, Australia, Canada, Denmark, Finland, France, Germany, Japan, Italy, Netherlands, Norway, Singapore, South Korea, Sweden, Switzerland, United Kingdom and the United States, where advanced technology adoption is common, and already IIoT has revolutionised industrial sectors [7]. However, to the best of the authors understanding developing countries, such as Brazil, China, Indonesia, Malaysia, Nigeria, Pakistan, Saudi Arabia, Thailand and Vietnam are lagging behind in adopting IIoT technologies within their manufacturing and production sectors. Several factors contribute to disparity including the individual, environmental, Organisational and technological factors [7].

IIoT facilitates the transition towards Industry 4.0 and Industry 5.0, where interconnected systems enable seamless

TABLE 1 Comparison of manufacturing and production SMEs based on SMEs' Features.

SME features	Manufacturing SMEs	Production SMEs
Focus	Produce goods or products from raw materials on a large scale	Provide both goods and services on a large scale
Processes	Transformation of raw materials into finished goods and products	Assembly or transformation of materials into finished goods and services
Tangibility	Tangible (goods and products) such as machinery, surgical and healthcare equipment, fibre glass, steel items, clothes and fabrics, spare parts and many more	Tangible or intangible (goods and services) such as food items, software, plastic materials, glass items and many more
Capital requirements	Mostly higher capital or initial investment is required for the installation of machinery and equipment.	Lower capital or initial investment is required for production and services.
Quality control	Essential for consistent product and goods quality	Essential for maintaining good and service quality
Regulations	Dependent on safety, environmental regulations and labour	Dependent on specific requirements and standards set by the industry
Skills	Requires skilled workforce for production and operations.	Requires specialised workforce for the production and services.
Customers' interaction	Mostly indirect interaction and communication with the customers through the distribution channels	Mostly direct interaction and communication with the customer
Resource management	Manage large quantities of resources such as raw materials, machineries assets, labours and inventory are managed efficiently.	Manage the materials, machineries, labours and services are managed efficiently.
Benefits from IIoT	IIoT can enhance production efficiency, predictive maintenance, supply chain optimisation, efficiency and quality control throughout the process.	IIoT can enhance service delivery, customer experience, business insights, predictive maintenance, efficiency and quality control throughout the process.

Abbreviation: SMEs, small medium enterprises.

communication and collaboration across the industrial sectors. The potential benefits of IIoT adoption for manufacturing and production SMEs in developing countries are significant that can overcome various challenges and limitations while open new opportunities for growth and innovation [8]. Through the digitisation of manufacturing and production processes by the adoption of IIoT technologies, SMEs can achieve greater agility, flexibility and resilience in the evolving market dynamics at a high level. IIoT also enhances collaboration between SMEs, large enterprises and multinational industries, by enabling ecosystem partnerships that drive collective innovation, economic growth, competitiveness and sustainable development [6].

The adoption of IIoT holds immense promise for transforming manufacturing and production SMEs in developing countries. However, there is a need for a comprehensive model that can support the adoption of IIoT technologies for manufacturing and production SMEs and help SME stakeholders and decision makers to follow the specific IIoT adoption model and adopt the IIoT technologies smoothly within their business environment. For this purpose, a comprehensive IIoT adoption model serves as a roadmap, guiding SMEs through the process of adopting IIoT technologies seamlessly into the manufacturing and production operations. Moreover, alongside the adoption model, there is also a need for detailed recommendations and suggestions. These recommendations and suggestions provide valuable insights for the manufacturing and production SME stakeholders and decision-makers in facilitating a smooth implementation and successful transition to IIoT. Therefore, this research study emphasises the need to fill the adoption and implementation gap and provide solutions for the specific issues and challenges experienced by SMEs in developing countries, during the adoption of IIoT technologies.

TOEI framework stands for technological, organisational, environmental, and individual. This framework is used to determine and classify the influencing factors for the successful adoption of technologies in industrial sectors. It is similar to other frameworks that are used for technological adoption such as Unified Theory of Acceptance and Use of Technology (UTAT), structural equation modelling (SEM), technology acceptance model (TAM), technology Organisation and environment (TOE Framework) etc. However, TOEI framework is an extended version of the TOE framework by adding the individual concept [8]. It is also referred to some time as TOEH (for technological, organisational, environmental, and human) framework [9]. The significance of this framework is it can be used to develop an actionable and structured technological adoption model. By integrating the individual concept in the TOE framework, the TOEI framework offers a broader view of the factors that influence the adoption of technologies. It ensures that the individual-centric aspects are considered along with the technological, environmental, and organisational requirements [8]. The framework is versatile and can be applied in different industries on different scales. The framework is mainly useful in situations where the technology adoption concentrates on both individual level and structural level engagement. The current study adopts the TOEI framework to help the manufacturing and production SMEs in the successful adoption of IIot technologies. The comprehensive approach of the framework that consider technological, organisational, environmental, and individual factors ensure that all the important aspects of influencing IIoT adoption are systematically addressed. It also allows the manufacturing and production SMEs to understand the challenges that arise from technological, organisational, environmental, and individual factors. It offers a structured and organised roadmap for the manufacturing and production SMEs to not only incorporate the IIoT technologies successfully but also adapt to the transforming requirements of the digital industrial revolution [10].

A conceptual IIoT adoption model for manufacturing and production SMEs for developing countries has already been proposed by Shah et al. [8]. The proposed conceptual IIoT adoption model has been developed based on the identification of 47 influencing factors, categorised into four groups based on TOEI framework as shown in Figure 2. Among the 47 influencing factors, this study aims to analyse the most critical influencing factors to finalise the IIoT adoption model by conducting the quantitative research method for the successful adoption and implementation of IIoT in manufacturing and production SMEs. Also, this research study intends to close the gap by looking at IIoT adoption and implementation comprehensively in Malaysia to increase efficiency, productivity and competitiveness for manufacturing and production SMEs.

The main contributions of this research study are given below:

- Provide the comparison of manufacturing and production SMEs based on SMEs' features and for a better understanding IoT to IIoT technological features in manufacturing and production SMEs are also evaluated.
- Utilisation of the technology organisation environment individual (TOEI) framework to overcome the limitation of existing TOE framework for the identification of influencing factors impacting the adoption of IIoT in manufacturing and production SMEs in Malaysia.

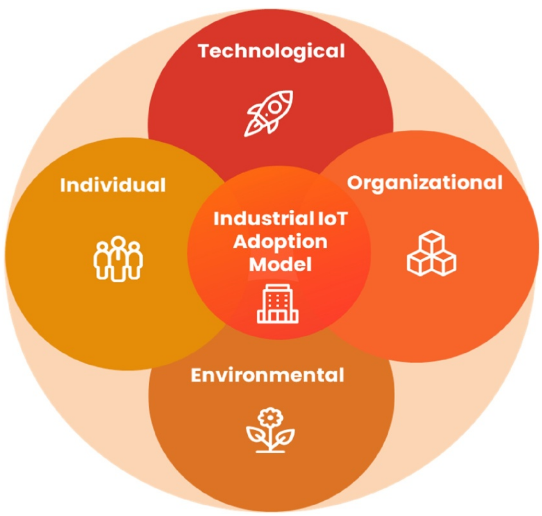

FIGURE 2 TOEI framework for IIoT adoption in SMEs. IIoT, Industrial Internet of Things; SMEs, small medium enterprises.

- Define and express the 17 influencing factors with the relevant equations for the adoption and implementations in manufacturing and production SMEs, and validate these 17 influencing factors for the IIoT adoption model through the data collection from 492 manufacturing and production SMEs in Malaysia.
- Comparative and statistical analysis of influencing factors for the reliability and validity of IIoT adoption model for manufacturing and production SMEs in Malaysia while design and development of IIoT adoption model based on validated 17 influencing factors for manufacturing and production SMEs in Malaysia.
- Provide details of potential advantages, risks, assumptions, and recommendations and suggestions for industry stakeholders, policy makers and decision makers for the smooth adoption and implementation of IIoT technologies within the manufacturing and production SMEs.

A well-organised research study makes it easier for the readers to understand the actual flow and structure of the research paper. Therefore, to maintain the quality of the research, this research study is organised as follows: Section 2 focuses on examining the existing studies on the adoption of IIoT for manufacturing and production SMEs in developed and developing countries, particularly Malaysia. Section 3 compares the technological features of IoT and the IIoT for manufacturing and production SMEs. Section 4 defines the problem formulation and elaborates the challenges faced by Malaysian manufacturing and production SMEs while adopting IIoT. Section 5 explains the research methodology of the study based on background, analysis and planning, conducting the survey, and data analysis and recommendation. Section 6 demonstrates the results and discussion based on demographic analysis, descriptive analysis, IIoT model assessment, analysis and discussion in detail. Section 7 presents the finalised IIoT adoption model for manufacturing and production SMEs in Malaysia. Section 8 is the evaluation of the IIoT adoption model from the SME's Experts. Section 9 concentrates on the potential advantages of IIoT adoption model for manufacturing and production SMEs. Section 10 sheds light on risks of the IIoT adoption model for the manufacturing and production SMEs, while Section 11 highlights the assumptions about the IIoT adoption model. Section 12 is the discussion of the finalised IIoT adoption model, while Section 13 presents the suggestions and recommendations regarding the IIoT adoption model for manufacturing and production SMEs. Finally, Section 14 conclusion and future works that summarise the key findings, contributions and implications of the research.

2 | RELATED WORKS

This section investigates the existing studies regarding the adoption of IoT for manufacturing and production SMEs.

For the developing countries, Ramos et al. [11] propose the readiness model for the adoption of IoT to identify the influencing factors for manufacturing SMEs in the Philippines. Quantitative research methodology is applied for the data collection from the 250 respondents. Profitability, ease of management, supply chain visibility, initial investment and risk are identified as key influencing readiness factors for the adoption of IoT for manufacturing in SMEs in the Philippines. The results show that the majority of the SMEs are shown the willingness to IIoT Adoption in their SMEs to minimise cost, improve quality control and reduce the waste. In the same way, Rajbhandari et al. [12] propose the readiness model for the adoption of IR 4.0 in SMEs in Nepal. For identifying the influencing factors, quantitative research methodology is applied for the data collection from the 287 respondents from the industrial sector of Kathmandu Valley in Nepal. 15 Enabling technologies are identified that include autonomous robot, simulation, vertical/horizontal integration, cyber security, cloud computing, additive manufacturing, cyber security, autonomous vehicles, M2M communication, smart factory, intelligent material, mobile computing, RFDI, artificial intelligent and cyber-physical system based on five technological factors those effect of SMEs decision making for the adoption of new technologies.

In India, Patil and Pramod [13] focus on the influencing factors to adopt the industrial IoT adoption for smart manufacturing Micro SME (MSME). Technology acceptance model is combined with TOE framework to capture the technological and organisational factors along with the user perspective. Quantitative research methodology is used for the data collection from the 307 respondents. Based on TOE-TAM framework, easy to use, benefits (relative advantage), competitive pressure, government rules, top management support and organisational commitment are identified for the successful IIoT adoption for smart manufacturing in Indian MSMEs. Specific educational qualifications and training are necessary for decision makers to adopt the Industrial IoT successfully. However, Mukherjee et al. [14] investigate the potential Industrial IoT technologies that can help Indian SMEs to improve their business performance. The study has prepared a questionnaire based on several factors, such as organisation, technology, environment and people. The findings of the study highlight that the factors including compatibility, trust, relative advantage, top management support, technical capability and competitive pressure have a closed and significant linked with the IIoT adoption However, factors such as infrastructure, organisational readiness, prior experience and internal excellence are not directly affecting the adoption of IIoT in the SMEs.

Similarly, Kumar et al. [15] propose a novel adoption IR 4.0 framework for digital manufacturing in Indian SMEs. For identifying the influencing factors, quantitative research methodology is applied for the data collection from the 121 respondents. Acceptability, Safety, Behaviour, Market and Cultural factors based on individual and organisational. Findings from the data analysis show that industrial experts and decision makers have a significant role in the adoption of IR 4.0 in Indian manufacturing SMEs. In the same way, Mittal et al. [16] investigate the necessities and challenges faced by manufacturing SMEs and developed a smart manufacturing adoption framework for the Indian manufacturing SMEs. The study examines the number of existing studies to understand the early adoption frameworks that were utilised by the early adopters. Furthermore, the study proposes an adoption model for smart manufacturing based on five steps to be followed for the successful adoption including identify manufacturing data available within the SME including the readiness assessment of the SME data-hierarchy, developing smart manufacturing awareness of SME leadership, staff develop a smart manufacturing tailored vision for the SMEs, and identify appropriate smart manufacturing tools and practices necessary to for smart manufacturing adoption in SMEs.

However, Narwane et al. [17] investigate the role of cloud of things for the adoption on the SMEs' performance and the various factors, which influence the privacy, security, ease of use, top management support, security risk, big data analytics, trust, customers and suppliers' intentions, manufacturing infrastructure IT support, knowledge sharing, and external environment support. The study is conducted in India and data from 96 SMEs is collected which is then analysed for the confirmatory factor analysis using structural equation modelling. The results of the study indicate that the influencing factors, such as big data analytics, top management support, trust and perceived security risk require the mediating support of cloud of things in the SMEs.

For Malaysia, Shahzad et al. [18] examine the influencing factors for the adoption of IR 4.0 in Malaysian SMEs. DOI is combined with TOE framework to capture the technological and organisational factors along with the user perspective. Quantitative research methodology is applied for the data collection from the 300 respondents. Relative advantage, compatibility, organisational readiness, top management support, competitive pressure and government rules are identified for the successful adoption of IR 4.0 in Malaysian SMEs. Policymakers understand the challenges during the adoption and implementation of IR 4.0 in Malaysian SMEs and should be ready to compete in the international market. Similarly, Jayashree et al. [19] propose the comprehensive IR 4.0 adoption model for improving the production and sustainability of SMEs through transforming the digitalisation. Quantitative research methodology is used for the data collection from the 314 respondents from Malaysia. The outcomes from the data analysis shows that resource availability, management leadership, teamwork, competitive pressure and external support have significant influence factors for the adoption of IR 4.0. Also, it provides the directions for both policy makers and industry experts to contribute in the field of IR 4.0.

Bumiputera represents the indigenous people of Malaysia. For this purpose, Abd Shukor et al. [20] focus on the decision of adopting IoT in Malaysian Bumiputera SMEs. Quantitative research methodology is applied for the data collection from the 384 respondents from the Bumiputera SMEs' owners. Organisational change, adhocracy and business transformation are identified as influencing factors of organisation. With great knowledge and awareness, SMEs will be able to adopt IoT in Malaysian industries. Furthermore, Yi et al. [21] propose the readiness and adoption IR 4.0 model for furniture manufacturing of Malaysian SMEs. A questionnaire-based survey is conducted to evaluate the influencing factors from the 160 SMEs. Government policy, relative advantage and external support are identified as influencing factors as the results of data analysis while the SMEs are hesitant to adopt the IR 4.0 due to the lack of financial resources and employees' skills among the furniture manufacturers. However, Abdulaziz et al. [22] explore the current practices, status and challenges of IoT adoption to develop an IoT based framework for IR 4.0 in Malaysia. The interviews have been conducted with five different participants from three different SMEs for thematic analysis for the qualitative research. The study findings show that the adoption of IoT in the context of IR 4.0 is low in Malaysia due to mostly SMEs face several challenges. Also, the study highlights the factors, such as education, training and lack of experience as main factors for influencing the adoption of IoT in SMEs in Malaysia. Furthermore, the study proposes an IoT adoption framework for IoT-based technologies implementation including ordering materials from suppliers' storage and production processes.

Smart factories are highly digitalised and use advanced technologies such as IoT, AI and Big Data to optimise the internal and external operations. Won and Park [23] investigate the organisational influencing factors for the adoption of smart factories for manufacturing in Korean SMEs with respect to IR 4.0 revolution. Relative advantage, organisational readiness and competitive pressure are identified as organisational influencing factors for the successful adoption of Smart factories in Korean SMEs. Digital technology-based manufacturing will be a successful growth of Korean SMEs. Similarly, Jung et al. [24] examine the influencing factors for the adoption of smart factories in Korean manufacturing SMEs. The study is based on quantitative research and focuses on identifying the success factors including top management support, relative advantage, performance and intention of Transformation for information systems. The results demonstrate useful insights for stakeholders and decisions makers to change traditional systems in production to smart factories. It also highlights the suggestions and guidelines for outsource experience.

Furthermore, Madhavan et al. [25] investigate the levels of practices and IR 5.0 readiness level for the processing of seafood in Thailand. Furthermore, the study developed a framework based on seven scenarios regarding the production line, major energy source, seafood processing, packaging, labelling and anti-bacterial testing methods sensory along with a questionnaire of 42 questions related to IR 1.0 and IR 5.0 practices in terms of seafood processing for the SMEs. The findings of the study show that the SMEs are still running their business under IR 1.0, IR 2.0 and IR 3.0 context. There is less attention towards the adoption of IR 4.0 However the interest rate toward IR 5.0 is quite high. Similarly, Nguyen and Luu [26] investigate the effect of factors that are influencing the adoption and implementation of IR 4.0 by SMEs in Ho Chi Minh City of China. Both qualitative and quantitative methods have used in the research by interviewing 12 participants and 365 respondents, who are the representatives of their SMEs. The SPSS and Smart PLS software have been deployed for the analysis. Furthermore, the study results indicate that cost, time, resources and conditions of the SMEs in their businesses environments, product quality, saving time, ease of use, usefulness, customer relationship and adoption intentions have a great positive impact toward actual adoption of IR 4.0.

For the developed countries, Parra-Sánchez et al. [27] explore Colombian SMEs for adopting new technologies and ready to adopt and accept these technologies in their business environment. The study utilised the data from the Annual Trade survey from 2017 to 2018 to investigate the policies based on ICT affect the SMEs' readiness for the adoption of new technologies. The results show that SMEs used digital technologies but the adoption of IoT technologies mainly for e-commerce is still very low, which is due to higher costs and unclear policies. The study suggests that the government should pay more attention to SMEs in terms of guidance and support for helping SMEs adopt IoT technologies. Furthermore, Marcon et al. [28] examine the enhancement of manufacturing SME integration and the adoption of smart manufacturing technologies, such as data exchange and automation technologies. The research is conducted in Denmark. The results of the study show that paying attention to the technologies is not the only solution the SMEs. Also, there is a need to pay attention to technical, social and environmental factors for the successful integration and adoption of the technologies in the context of IR 4.0. The study has chosen case study about Danish SME that has adopted technologies in their business in the context of IR 4.0 in a faster and better way the reason is because the SME is focusing on both social and technological factors.

Furthermore, the study also highlights the importance of workers in SMEs. It reveals that the companies should invest more in worker skills and involve them in more trainings, which will help SMEs to adopt IIoT technologies more quickly. Moreover, Ghafari et al. [29] explore the cost-effectiveness of IIoT adoption in U.S. manufacturing SMEs. The data that combines energy assessment for U.S SMEs has been collected from the Industrial Assessment Centers database for the study analysis focussing on 62 U.S. manufacturing SMEs across 10 states and 25 Standard Industrial Classifications. Furthermore, the study demonstrates the challenges related to the financial adoption of IIoT in the industry. The aim is to examine whether IIoT financial aspects advantage the initial costs in SMEs. The results of the study highlights that the difference between implementation costs and saving based on statistics analysis is significant which indicates that SMEs faces high initial costs is expected to be invested in counter balanced through substantial savings.

Table 2 shows the detailed comparison of existing studies focused on the adoption of various advanced technologies in SMEs including the adoption of IoT, Industrial IoT, IR 4.0, IR 5.0, digital manufacturing, smart factory and cloud of things with various aspects. The studies use a combination of qualitative and quantitative research methods and are conducted in various developed and developing countries, including the

TABLE 2 Comparison of existing studies and current research study for IIoT adoption in manufacturing and production SMEs.

References	Objectives	Theory	Coverage	Factors	Respondents from SMEs	Qualitative/ Quantitative/Mixed	SME type	Countries
Abd Shukor et al. [20]	Decision to adopt IoT	TOE	Organisational	• Adhocracy • Awareness • Business transformation • Knowledge • Openness to change	384	Quantitative	Bumiputera	Malaysia
Abdulaziz et al. [22]	Implementation of IoT	Not mentioned	Individual and organisational	• Internal communication • Product quality • Safety • Skills	5 participants from 3 SMEs	Qualitative	Manufacturing	Malaysia
Ghafari et al. [29]	Financial impact of IIoT adoption	Not mentioned	Organisational	• Cost	64	Quantitative	Manufacturing	United state
Jayashree et al. [19]	Adoption of IR 4.0	DOI-TOE	Technological, organisational and environmental	• Competitive pressure • Management leadership • Resources • Support • Teamwork	314	Quantitative	Not mentioned	Malaysia
Jung et al. [24]	Adoption of smart factory	Not mentioned	Organisational Technological	• Openness to change • Performance • Relative advantage • Support	1067	Quantitative	Manufacturing	Korea
Kumar et al. [15]	Adoption of digital manufacturing	TSTT and SCT	Organisational and individual	• Acceptability • Behaviour • Competitive pressure • Cultural • Safety	121	Quantitative	Manufacturing	India
Madhavan et al. [25]	Readiness of IR 5.0	Not mentioned	Not mentioned	Not mentioned	6	Qualitative	Seafood processing	Thailand
Marcon et al. [28]	Implementation of IR 4.0	TOE	Technological, organisational and environmental	• Openness to change • Performance • Training	231	Quantitative	Manufacturing	Denmark
Mittal et al. [16]	Adoption of smart manufacturing	Not mentioned	Technological	• Awareness	2	Qualitative	Manufacturing	India
Mukherjee et al. [14]	Adoption of IIoT	TOE	Organisational	• Competitive pressure	375	Qualitative	Manufacturing	India

(Continues)

TABLE 2 (Continued)

References	Objectives	Theory	Coverage	Factors	Respondents from SMEs	Qualitative/Quantitative/Mixed	SME type	Countries
				• Infrastructure • Performance • Readiness • Relative advantage • Support • Trust				
Nguyen and LUU [26]	Adoption of IR 4.0	TAM, TRA and TBP	Technological, organisational and environmental	• Cost • Customer relationship • Ease of use • Product quality • Recourses	365 participants from 12 SMEs	Quantitative and qualitative both	Manufacturing	China
Parra-Sánchez et al. [27]	Adoption of IoT	Not mentioned	Technological	• Government policies	6845	Qualitative	Trading	Colombia
Patil and Pramod [13]	Adoption of IIoT	TAM-TOE	Technological, organisational and environmental	• Competitive pressure • Ease to use • Government policies • Organisational commitment • Relative advantage • Support	307	Quantitative	Manufacturing	India
Rajbhandari et al. [12]	Adoption of IR 4.0	SEM	Technological	• Government policies	287	Quantitative	Not mentioned	Nepal
Ramos et al. [11]	Adoption of IoT	SEM	Organisational	• Profitability • Ease of management • Supply chain visibility • Initial investment • Risk	250	Quantitative	Manufacturing	Philippine
Shahzad et al. [18]	Adoption of IR 4.0	DOI-TOE	Technological, organisational and environmental	• Compatibility • Competitive pressure • Government policies • Readiness • Relative advantage • Support	300	Quantitative	Manufacturing	Malaysia

TABLE 2 (Continued)

References	Objectives	Theory	Coverage	Factors	Respondents from SMEs	Qualitative/ Quantitative/Mixed	SME type	Countries
Narwane et al. [17]	Adoption of cloud of things	SEM	Technological, organisational and environmental	• Big data • Customer–Supplier intention • Ease of use • Infrastructure • Knowledge • Privacy and security • Safety • Support • Trust	96	Quantitative	Not mentioned	India
Won and park [23]	Smart factory adoption	Not mentioned	Organisational	• Competitive pressure • Readiness • Relative advantage	2040	Quantitative	Manufacturing	Korea
Yi et al. [21]	Adoption of IR 4.0	Not mentioned	Organisational	• Government policies • Relative advantage • Support	160	Quantitative	Furniture	Malaysia
Current Study	Adoption of IIoT	TOEI	Technological, organisational, environmental and individuals	• Adaptability • Cost • Ease of use • Efficiency • Government policies • Infrastructure • Knowledge • Legal & ethical concerns • Network & communication • Performance • Privacy and security • Real-time tracking • Resources • Safety • Skills • Tools • Training	492	Quantitative	Manufacturing	Malaysia

Abbreviations: DOI, diffusion of innovation; SEM, structural equation model; SCT, social cognitive theory; TAM, technology adoption model; TOE, technological, organisational, environmental; TPB, theory of planned behaviour; TRA, theory of reasoned action; TSTT, theory of socio-technical transition.

United States, Demark, Columbia, India, China, Korea, Thailand, Philippines, Nepal and Malaysia.

The dynamic nature of IIoT adoption research, shifting from exploratory studies to implementation-focused analyses. Furthermore, in terms of theory or framework majority of the existing studies rely only on the established frameworks such as TOE and DOI-TOE etc. However, there is a need for a more structured framework for the adoption of IIoT within the manufacturing and production SMEs. Furthermore, the majority of the existing studies primarily emphasise the technological, environmental and organisational. However, less attention has been paid to the individuals who play a significant role in any organisation including the manufacturing and production SMEs, it is suggested that there is a need to pay attention to the individuals as well to ensure the successful adoption of IIoT within the manufacturing and production SMEs.

In terms of SME respondents, the majority of the existing studies have taken surveys from either manufacturing or production SMEs, also some of the studies have not even clarified whether the data they collected is from manufacturing or production SME respondents. The majority of SMEs collected data from many respondents from a few SMEs such as 5 participants from 3 SMEs, and 365 participants from 12 SMEs that do not represent the whole manufacturing and production SMEs population. In order to ensure the successful adoption of IIoT in both manufacturing and production SMEs the responses must be collected from both manufacturing and production SME respondents on a large scale while one respondent should represent only one SME.

According to the findings from the literature review, a significant research gap has been identified. Majority of the existing research studies about IIoT adoption in manufacturing and production SMEs are conducted based on TOE framework in developing countries neglecting the individual aspect which plays an important role in the industrial sector. Furthermore, developing countries specifically Malaysia only focus on the adoption and implementation of IoT in the manufacturing sector based on TOE framework. To address this gap, this current research study is finalising and designing an IIoT adoption model for manufacturing and production SMEs in Malaysia based on TOEI framework to adopt and implement IIoT technologies successfully.

3 | COMPARISON OF INTERNET OF THINGS AND INDUSTRIAL INTERNET OF THINGS BASED ON TECHNOLOGICAL FEATURES IN MANUFACTURING AND PRODUCTION SMES

This section of the study demonstrates a comparison of IoT and IIoT according to the technological features including a wide range of industrial applications, devices or tools, software and systems as shown in Table 3.

Table 3 compares the technological features of the IoT and IIoT in manufacturing and production SMEs. The table focuses on three aspects, including applications, devices/tools, and systems/software. In terms of applications, the IoT concentrates on convenience and consumers including tasks, such as asset tracking, smart packaging, monitoring and remote quality control. However, the IIoT is more focused on the industrial applications. It supports advanced activities, such as machine monitoring, real-time production tracking, automated quality checks, and predictive maintenance. The IIoT also allows for features, such as just-in-time inventory management, smart inventory tracking and remote machine management that are required for optimising industrial operations.

Regarding the devices and tools, IoT includes sensors for humidity, temperature, light, and air quality, as well as wearable devices, smart plugs, RFID tags, and barcode scanners that are particularly utilised for monitoring, detecting changes, and ensuring basic automation. However, IIoT on the other hand focuses on more advanced tools, such as advanced machine health sensors, industrial robots, acoustic emission sensors and collaborative robots (cobots). Furthermore, IIoT also focuses on virtual reality, augmented reality (AR) and advanced robotics to help with design, maintenance, and hands-free operations. In terms of systems and software, IoT concentrates on energy management, environmental monitoring and security, utilising systems such as process control and warehouse management that are particularly useful for small-scale management. However, the IIoT goes a step further by utilising systems such as human-machine interfaces, machine vision and predictive maintenance, and advanced inventory management.

From Table 3, it can be concluded that IoT is more consumer-oriented concentrating on making tasks easier and more convenient in smaller-scale settings. However, IIoT concentrates on large-scale industrial use, focusing on efficiency, automation, and advanced technology for optimising production processes. This comparison shows that while IoT is about improving everyday operations, IIoT addresses the complex needs of industries by integrating smart and automated systems.

Mainly, IoT focuses on consumers and enhancing convenience in daily life, whereas IIoT primarily focuses on industrial applications that aim to improve overall efficiency in manufacturing and production processes.

Applications or devices used in manufacturing and production SMEs, IoT devices are often used for basic tasks, such as asset tracking, object monitoring, data collection, smart packaging, remote quality control and inventory management. On the other hand, IIoT devices or applications are more specialised for industrial use, including machine monitoring, predictive maintenance, real-time production tracking, automated quality checks, real-time defect detection, smart inventory tracking, just-in-time inventory management and remote machine management [6].

In terms of devices and tools, IoT commonly utilises temperature sensors, humidity sensors, smart electrical appliances, light sensors, smart plugs, proximity sensors and wearable sensor devices. However, IIoT employs more advanced tools such as programmable logic controllers (PLCs) for automated control, industrial robots, Collaborative robots (cobots), advanced sensors for machine health monitoring

TABLE 3 Comparison of IoT and IIoT based on technological features in manufacturing and production SMEs.

Features	IoT	IIoT
Focus	Consumers and convenience	Industrial application and efficiency
Applications in manufacturing and production SMEs	• Asset tracking • Monitoring • Collecting data • Smart packaging • Remote quality control • Inventory management • Automation	• Machine monitoring and predictive maintenance • Real-time production tracking • Automated quality checks • Real-time defect detection • Smart inventory tracking • Just-in-time inventory management • Remote machine management
Devices/Tools	• Temperature sensors • Humidity sensors • Smart electrical appliances • Light sensors • Smart plugs • Proximity sensors • Air quality sensors • Wearable sensor devices • Basic leak detection sensors • Smart water flow metres • RFID tags and readers • Barcode scanners • Smart manufacturing sensors	• PLCs for automated Control • Industrial robots • Cobots (collaborative robots) • Advanced sensors for machine health monitoring (vibration, temperature) • Smart metres for tracking energy consumption/energy-guzzling • Thermal imaging cameras • Smart laser scanners for 3D products • Advanced thickness gauges for measurement • Acoustic emission sensors for real-time machinery sound detection • Spectrometers • Industrial drones for inventory management and inspection • AR for remote assistance and training • VR for immersive design and simulation • Advanced real-time electrical industrial appliances • Industrial wearables for hands-free operation • Advanced robotics for material handling and assembly
Systems/Softwares	• Environmental monitoring systems • Track and trace systems • Security and safety system • Access control systems • Energy monitoring systems • Process control systems • Warehouse management systems • Smart lighting systems	• Machine vision systems • HMIs • Smart inventory management software • Automated inventory picking systems • WMS • SCADA systems • Predictive maintenance software • Cloud-based MES • Advanced industrial data analytics software • Access control systems with IIoT integration • Real-time GPS tracking for delivery vehicles • RTLS • CNC machines • Automated material handling systems • RPA for repetitive tasks • Automated inspection systems for quality assurance • Automated inventory management systems

Abbreviations: AR, augmented reality; CNC, computer numerical control; HMIs, human-machine interfaces; IoT, Internet of Things; MES, manufacturing execution systems; PLCs, programmable logic controller; RPA, robotics process automation; RTLS, real-time location systems; SCADA, supervisory control and data acquisition; SMEs, small medium enterprises; VR, virtual reality; WMS, warehouse management systems.

(such as vibration, temperature etc), smart metres for tracking energy consumption, thermal imaging cameras, smart laser scanners for 3D products and AR glasses [30].

Moreover, IoT systems and software often include environmental monitoring systems, track and trace systems, security and safety systems, access control systems, energy monitoring systems, and warehouse management systems. However, IIoT systems and software are more advanced, such as machine vision systems, smart inventory management software, automated inventory picking systems, supervisory control and data acquisition systems, predictive maintenance software, cloud-based manufacturing execution systems, advanced industrial data analytics software, access control systems with IIoT integration, and real-time GPS tracking for delivery vehicles [31].

While both IoT and IIoT technologies involve interconnected devices and systems, IIoT is more focused on industrial settings, offering specialised tools and software to optimise manufacturing and production processes.

4 | PROBLEM STATEMENT

By analysing, the existing studies reveals a significant gap in the adoption of IIoT technologies in manufacturing and production SMEs. It shows that developed countries, such as the United States, Denmark and Columbia have adopted IIoT technologies within their business environment and have revolutionised their industrial sectors. Though, the major focus of these studies is focusing on the financial impact of IIoT adoption only within the organisation, IR 4.0 and IoT adoption, respectively. Particularly in developing countries, India is trying to focus on IIoT adoption in SMEs based on TOE framework. China and Nepal focus on IR 4.0 adoption, whereas Thailand focuses on the adoption of IR 5.0. Moreover, the studies conducted in Malaysia focus only on the decisions to adopt IoT and IR 4.0 for manufacturing SMEs only while neglecting the adoption of IIoT in production SMEs.

Additionally, most of the existing studies focus on the technology adoption framework, such as TOE, TAM and DOI with respect to technological, organisational and environmental. However, individuals are the main part and play an important role in the industrial sectors that are not paying attention during the adoption of advanced technologies. Furthermore, the adoption models developed in the existing studies are based on three to seven influencing factors while some more key influencing factors should be included according to the TOEI framework equally. However, there is a need for the adoption of IIoT for manufacturing and production SMEs in developing countries, especially in Malaysia. To address the gap the main research question is as follows:

> How a reliable and validated IIoT adoption model can be designed and developed for Malaysian manufacturing and production SMEs to adopt IIoT technologies?

5 | RESEARCH METHODOLOGY

A good comprehensive research framework enhances the quality of any research project [32, 33]. It helps researchers to manage research steps in the right order. Each step of the process has its own deliverables and guides the researchers to confidently move to the research's next steps. This research consisted of three main phases: Phase I: Background, Analysis and Planning, Phase II: Conducting Survey and Phase III: Data Analysis and Recommendations as shown in Figure 3.

For the background analysis and planning, Shah et al. [8] examine the existing studies concerning the adoption of IIoT in manufacturing and production SMEs, to identify a significant research gap in developing countries, comprehensively. Forty-seven key influencing factors have been identified based on a thorough literature review. After the identification, these 47 factors have been classified into four main groups based on the technology, organisation, environment and individual (TOEI) framework. By using this classification, researchers and industrial experts will gain a better understanding, knowledge and importance of these influencing factors with their relationship with each other for the adoption of IIoT and its impact on Manufacturing and production SMEs. Shah et al. [8] have been proposed a conceptual model for IIoT adoption in manufacturing and production SMEs based on the TOEI framework. The proposed IIoT conceptual model serves as a foundation to guide policymakers and stakeholders of manufacturing and production SMEs in developing countries that are looking to adopt and implement IIoT technology within industrial sectors. Additionally, the model visually represents the factors and their interactions in the context of IIoT adoption for manufacturing and production SMEs.

Following the proposed IIoT conceptual model, a comprehensive survey has been conducted involving both academic experts and industry professionals by Shah et al. [34]. The aim was to prioritise and rank the highly key influencing factors for the successful adoption and implementation of IIoT in manufacturing and production SMEs. Both academic experts and industrial professionals rated these factors within each category based on their perceived importance and priority for IIoT adoption. By analysing both factors based on existing studies and factors ranked based on experts' surveys, Table 4 highlights the strategy for selecting the factors for the finalised IIoT adoption model for manufacturing and production SMEs based on Equation (1). The factors for the finalised adoption model are selected based on the common factors in both Factors Ranked based on Experts Survey (Fac_E) and the Top-Rated Factors based on Existing Studies (Fac_R).

$$Fac_E \cap Fac_R = Fac_S \quad (1)$$

In terms of technological factors, there are six factors ranked by experts based on the survey conducted including the ease of use, technical support, efficiency, privacy and security, real-time tracking, and Network and communication. Similarly, six factors are highlighted in the majority of existing studies, including efficiency, capability, privacy and security, real-time tracking, flexibility, and network and communication. The technological factors selected for the finalised adoption model including the ease-of-use, efficiency, network and communication, privacy and security, and real-time tracking, are common in both sets. For the organisational factors, the experts highlighted training, infrastructure, readiness, performance, and openness to change as organisational factors for the adoption of IIoT in manufacturing and production SMEs, whereas existing studies ranked cost, performance, infrastructure, support and training factors. Therefore, the organisational factors selected for the finalised adoption model including the cost, infrastructure, performance and training, are common in both factors ranked by both existing studies and experts.

Furthermore, in terms of environmental factors experts raked resources, government policies, legal and ethical concerns, tools, and imposition by the environment. In existing studies, highlighted factors are tools, sustainability, government policies, business environment and legal and ethical issues. However, selected factors for the finalised model are government policies, legal and ethical concerns, resources and tools, which are based on the combination of both experts' ranking and existing studies. Finally, the individual factors that are ranked by experts include safety, knowledge, adaptability, acceptability and skills, while existing studies ranked safety, adaptability, acceptability, knowledge, and skills as the main factors for the IIoT adoption. However, factors chosen for the finalised model include adaptability, knowledge, safety and skills. All selected influencing

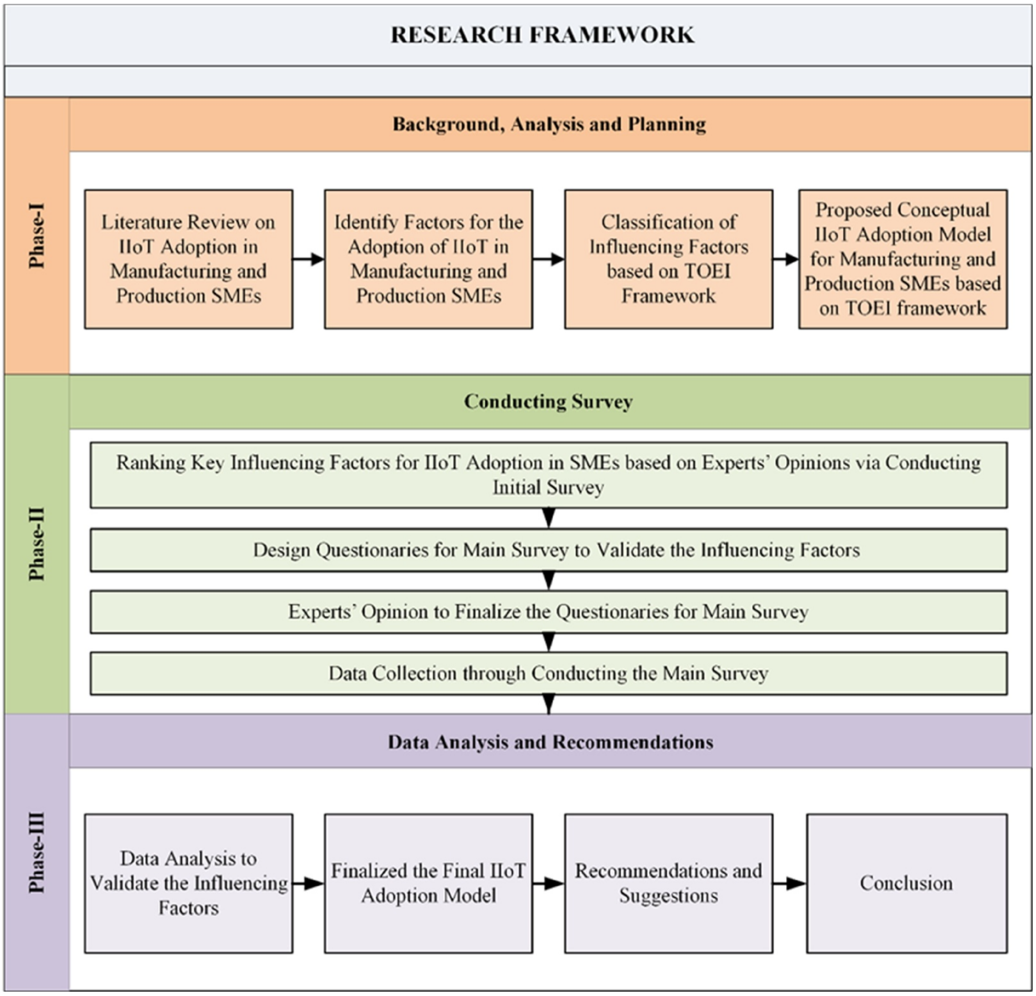

FIGURE 3 Research framework of the study.

factors are briefly defined and expressed with the help of equations from Equations (2)–(17) in Table 5 for IIoT adoption and implementation in manufacturing and production SMEs. Furthermore, Industrial IoT is also briefly defined and expressed with the help of Equation 18.

A total of 51 questions was created for the questionnaire based on selected 17 influencing factors for finalising IIoT adoption model for manufacturing and production SMEs. The questionnaire was designed using an online platform Google Forms, which is widely used for data gathering and ensure the reliability of the data. Additionally, survey questionnaires were printed for personal data collection to get a fast response.

Before conducting the data collection, experts' opinions have been taken to further refine and finalise the questionnaires. Based on the feedback from experts, the questionnaire items were revised as necessary. The experts were stakeholders such as SMEs' owners, entrepreneurs and professional academic staff. Experts reviewed the questionnaires and provided feedback on their clarity, relevance and effectiveness for making the survey and data collection process more smoothly and to maintain the quality of the survey. To ensure the instrument's reliability, five experts were selected for content validity and face validity of the questionnaire. Content validity refers to ensuring that all the questions or items in a survey are accurate and right and cover the entire range of the concept it is intended to measure [46]. However, Face validity is a subjective measure that determines whether a measurement tool looks to measure what it is supposed to measure [47]. It is essentially a decision regarding whether the instrument "looks like" it is measuring what it promises to measure. For the data collection, a list of registered Malaysian SMEs from the website of "SME Corporation Malaysia [48]" has been used. The contact information of has been obtained and shortlist only the manufacturing and production SMEs of Malaysia for sending questionnaires through emails, social media channels and physical visits to the SMEs.

A sample of 627 manufacturing and production SMEs were invited to participate in the main research survey. A total of 543 responses have been received, out of which 51 responses have been terminated during the data screening and cleaning process. Data screening refers to checking the data for any errors, inconsistencies, or missing information. While data cleaning is the process of correcting mistakes and inconsistencies that are discovered during the screening process. This could include eliminating duplicate entries, correcting

TABLE 4 Criteria for selecting factors to finalise the IIoT adoption model.

Sr No.	Factors ranked based on experts survey (Fac_E)	Top rated factors based on existing studies (Fac_R)	Selected factors for the finalise IIoT adoption model (Fac_S)
Technological			
1	Ease of use	Efficiency	Efficiency
2	Technical support	Capability	Ease of use
3	Efficiency	Privacy & security	Network and communication
4	Privacy and security	Real-time tracking	Privacy and security
5	Real time tracking	Flexibility	Real-time tracking
6	Network and communication	Network and communication	
Organisational			
1	Training	Cost	Cost
2	Infrastructure	Performance	Infrastructure
3	Readiness	Infrastructure	Performance
4	Performance	Support	Training
5	Openness to change	Training	
Environmental			
1	Resources	Tools	Government policies
2	Government policies	Sustainability	Legal and ethical concerns
3	Legal and ethical concerns	Government policies	Resources
4	Tools	Business environment	Tools
5	Imposition by the environment	Legal and ethical issues	
Individual			
1	Safety	Adaptability	Adaptability
2	Knowledge	Safety	Knowledge
3	Adaptability	Ability	Safety
4	Acceptability	Skills	Skills
5	Skills	Knowledge	

mistakes, or filling in missing values [49]. Both data screening and cleaning are essential and play significant roles in the research because accurate and reliable data is required to derive meaningful conclusions and make data-driven decisions [50]. Furthermore, if the data is inaccurate or unreliable it can lead to produce incorrect or wrong results and unreliable findings [51]. Therefore, to maintain the standard of the survey and produce meaningful results with high quality information. Following successful data collection, the data was screened and inspected for high quality checks that will lead to more reliable and accurate results for the analysis. During this process, the responses from other SMEs, such as logistics, retail, agriculture etc. were removed and the responses only from manufacturing and production SMEs were retained as the main focus of the study is IIoT adoption model for manufacturing and production SMEs only. Also, the duplicate records, missing values and incomplete responses have been removed during this stage. And after the screening and cleaning we have successfully finalised a sample of 492 for the analysis to validate and finalise the influencing factors for the successful adoption of IIoT in manufacturing and production Malaysian SMEs.

In the final phase, the comparative and statistical analysis of the research are performed using structural equation modelling (SEM) in Smart PLS tool. Respondent demographics analysis, descriptive analysis, reliability and validity are accomplished for analysis and validation of collected data and finalising the influencing factors for the successful adoption of IIoT for manufacturing and production SMEs in Malaysia. The measurement model and structural model are assessed successfully, and the results of each are shown in Figures 4–7, Tables 6–12.

After successful data analysis and validation, the final IIoT adoption model is developed for manufacturing and production SMEs to adopt IIoT technologies in Malaysia. This model incorporates the validated influencing factors and provides a comprehensive understanding and recommendation for the future policymakers of the Malaysian manufacturing and production SMEs in order to help them speed up industrial operations, increase efficiency, productivity and competitiveness for

TABLE 5 Definitions of selected influencing factors for IIoT adoption and implementation in manufacturing and production SMEs.

Influencing factors	Definitions
T-EFC	The use of resources in manufacturing and production processes to maximise the production output and operations while minimise the resources and unnecessary efforts [55]. $$EFC = \sum_{i=1}^{n} \left(\frac{O/P_{Pro}}{I/P_{Res}} \right)_i \quad (2)$$ where; O/P_{Pro}: Production output and I/P_{Res} : Resources input of i^{th} processes for utilising IIoT technologies
T-EOU	The way in which the IIoT technologies within the manufacturing and production SMEs can be utilised, configured and managed in terms of interface, complexity and testing without any difficulty by the individuals is known as ease of use [14]. $$EOU = \sum_{i=1}^{n} (User_{Int} \cup Int_{Com} \cup Use_{Test})_i \quad (3)$$ where; $User_{Int}$: User interface, Int_{Com} : Integration complexity and Use_{Test} : Usability testing of i^{th} Resources for utilising IIoT technologies
T-NWC	Network and communication refers to interconnected IIoT technologies such as sensors, actuators, smart devices and control systems in terms of reliability, bandwidth, privacy and security, and compatibility that are utilised to support the exchange of data, information, and instructions within the manufacturing and production settings as well as with external parties such as distributors, stakeholders, and suppliers [56]. $$NWC = \sum_{i=1}^{n} (Rel \cup BW \cup PS \cup Cpt)_i \quad (4)$$ where; Rel: Reliability, BW : Bandwidth PS : Privacy and security, and Cpt : Compatibility of i^{th} Resources for utilising IIoT technologies
T-PS	Privacy and security refer to the protection of IIoT technologies including sensitive information, unauthorised access, misuse of information or breacher from access or misuse by implementing cybersecurity measures, access control and utilising protection protocol to make sure the integrity and confidentiality of the information assets within the manufacturing and production SMEs [57]. $$PS = \sum_{i=1}^{n} ((CIA \cup Auth) \cap Cyb_{Mur})_i \quad (5)$$ where; CIA: Confidentiality, integrity and availability, $Auth$: Authorisation and Cyb_{Mur} : Cybersecurity measurement of i^{th} Resources for utilising IIoT technologies
T-RTT	Real time tracking enables the manufacturing and production SMEs stakeholders or staff to observe, continuously monitor and report the status, location, and condition of the products, assets, processes or materials throughout the manufacturing production cycle in real-time. It helps SMEs to track up-to-the-moment information and data for fast response to issues, and optimisation of operations [58]. $$RTT = \sum_{i=1}^{n} (D_{Sen} \cup S_{Mch} \cup S_{Inv} \cup S_{Wrk} \cup Qua)_i \quad (6)$$ where: D_{Sen}: Sensor data (temperature, humidity or pressure), S_{Mch} : Machinery status S_{Inv} Inventory status, S_{Wrk} : Workforce status and Qua : Quality of i^{th} Resources for the adoption of IIoT technologies
O-CST	Cost refers to the initial investment essential for the adoption of IIoT technologies and including the resource costs such as raw materials, labour and energy, as well as indirect costs for operations and maintenance such as expenses, maintenance and repairing of equipment [8]. $$CST = \sum_{i=1}^{n} \left((Cst_{Inv} \cup Cst_{Opr} \cup Cst_{Mnt}) \cap Cst_{Res} \right)_i \quad (7)$$ where; Cst_{Inv} : Investment cost, Cst_{Oper} : Operational cost Cst_{Mnt} : Maintenance cost, Cst_{Rec} : Resources cost of i^{th} Resources for the adoption of IIoT technologies
O-INF	Infrastructure means the initial and basic facilities, systems and services such as buildings or locations, equipment, utilities, transportation networks and communication systems that are required for the adoption and implementation of IIoT technologies within the manufacturing and production SMEs [59]. $$INF = \sum_{i=1}^{n} \left(H/W \cup S/W \cup NWC \cup D_{PS}) \cap Cap_{Ing} \right)_i \quad (8)$$ where; H/W: Hardware, S/W Software NWC : Network and communication and D_{PS} : Data privacy and security and Cap_{Ing} : Integration capability of i^{th} Resources for the adoption of IIoT technologies

(Continues)

TABLE 5 (Continued)

Influencing factors	Definitions
O-PER	Performance is the measurement of the efficiency and productivity of IIoT technologies to achieve a specific goal or objective within the manufacturing and production that includes productivity, quality, manufacturing and production cycle time, and cost efficiency [8]. $PER = \sum_{i=1}^{n} \left((Pro \cup Qua \cup Time_D) \cap Cst_{Eff}\right)_i$ (9) where; Pro: Productivity, Qua : Quality, $Time_D$: Down time and Cst_{Eff} : Cost efficiency of i^{th} Resources for the adoption of IIoT technologies
O-TRN	Training is the process of improving IIoT technologies-related knowledge, competencies and skills of workers or employees in terms of technical, data and IT within manufacturing and production SMEs to enhance their productivity and performance [6]. $TRN = \sum_{i=1}^{n} \left((Tec_{Skl} \cup D_{Skl} \cup IT_{Skl}) \cap Cha_{Mgt}\right)_i$ (10) where: Tec_{Skl}: Technical skills, D_{Skl} : Data skills, IT_{Skl} : Information technological skills and Cha_{Mgt} Change management of i^{th} Individuals for utilising IIoT technologies
E-GP	Government policies refer to the set of regulations, rules, standards and initiatives such (taxation, trading agreements, environmental standards and regulations, labour laws, and incentives or subsidies) implemented by the governing bodies' adoption of IIoT technologies within manufacturing and production SMEs [60]. $GP = \sum_{i=1}^{n} \left(Fin_{Inc} \cup Reg_{FW} \cup Std\right)_i$ (11) where: Fin_{Inc}: Financial incentives, Reg_{FW} : Regulatory framework and Std Standards of i^{th} Resources for implementing IIoT technologies
E-LEC	Legal and ethical concerns mean the consideration of regulations, relevant laws and ethical principles that govern the manufacturing and production process to ensure its compliance with legal requirements and standards to reduce the risks and maintain responsible business practices [61]. $LEC = \sum_{i=1}^{n} \left(\left(Reg_{Cmpl} \cup Eth_{Concs}\right) \cap D_{PS}\right)_i$ (12) where: Reg_{Cmpl}: Regulatory compliance, Eth_{Concs} : Ethical concerns and D_{PS}: Data privacy and security of i^{th} Resources for utilising IIoT technologies
E-RES	Resources include finance, individuals, potential technologies, raw materials, equipment's, labour and energy required for the adoption of IIoT within the manufacturing and production SMEs [62] $RES = \sum_{i=1}^{n} \left((Fin \cup Ind_{Cap}) \cap (Tec_{Inf} \cup Ext_{Res}\right)_i$ (13) where: Fin: Finance, Ind_{Cap} : Individual capital, Tec_{Inf}: Technological infrastructure and Ext_{Res} External resources of i^{th} Resources for utilising IIoT technologies
E-TLS	Tools include various inputs such as software, hardware, communication technologies, equipment and integration support within the manufacturing and production environment that facilitate SMEs towards the adoption of IIoT technologies [63]. $TLS = \sum_{i=1}^{n} (B_{Tls} \cup A_{Tls}) \cap \left(H/W \cup S/W \cup Int_{Sup}\right)_i$ (14) where: B_{Tls}: Basic tools, A_{Tls}: Advance tools, H/W : Hardware, S/W : Software and Int_{Sup}: Integration support of i^{th} Resources for utilising IIoT technologies
I-ADP	Adaptability refers to the ability to change and adapt to new situations and environments for rapid process adjustments, systems, optimisation, improved productivity and operations to support the adoption of IIoT technologies seamlessly within the manufacturing and production SMEs [64]. $ADP = \sum_{i=1}^{n} (CT \cup LC \cup RF)_i$ (15) where: CT: Change tolerance, LC: Learning capacity and RF: Resource flexibility of i^{th} Individuals for utilising IIoT technologies

TABLE 5 (Continued)

Influencing factors	Definitions
I-KNW	Knowledge means a set of skills, understandings, expertise, insights and the awareness about the usage of IIoT technologies that workers or employees learn within in the manufacturing and production SMEs to make informed decisions, optimise operations, improve efficiency, and enhance innovation within the organisations [60]. $KNW = \sum_{i=1}^{n} (Tec \cup Dom \cup Awr)_i$ (16) where: Tec: Technology, Dom: Domain and Awr: Awareness of i^{th} Individuals for utilising IIoT technologies
I-SFT	Safety is the practices and measures implemented within the manufacturing and production SMEs to make sure the security and protection of individuals (workers/Clients) and IIoT technologies against any potential attack, accident, physical hazards, risks to personnel or threat [65]. $SFT = \sum_{i=1}^{n} \left(BL \cup (((Risk \cup Threat) \cap Mit)\right)_i$ (17) where: BL : base line of existing safety, Mit : Mitigation of i^{th} Individuals for utilising IIoT technologies
I-SKL	Skills are the specific abilities and expertism knowledge of the individuals including workers, employees, clients and staff required for the efficient adoption and implementation IIoT technologies [65]. $SKL = \sum_{i=1}^{n} (Knw \cup Exp \cup Abl)_i$ (18) where: Knw: Knowledge, Exp: Experience, Abl: Ability of i^{th} Individuals for utilising IIoT technologies
IIoT	IIoT refers to the interconnected advanced sensors, software and communication technologies in terms of internet of things, operation technology and information technology within manufacturing and production SMEs for utilising the processes, real-time data collection and automation while improving productivity and competitiveness [6]. $IIoT = \sum_{i=1}^{n} (IoT \cup OT \cup IT)^i$ (19) where; IoT: Internet of things, OT: Operation technology, IT: Information technology of i^{th} Resources

Abbreviation: E-GP, E-government policies; E-LEC, E-legal and ethical concerns; E-RES, E- resources; E-TLS, E-tools; I-ADP, I-adaptability; IIoT, Industrial Internet of Things; I-KNW, I-Knowledge; I-SFT, I-safety; I-SKL, I-skills; O-CST, O-cost; O-INF, O-infrastructure; O-PER, O-performance; O-TRN, O-training; SMEs, small medium enterprises; T-EFC, T-efficiency; T-EOU, T-ease of use; T-NWC, T-network and communication; T-PS; T-privacy and security; T-RTT, T-real time tracking.

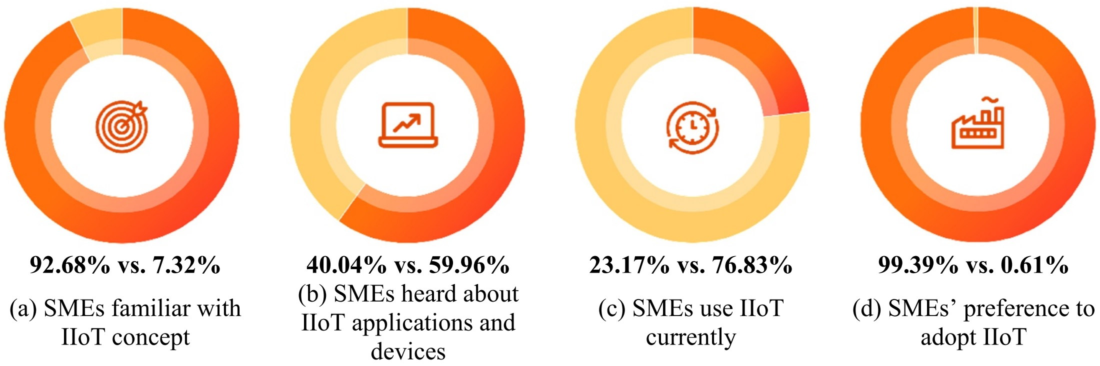

FIGURE 4 Analysis of IIoT familiarity, usage and preference for adoption of IIoT in SMEs. IIoT, Industrial Internet of Things; SMEs, small medium enterprises.

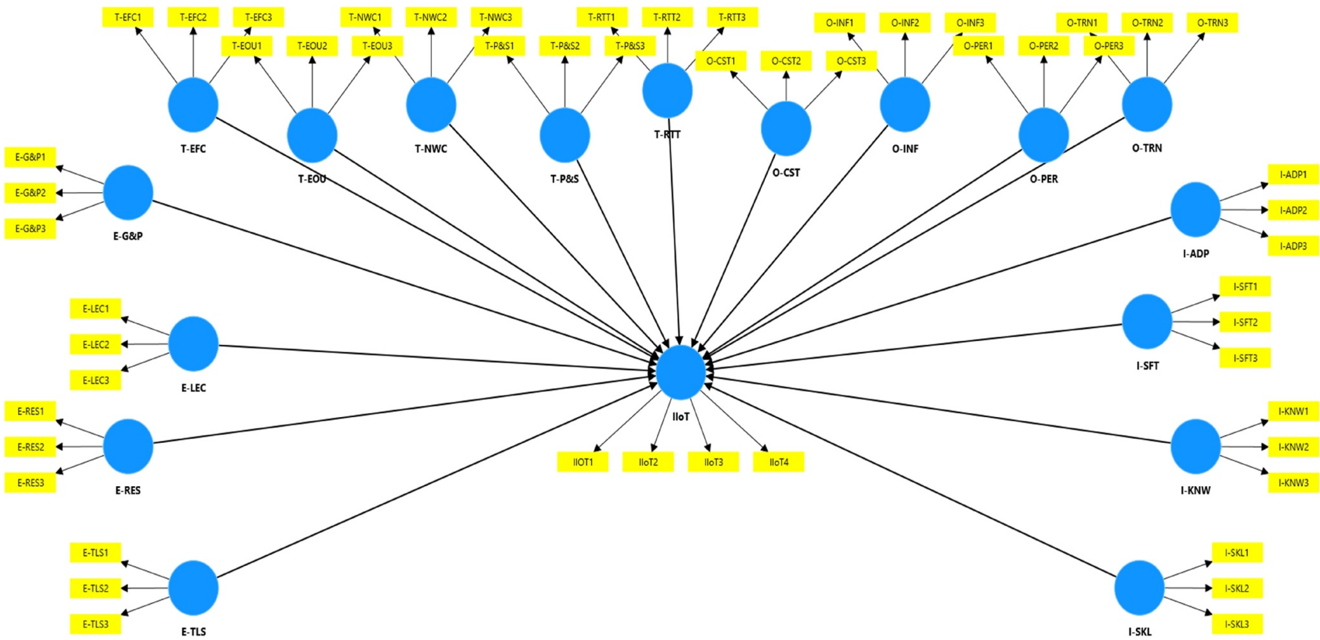

FIGURE 5 IIoT adoption model for manufacturing and production SMEs in smart PLS. IIoT, Industrial Internet of Things; SMEs, small medium enterprises.

manufacturing and production SMEs. Based on the analysis of the feedback from manufacturing and production SMEs' stakeholders and the final IIoT adoption model, recommendations and suggestions are proposed for future policymakers and SMEs' stakeholders to adopt the IIoT technologies in manufacturing and production SMEs in Malaysia. Furthermore, potential advantages, risks and assumptions regarding the finalised IIoT adoption model are also comprehensively discussed. Finally, the final IIoT adoption model has been evaluated and validated by the experts from manufacturing and production SMEs.

6 | RESULTS AND DISCUSSIONS

The result and discussion section is divided into five main subsections: demographic analysis, descriptive statistics, IIoT model assessment, analysis the IIoT model results and discussion of IIoT model assessment results.

6.1 | Demographic analysis

Table 6 provides an overview of the demographic analysis of the respondents during the data collection for the IIoT adoption for the Manufacturing and Production SMEs in Malaysia. In total, 492 respondents have been surveyed. The 492 respondents are actually the individuals working in various manufacturing and production SMEs including owners, directors, supervisors, managers and decision makers within the manufacturing and production SMES. Among the 492 respondents that represent 492 SMEs, the majority belong to manufacturing SMEs comprising of 73.98%, whereas 26.02% of SMEs belong to production. Regarding the number of employees: 43.90% of SMEs have 10–50 employees, 33.54% of SMEs have 51–100 employees, 15.65% have 101–150 employees, 4.88% have 151–200 employees, 1.83% have 201–250 employees and only 0.20% have more than 250 employees.

In terms of job status, 96.34% of the respondents are employed full-time, whereas 3.59% worked part-time.

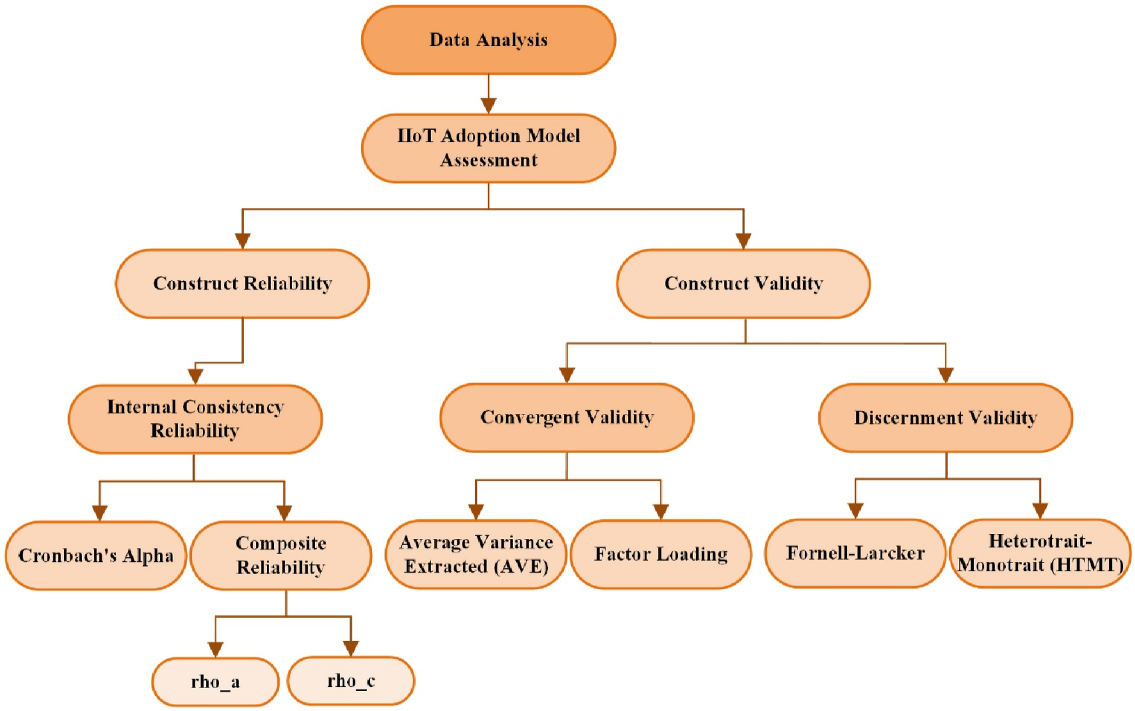

FIGURE 6 Data analysis of IIoT adoption model for manufacturing and production SMEs in smart PLS. IIoT, Industrial Internet of Things; SMEs, small medium enterprises.

Regarding gender representation, 47.36% of the respondents who participated in this survey are female, while 44.51% are male and 8.13% are identified as others. Age-wise, 47.76% lie between 26 and 35 years, 38.41% are between 36 and 45 years, 7.32% of the respondents are between 20 and 25 years and 6.50% are above 45 years old.

Based on the experience, 40.45% have six (06) to 10 years of experience, 35.98% have one (01) to five (05) years of experience, 17.28% have 11–15 years of experience, 5.49% have more than 15 years of experience and 0.81% of the respondents have less than one year of experience.

When asked about familiarity with the concept of Industrial IoT (IIoT), 92.68% of the respondents indicated that they were familiar with the concept of IIoT while 7.32% specified that they were not familiar as shown in Figure 4a. Regarding awareness of specific IIoT applications or devices, 40.04% of the respondents have heard about IIoT applications and devices while 59.96% said that they are not aware of the application and devices of IIoT as shown in Figure 4b. When it comes to knowing the usages of IIoT applications or devices, only 23.17% of the respondents indicated that they are currently using IIoT technologies while 76.83% of respondents said that they are not using any kind of IIoT technologies in their SMEs as shown in Figure 4c. However, after examining the responses in detail, we found that these SMEs are actually using basic IoT devices, such as temperature sensors, gas sensors, light sensors, smart water flow metres, detection sensors, smart electrical appliances, smart plugs, security alarm system, barcode scanners, RFID tags and readers, pressure sensors and quality sensors, security and safety systems, CCTV cameras, proximity sensors, wearable sensors, motion sensors and condition monitoring sensors, do not specifically belong to IIoT but due to the lack of knowledge they are considering these technologies as IIoT technologies. However, in reality, these devices or applications fall under IoT as shown in Table 3 that highlights the difference between IoT and IIoT in detail based on applications, devices or tools and systems or software. Although in reality, IoT mainly focuses on the consumers and convenience while IIoT focuses on industrial applications and efficiency of the SMEs. In conclusion, the majority of the 99.39% of respondents are preferred a preference for the adoption and implementation of IIoT in their SMEs while only 0.61% were not interested in the adoption of IIoT in manufacturing and production SMEs as shown in Figure 4d.

6.2 | Descriptive analysis

Table 7 highlights the descriptive analysis of the collected data from a sample of 492 manufacturing and production SMEs in Malaysia. For the descriptive analysis, mean, median, minimum, maximum, standard deviation, excess kurtosis and skewness methods are calculated for each item of the IIoT adoption model. Mostly, the average values of Mean and Median are lied around 4 that means respondents agree according to the Likert-scale for the adoption the IIoT while in a few cases the average values are lied around 2 that means respondents are disagreed according to the Likert-scale in terms of insufficient skills and tools. However, in most of the cases the minimum value is 1 and the maximum value is 5 that shows the unbiased of the data.

According to the observation, standard deviation with smaller values shows that the values are closer to the mean which suggests that there is less dispersion or variability in the data [52]. The standard deviation of a majority of the items in data

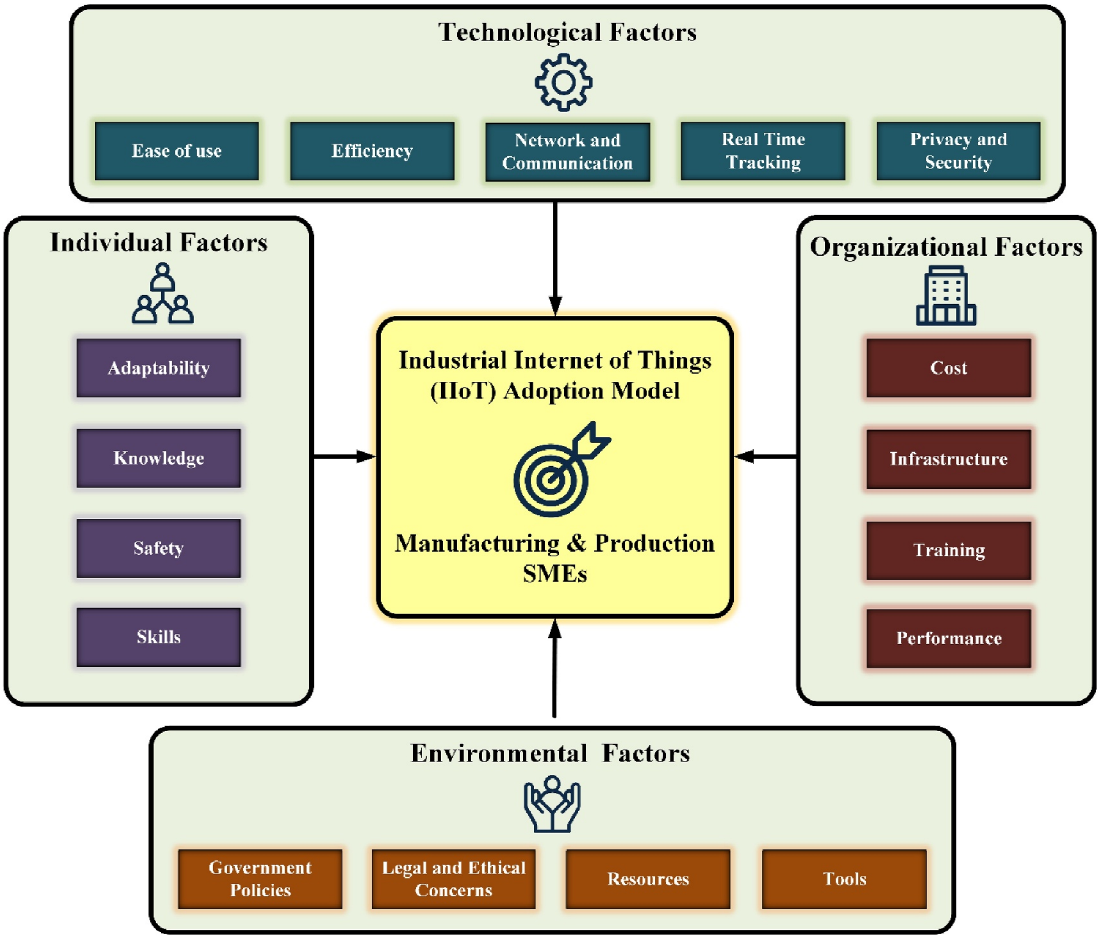

FIGURE 7 Final IIoT adoption model for manufacturing and production SMEs. IIoT, Industrial Internet of Things; SMEs, small medium enterprises.

collected is less than 1 and closer to zero that clearly shows that there is no variability or dispersion in data. Normal data distribution occurs when skewness and kurtosis are both zero. However, according to the [53, 54], the kurtosis value is less than seven, and the Skewness value of less than two is acceptable. The Excess Kurtosis calculated for the items outlines a universal threshold for excess kurtosis that shows acceptable it's applicability. Lastly, the skewness of each item in the data also fulfills its criteria as the skewness of each item falls within an acceptable range based on the specific analysis, and therefore it can be considered "good" for the intended IIoT adoption model.

6.3 | IIoT model assessment

The IIoT adoption model has been assessed in two primary adoption model assessment methods: construct reliability and construct validity. Figure 6 demonstrates the process of data analysis for assessing the IIoT adoption model.

6.3.1 | Construct reliability

It is the assessment of multiple items (items/constructs) that are used to measure a specific factor (factor/variable) to ensure that the factors are measuring the true idea or concept it is supposed to measure. Construct reliability ensures that the items those are used for the IIoT adoption model are reliable, constant and measuring the intended concepts. If items of an adoption model are not reliable it can lead to an unreliable adoption model [55, 56].

Internal consistency reliability

It can be defined as a measurement which is closely related to a set of items in a group. It evaluates the extent to which the items that are designed to measure the same construct produce consistent or homogeneous scores. In other words, internal consistency reliability assesses whether the items that make up a construct or scale are all measuring the same underlying dimension or concept. If an adoption model has strong or high internal consistency reliability then the factors of the model are considered as robust and reliable which enhances and improves the overall trustworthiness and quality of the adoption model [56].

However, if the items or constructs are having weak or low internal consistency, it demonstrates that items are measuring different aspects or are not aligning properly with factors, which can compromise the validity and reliability of the adoption model.

Cronbach's alpha Cronbach's alpha is a statistical technique that is used for the measurement of the internal

TABLE 6 Respondents' demographic analysis.

Demographic analysis		
Type of SMEs	**Frequency**	**Percent (%)**
Manufacturing	364	73.98
Production	128	26.02
Total	492	100.0
Number of employees in SMEs		
10–50	216	43.90
51–100	165	33.54
101–150	77	15.65
151–200	24	4.88
201–250	09	1.83
More than 250	01	0.20
Total	492	100
Job status		
Full time	474	96.34
Part time	17	3.59
Total	492	100
Gender		
Female	233	47.36
Male	219	44.51
Others	40	8.13
Total	492	100
Age		
20–25 years	36	7.32
26–35 years	235	47.76
36–45 years	189	38.41
Above 45 years	32	6.50
Total	492	100.0
Working experience in SMEs		
Less than one (01) Year	04	0.81
One (01)–Five (05) Years	177	35.98
Six (06)–10 Years	199	40.45
11–15 Years	85	17.28
More than 15 Years	27	5.49
Total	492	100
Are you familiar with the concept of IIoT?		
Yes	456	92.68
No	36	7.32
Total	492	100
Have you ever heard about IIoT applications or devices before?		
Yes	197	40.04
No	295	59.96
Total	492	100

(Continues)

TABLE 6 (Continued)

Demographic analysis		
Type of SMEs	**Frequency**	**Percent (%)**
Is your SME currently using any IIoT technologies or solutions?		
Yes	114	23.17
No	378	76.83
Total	492	100
Would you like to prefer the adoption and implementation of IIoT in your SME?		
Yes	489	99.39
No	3	0.61
Total	492	100

Abbreviations: IIoT, Industrial Internet of Things; SMEs, small medium enterprises.

consistency of the set of items of an adoption model. It is a statistical measure that indicates the internal consistency or reliability of a set of items used to measure a particular concept. Cronbach's alpha demonstrates an estimate of the items and whether they are measuring the expected concept or not. A higher value of Cronbach's alpha indicates that items are close to each other and are measuring consistently the expected concept for a desired factor, which is important for the reliability of an adoption model. If a set of items or constructs has low Cronbach's alpha value it highlights that the items are not measuring the expected concept and revision or modification of the items for a desired factor or variable may be needed [57, 58].

Composite reliability Another technique that is used for assessing the internal consistency reliability is the composite reliability, which examines and evaluates the overall reliability or internal consistency of a set of items that are used for the measurement of a single factor in an adoption model. Unlike Cronbach's alpha, composite reliability counts various loadings of each item on the factor. The calculation of composite reliability is based on the summation of the factors loading and the summation of the variance error that is associated with each item. If an adoption model has higher or stronger composite reliability measures, it shows that the items are highly reliable and consistently measure the desired concept for a variable or factor even though the factor loading of the items may differ [59].

Similarly, if an adoption model has lower or weak composite reliability it demonstrates that the items are not reliable and consistently measuring the expected concept for a desired factor which can affect the overall validity and reliability of an adoption Model. The composite reliability of an adoption model can be further assessed through two commonly used coefficients, rho_a (Jöreskog's rho) and rho_C (Dillon-Goldstein's rho).

- Rho_a and Rho_c

Rho_a is the measurement of composite reliability that considers various factor loadings of a set of items to represent a factor. It is calculated based on the summation of the squared of factor loading and the summation of item measurement or error variances. It provides a more accurate estimate of the reliability of an adoption model as compared to Cronbach's Alpha. Similarly, it is also a measurement of the composite reliability of an adoption model that is used to determine the internal consistency of a set of items, which represent a factor or variable within an adoption model. Its calculation is the same as rho_a and takes various factor loading to represent a single variable or factor and demonstrates its reliability and internal consistency. Both rho_a and rho_C are the appropriate measures of the internal consistency reliability of an adoption model, especially when evaluating factors that are represented by multiple or a set of items or constructs with various factor loading.

6.3.2 | Construct validity

The second method for assessing the adoption model is construct validity, which is the accurate measurement of a set of items to represent or measure a desired concept that they are expected to measure. Construct validity is very important for an adoption because it ensures the accurate measurement of various factors that influence the adoption model. Without determining the construct validity of an adoption model the model can be inaccurate [55, 56]. Construct validity can be assessed further using convergent validity and discriminant validity.

Convergent validity

Convergent validity is the measurement of a set of items to shape or converge a high proportion of variance. Convergent validity is essential for an adoption model because it indicates the desired constructs or items are being measured accurately and consistently. Discriminant validity is the degree to which a set of items is different from other items in the adoption model. This means that the measures or values of various items should not be highly correlated or share a significant proportion of variance. Discriminant validity of an adoption model is important because it ensures that a set of items or constructs within an adoption

TABLE 7 Descriptive analysis.

Items	Mean	Median	Minimum	Maximum	Standard deviation	Excess kurtosis	Skewness	No. of observations used
IIoT1	4.276	4	2	5	0.664	−0.576	−0.418	492
IIoT2	4.163	4	1	5	0.709	2.377	−0.932	492
IIoT3	4.201	4	2	5	0.649	0.276	−0.448	492
IIoT4	4.333	4	3	5	0.640	−0.691	−0.433	492
T-EFC1	4.303	4	1	5	0.776	2.632	−1.318	492
T-EFC2	4.268	4	1	5	0.764	1.759	−1.101	492
T-EFC3	4.266	4	1	5	0.761	1.698	−1.074	492
T-EOU1	4.329	4	1	5	0.679	1.611	−0.909	492
T-EOU2	4.407	4	1	5	0.664	2.205	−1.097	492
T-EOU3	4.419	5	1	5	0.696	2.548	−1.255	492
T-NWC1	4.242	4	1	5	0.714	2.185	−0.964	492
T-NWC2	4.319	4	1	5	0.721	1.262	−0.957	492
T-NWC3	4.159	4	1	5	0.779	1.413	−0.882	492
T-PS1	3.862	4	1	5	0.864	0.988	−0.795	492
T-PS2	4.264	4	1	5	0.765	1.239	−1.008	492
T-PS3	3.949	4	1	5	0.920	−0.158	−0.671	492
T-RTT1	4.325	4	1	5	0.675	1.426	−0.899	492
T-RTT2	4.323	4	1	5	0.710	0.924	−0.900	492
T-RTT3	4.346	4	1	5	0.680	1.426	−0.947	492
O-CST1	4.266	4	1	5	0.784	0.330	−0.863	492
O-CST2	4.252	4	1	5	0.743	3.080	−1.222	492
O-CST3	4.130	4	1	5	0.809	2.133	−1.121	492
O-INF1	3.809	4	1	5	0.962	1.582	−1.155	492
O-INF2	4.120	4	1	5	0.987	2.355	−1.482	492
O-INF3	3.886	4	1	5	0.924	2.604	−1.418	492
O-PER1	4.394	4	1	5	0.690	3.312	−1.337	492
O-PER2	4.366	4	1	5	0.673	3.576	−1.276	492
O-PER3	4.346	4	1	5	0.671	3.495	−1.228	492
O-TRN1	4.313	4	1	5	0.675	0.614	−0.713	492
O-TRN2	4.232	4	2	5	0.663	−0.209	−0.422	492
O-TRN3	4.067	4	2	5	0.751	−0.864	−0.226	492
E-GP1	4.158	4	1	5	0.868	2.578	−1.364	492
E-GP2	3.829	4	1	5	0.884	1.311	−0.921	492
E-GP3	4.148	4	1	5	0.840	2.405	−1.260	492
E-LEC1	4.191	4	1	5	0.690	2.980	−1.016	492
E-LEC2	4.225	4	1	5	0.739	0.643	−0.781	492
E-LEC3	4.288	4	1	5	0.692	1.229	−0.860	492
E-RES1	4.361	4	1	5	0.663	1.549	−0.937	492
E-RES2	4.294	4	2	5	0.673	0.165	−0.632	492
E-RES3	4.256	4	1	5	0.675	0.679	−0.639	492

(Continues)

TABLE 7 (Continued)

Items	Mean	Median	Minimum	Maximum	Standard deviation	Excess kurtosis	Skewness	No. of observations used
E-TLS1	2.168	2	1	5	1.198	−0.825	0.677	492
E-TLS2	2.156	2	1	5	0.990	−0.255	0.606	492
E-TLS3	1.723	1	1	5	0.999	0.561	1.252	492
I-ADP1	4.059	4	1	5	0.846	1.405	−0.984	492
I-ADP2	3.829	4	1	5	0.951	0.435	−0.782	492
I-ADP3	3.161	3	1	5	0.949	−0.366	−0.082	492
I-KNW1	3.699	4	1	5	1.046	0.169	−0.756	492
I-KNW2	4.063	4	1	5	0.988	1.048	−1.145	492
I-KNW3	3.669	4	1	5	1.169	−0.137	−0.761	492
I-SFT1	3.837	4	1	5	1.065	0.151	−0.819	492
I-SFT2	3.980	4	1	5	0.959	0.943	−1.030	492
I-SFT3	4.126	4	1	5	0.805	1.455	−0.961	492
I-SKL1	2.606	2	1	5	1.138	−0.649	0.492	492
I-SKL2	2.006	2	1	5	0.948	0.022	0.723	492
I-SKL3	1.953	2	1	5	0.993	0.200	0.871	492

model are empirically and conceptually distinct from each other. If an adoption model lacks discriminant validity, it can affect the adoption model and provide inaccurate results about the relationships between factors [60, 61].

Average variance extracted Average variance extracted (AVE) is the measurement of the total amount of variance of a desired factor from its construct or item (e.g. survey questions). It demonstrates the strength of a specific item representing a variable or factor. The higher value of the AVE suggests higher validity and reliability of the measurements [62].

Factor loading Factor loadings are the coefficients that represent the direction, strength and relationship among the various items and their factors. It actually determines the level of an item contributes towards the underlying variable or factor [63].

Discriminant validity

Discriminant validity is defined as the measurement of various factors that are distinct from each other. It ensures that the measures that are intended to capture different concepts or ideas do not overlap much by confirming the uniqueness of each factors in the adoption model [64]. In the context of an adoption model, discriminant validity refers to the extent to of different items (such as adaptability towards adoption vs. ease of use) are truly distinct from each other. It ensures that the measures intended to capture separate concepts do not overlap too much, thereby confirming the uniqueness of each item in the model. Discriminant validity is further assessed using two methods, such as Fornell-Larcker and Heterotrait-Monotrait (HTMT) [65].

Fornell-Larcker. Fornell-Larcker criterion compares the square root of the AVE of a set of items with the correlations between those factors and all other factors in the model. It is calculated to examine the discriminant validity. In order for the discriminant validity to be well established in an adoption model, the square root of AVE for a desired construct or item should be greater than the correlation between that item and all other items in the adoption model. It shows that the items share more variance with its factors than other items [66].

HTMT. HTMT (Heterotrait-Heterotrait ratio of correlations) is a statistical criterion that is used to assess the discriminant validity of an adoption model. It ensures that all the items within a model are accurately different from each other by comparing their correlation. Discriminant validity suggests the items or constructs that represent factors in a model are sufficiently different. It is considered as a more reliable and sensitive measure of discriminant validity than the Fornell-Larcker criterion [66].

All the above methods, including assessing construct reliability through measures such as Cronbach's alpha and composite reliability (rho_a and rho_c), as well as evaluating construct validity through convergent validity (using AVE and factor loadings) and discriminant validity (using cross-loadings, Fornell-Larcker and HTMT) must be assessed for the adoption model in order to ensure that the model is robust, reliable, and valid. The required criteria for each method are shown in Table 13.

6.4 | Assessment of measurement model of IIoT adoption

In this section, the results of IIoT adoption model assessment have been demonstrated based on construct Reliability and validity for the manufacturing and production SMEs.

TABLE 8 Construct reliability and validity.

Influencing factors	Cronbach's alpha	Composite reliability rho_a	Composite reliability rho_c	AVE
T-EFC	0.805	0.932	0.840	0.652
T-EOU	0.727	0.952	0.817	0.603
T-NWC	0.697	0.728	0.827	0.616
T-PS	0.742	0.779	0.846	0.647
T-RTT	0.709	0.969	0.827	0.622
O-CST	0.757	0.848	0.857	0.668
O-INF	0.879	0.945	0.923	0.800
O-PER	0.735	0.722	0.831	0.623
O-TRN	0.718	0.985	0.782	0.558
E-GP	0.725	0.772	0.835	0.628
E-LEC	0.842	0.980	0.898	0.747
E-RES	0.706	0.712	0.836	0.630
E-TLS	0.823	0.960	0.883	0.716
I-ADP	0.910	0.962	0.942	0.844
I-KNW	0.806	0.991	0.873	0.697
I-SFT	0.810	0.924	0.880	0.711
I-SKL	0.707	0.753	0.833	0.626
IIoT	0.819	0.840	0.878	0.644

Abbreviations: E-GP, E-government policies; E-LEC, E-legal and ethical concerns; E-RES, E- resources; E-TLS, E-tools; I-ADP, I-adaptability; IIoT, Industrial Internet of Things; I-KNW, I-Knowledge; I-SFT, I-safety; I-SKL, I-skills; O-CST, O-cost; O-INF, O-infrastructure; O-PER, O-performance; O-TRN, O-training; T-EFC, T-efficiency; T-EOU, T-ease of use; T-NWC, T-network and communication; T-PS; T-privacy and security; T-RTT, T-real time tracking.

6.4.1 | Internal consistency reliability

The initial criteria for the measurement of IIoT adoption model reliability is construct reliability, which is assessed with the help of Cronbach Alpha, a common method for assessing and evaluating the internal consistency of the adoption model. The results highlight all the Cronbach Alpha's values of selected influencing factors for IIoT adoption model, all the values lied between 0.697 and 0.910 as shown in Table 8. All the values are more than 0.700 which means all Cronbach Alpha's values are considered good for the IIoT adoption model. However, only one factor T-Network and Communication (T-NWC) has a value 0.697, which is still acceptable as it is above 0.400 and does not influence the reliability of the IIoT adoption model, according to Table 13. Similarly, Composite reliability is another method for assessing the internal consistency of the IIoT adoption model, rho_a and rho_c are used to assess the composite reliability. For the rho_a, all the values are lied between 0.710 and 0.991 while for the rho_c, all the values are lied between 0.782 and 0.923 as shown in Table 8. All the values of rho_a and rho_c are more than 0.700 that means all composite reliability's values are considered good for IIoT adoption model, according to Table 13. The findings show that all the items have adequate internal consistency reliability, which means that all the influencing factors of IIoT adoption model are reliable.

6.4.2 | Convergent validity

Convergent validity is related to the measurement of how well items measure the factors it is intended to measure. The AVE is one of the most common and widely used methods for assessing the convergent validity. The results of the AVE demonstrate that all the influencing factors for IIoT adoption model are lied between 0.558 and 0.844 for the convergent validity as shown in Table 8. All the values are more than 0.500 which means all AVE's values are considered good for IIoT adoption model, according to Table 13.

Factor loadings are used to check the direction, strength and relationship between factors and their item for the adoption model. All the values of factor loading are lied between 0.489 and 0.966 for the adoption of IIoT model as shown in Table 9. Most of the values are more than 0.700 which means all factor loading's values are considered good for IIoT adoption model. However, few values of T-EFC2, T-EOU1, T-RTT2 and O-TRN2 have the values 0.489, 0.667, 0.593 and 0.573, respectively, which are still acceptable as it is above 0.400 and does not effect on the validity of the IIoT adoption model, according to Table 13.

6.4.3 | Discriminant validity

Discriminant validity refers to the level of a factor in the adoption model that differs from other factors using the Fornell-Larcker and HTMT methods. The standard conventional criteria for Fornell-Larcker are that the square root of AVE should be bigger than its correlation as shown in Table 13, and similarly, one of the criteria is required for the discriminant validity of the IIoT adoption model. The square root of AVE of all factors (IIoT: 0.803, T-EFC: 0.807, T-EOU: 0.776, T-NWC: 0.785, T-PS: 0.804, T-RTT: 0.789, O-CST: 0.817, O-INF: 0.894, O-PER: 0.789, O-TRN: 0.747, E-GP: 0.792, E-LEC: 0.864, E-RES: 0.794, E-TLS: 0.846, I-ADP: 0.919, I-KNW: 0.835 and I-SFT: 0.843) are greater than its correlations values of remaining factors (column-wise) as shown in Table 10. The results of Fornell-Larcker show the positive discriminant validity for the IIoT adoption model.

The standard criteria for the HTMT are all the factors' values should be less than 0.850 which are considered good results and all the values should not be closer or equal to one as shown in Table 13. The results show that HTMT values of all influencing factors lied between 0.032 and 0.841 as shown in Table 11. All the values of HTMT are less than 0.850 and far away from one that shows the positive discriminant validity for the IIoT adoption model.

TABLE 9 Factor/item loadings.

	IIoT	T-EFC	T-EOU	T-NWC	T-PS	T-RTT	O-CST	O-INF	O-PER	O-TRN	E-GP	E-LEC	E-RES	E-TLS	I-ADP	I-KNW	I-SFT	I-SKL
IIoT1	0.725																	
IIoT2	0.829																	
IIoT3	0.802																	
IIoT4	0.849																	
T-EFC1		0.885																
T-EFC2		0.489																
T-EFC3		0.966																
T-EOU1			0.667															
T-EOU2			0.911															
T-EOU3			0.731															
T-NWC1				0.702														
T-NWC2				0.819														
T-NWC3				0.827														
T-PS1					0.850													
T-PS2					0.824													
T-PS3					0.735													
T-RTT1						0.924												
T-RTT2						0.593												
T-RTT3						0.813												
O-CST1							0.771											
O-CST2							0.765											
O-CST3							0.908											
O-INF1								0.872										
O-INF2								0.919										
O-INF3								0.892										
O-PER1									0.853									
O-PER2									0.728									
									0.781									

TABLE 9 (Continued)

	IIoT	T-EFC	T-EOU	T-NWC	T-PS	T-RTT	O-CST	O-INF	O-PER	O-TRN	E-GP	E-LEC	E-RES	E-TLS	I-ADP	I-KNW	I-SFT	I-SKL
O-PER3																		
O-TRN1										0.652								
O-TRN2										0.573								
O-TRN3										0.960								
E-GP1											0.826							
E-GP2											0.746							
E-GP3											0.802							
E-LEC1												0.908						
E-LEC2												0.744						
E-LEC3												0.929						
E-RES1													0.787					
E-RES2													0.753					
E-RES3													0.840					
E-TLS1														0.868				
E-TLS2														0.755				
E-TLS3														0.909				
I-ADP1															0.933			
I-ADP2															0.909			
I-ADP3															0.913			
I-KNW1																0.833		
I-KNW2																0.762		
I-KNW3																0.904		
I-SFT1																	0.859	
I-SFT2																	0.777	
I-SFT3																	0.890	
I-SKL1																		0.748
I-SKL2																		0.750
I-SKL3																		0.870

Abbreviations: E-GP, E-government policies; E-LEC, E-legal and ethical concerns; E-RES, E- resources; E-TLS, E-tools; I-ADP, I-adaptability; IIoT, Industrial Internet of Things; I-KNW, I-Knowledge; I-SFT, I-safety; I-SKL, I-skills; O-CST, O-cost; O-INF, O-infrastructure; O-PER, O-performance; O-TRN, O-training; T-EFC, T-efficiency; T-EOU, T-ease of use; T-NWC, T-network and communication; T-PS; T-privacy and security; T-RTT, T-real time tracking.

TABLE 10 Fornell-Larcker discriminant validity.

	IIoT	T-EFC	T-EOU	T-NWC	T-PS	T-RTT	O-CST	O-INF	O-PER	O-TRN	E-GP	E-LEC	E-RES	E-TLS	I-ADP	I-KNW	I-SFT	I-SKL
IIoT	0.803																	
T-EFC	0.044	0.807																
T-EOU	0.092	0.562	0.776															
T-NWC	0.088	0.482	0.573	0.785														
T-PS	0.105	0.238	0.246	0.344	0.804													
T-RTT	0.031	0.317	0.355	0.360	0.263	0.789												
O-CST	0.050	0.212	0.170	0.248	0.153	0.118	0.817											
O-INF	0.049	0.271	0.291	0.232	0.152	0.233	0.153	0.894										
O-PER	−0.064	0.261	0.326	0.216	0.090	0.195	0.038	0.120	0.789									
O-TRN	0.084	0.414	0.396	0.365	0.144	0.273	0.238	0.230	0.143	0.747								
E-GP	−0.029	0.292	0.261	0.194	0.008	0.178	0.100	0.241	0.208	0.204	0.792							
E-LEC	0.008	0.279	0.290	0.352	0.157	0.296	0.263	0.208	0.082	0.289	0.302	0.864						
E-RES	0.055	0.349	0.431	0.471	0.237	0.357	0.295	0.236	0.175	0.366	0.305	0.363	0.794					
E-TLS	−0.109	−0.153	−0.140	−0.209	−0.052	−0.145	−0.107	−0.191	−0.130	−0.116	−0.139	−0.191	−0.191	0.846				
I-ADP	−0.058	0.277	0.343	0.301	0.093	0.236	0.225	0.212	0.164	0.369	0.168	0.244	0.289	0.057	0.919			
I-KNW	−0.161	−0.016	0.010	0.075	−0.005	0.069	0.142	−0.068	−0.028	−0.032	0.004	0.122	0.093	−0.056	−0.033	0.835		
I-SFT	−0.068	0.257	0.262	0.217	0.077	0.205	0.211	0.184	0.081	0.263	0.320	0.179	0.239	−0.056	0.153	0.142	0.843	
I-SKL	−0.198	−0.118	−0.073	−0.117	−0.051	−0.111	−0.185	−0.126	−0.003	−0.164	−0.087	−0.188	−0.168	0.384	0.066	0.120	−0.031	0.791

Abbreviations: E-GP, E-government policies; E-LEC, E-legal and ethical concerns; E-RES, E- resources; E-TLS, E-tools; I-ADP, I-adaptability; IIoT, Industrial Internet of Things; I-KNW, I-Knowledge; I-SFT, I-safety; I-SKL, I-skills; O-CST, O-cost; O-INF, O-infrastructure; O-PER, O-performance; O-TRN, O-training; T-EFC, T-efficiency; T-EOU, T-ease of use; T-NWC, T-network and communication; T-PS; T-privacy and security; T-RTT, T-real time tracking.

TABLE 11 HTMT discriminant validity.

	IIoT	T-EFC	T-EOU	T-NWC	T-PS	T-RTT	O-CST	O-INF	O-PER	O-TRN	E-GP	E-LEC	E-RES	E-TLS	I-ADP	I-KNW	I-SFT	I-SKL
IIoT																		
T-EFC	0.064																	
T-EOU	0.098	0.788																
T-NWC	0.124	0.679	0.841															
T-PS	0.122	0.323	0.322	0.460														
T-RTT	0.059	0.523	0.549	0.565	0.376													
O-CST	0.080	0.333	0.287	0.368	0.204	0.215												
O-INF	0.072	0.331	0.361	0.271	0.170	0.309	0.191											
O-PER	0.082	0.440	0.519	0.382	0.175	0.360	0.238	0.225										
O-TRN	0.075	0.636	0.665	0.566	0.212	0.469	0.375	0.286	0.402									
E-GP	0.051	0.432	0.399	0.264	0.180	0.287	0.151	0.289	0.323	0.330								
E-LEC	0.032	0.353	0.394	0.459	0.179	0.399	0.338	0.215	0.285	0.418	0.390							
E-RES	0.078	0.559	0.641	0.680	0.304	0.558	0.433	0.283	0.352	0.605	0.426	0.496						
E-TLS	0.111	0.181	0.192	0.242	0.085	0.189	0.142	0.204	0.196	0.173	0.166	0.185	0.230					
I-ADP	0.067	0.373	0.453	0.375	0.112	0.324	0.281	0.223	0.248	0.500	0.214	0.274	0.359	0.105				
I-KNW	0.168	0.124	0.190	0.211	0.069	0.139	0.215	0.082	0.107	0.177	0.098	0.165	0.189	0.082	0.125			
I-SFT	0.093	0.389	0.364	0.280	0.111	0.295	0.257	0.233	0.208	0.369	0.417	0.198	0.321	0.093	0.201	0.233		
I-SKL	0.240	0.174	0.179	0.192	0.151	0.186	0.290	0.155	0.188	0.267	0.159	0.244	0.258	0.450	0.204	0.131	0.136	

Abbreviations: AVE, average variance extracted; E-GP, E-government policies; E-LEC, E-legal and ethical concerns; E-RES, E- resources; E-TLS, E-tools; I-ADP, I-adaptability; IIoT, Industrial Internet of Things; I-KNW, I-Knowledge; I-SFT, I-safety; I-SKL, I-skills; O-CST, O-cost; O-INF, O-infrastructure; O-PER, O-performance; O-TRN, O-training; T-EFC, T-efficiency; T-EOU, T-ease of use; T-NWC, T-network and communication; T-PS; T-privacy and security; T-RTT, T-real time tracking.

TABLE 12 Manufacturing and production SMEs expert's demographics.

SMEs' expert	Area of expertise	Working experience	SME name	Type of SME
Expert 1	Industrial IoT, technology adoption and digital transformation	11–15 years	Company A	Manufacturing
Expert 2	Industrial IoT	6–10 years	Company B	Manufacturing
Expert 3	Industrial IoT, technology adoption and digital transformation	6–10 years	Company C	Production

Abbreviations: IoT, Internet of Things; SMEs, small medium enterprises.

TABLE 13 Construct reliability and validity criteria for IIoT adoption model assessment.

Measurement	Criteria
Reliability	Cronbach Alfa ≥0.400 (acceptable) ≥ 0.700 (good)
	Composite reliability (rho_a and rho_c) ≥ 0.400 (acceptable) ≥ 0.700 (good)
Convergent validity	AVE ≥ 0.500 (good)
	Factor loading ≥0.400 (acceptable) ≥ 0.700 (good)
Discriminant validity	Fornell-Larcker = sqrt (AVE) > correlation
	HTMT ≤0.85 (good) and ≠ 1

Abbreviation: AVE, average variance extracted.

7 | FINALISED INDUSTRIAL INTERNET OF THINGS ADOPTION MODEL FOR MANUFACTURING AND PRODUCTION SMES

The finalised IIoT adoption model for the manufacturing and production SMEs is demonstrated in Figure 7, after the detailed assessment and analysation of IIoT adoption mode for seamlessly adopting IIoT technologies within the industrial environment. The model has been developed based on TOEI framework as shown in Figure 5 that contain technological, organisational, environmental and individual factors. The final IIoT adoption model contains 17 influencing factors for the successful adoption of IIoT in manufacturing and production SMEs including five technological factors (efficiency, ease of use, network and communication, privacy and security, and real-time tracking) that can optimise their operations, improve productivity, and gain a competitive edge, four organisational factors (cost, infrastructure, performance and training) to ensure a strategic and well-planned approach, aligning IIoT adoption with business goals and resource allocation, four environmental factors (government policies, legal and ethical concerns, resources and tools) to create an enabling environment for successful adoption of IIoT technologies and four individual factors (adaptability, knowledge, safety and skills) to embrace change and effectively utilise the new technologies, promoting a culture of continuous improvement and innovation. By considering all these influencing factors of the IIoT adoption Model will help SMEs to successfully adopt IIoT technologies without any difficulty.

8 | EVALUATION OF THE INDUSTRIAL INTERNET OF THINGS ADOPTION MODEL FROM THE SMALL MEDIUM ENTERPRISES'S EXPERTS

To evaluate the finalised IIoT adoption model, a survey has been created and sent to the manufacturing and production SME experts that contains two sections: an introduction to the model and an expert opinion on IIoT adoption model. The purpose of the evaluation from the experts is to observe the expert's opinion based on the findings of the IIoT adoption model.

The targeted experts for the evaluation of IIoT adoption model are particularly the experts from manufacturing and production SMEs, those who have relative IIoT, technological adoption and digital transformation experience. The demographic information of the respondents includes the area of expertise, working experience, SME name and the type of the SME as shown in Table 12.

The questions asked from the experts for evaluation of the IIoT adoption model include the relevance and importance of the IIoT adoption model dimensions including technological, organisational, environmental and individual, and show each category of model dimensions accuracy in reflecting the consideration of adopting IIoT for Malaysian SMEs. Also, whether the designed IIoT adoption model can be used for practical implementation of IIoT technologies within the manufacturing and production SMEs in Malaysia. A total of three 3 manufacturing and production SMEs participated in the evaluation phase and the results from the experts have been presented in Figure 8.

The first question of the model is to what degree the four dimensions of the model (technology, organisation, environment and individual) are essential for the successful adoption of IIoT technologies in the manufacturing and production SMEs. The primary aim of the question was to gain a better understanding of experts' insights into the four main dimensions of the IIoT adoption model defined in the initial stages of the research. The finding of the survey shows that all three experts strongly agree and agree that the model dimension is truly significant and has a very important role in the adoption of IIoT technologies within manufacturing and production SMEs.

The second question focuses on the significance of the technological factors (efficiency, ease of use, network and communication, privacy and security and real-time tracking). The third question is about the organisational factors importance (cost, infrastructure, performance and training). The fourth question focuses on the significance of environmental factors (government policies, legal and ethical concerns, resources, and tools). The fifth question mainly emphasis on the individual factors' importance (adaptability, knowledge, safety and skills). The results of the analysis presented in Figure 8 show that all experts strongly believe and agree that all 17 key influencing factors have a positive effect and play a highly significant role for the successful adoption of IIoT technologies in the manufacturing and production SMEs in Malaysia.

Question six is whether all the 17 key influencing factors accurately reflect the key considerations of SMEs when adopting IIoT technologies. The ranking for this question is agree, strongly agree, and agree which shows that all the experts agree that the model accurately addresses all the main considerations of the manufacturing and production SMEs regarding the IIoT technologies adoption.

The degree of the IIoT adoption model contains important factors for the adoption of IIoT technologies that need to be considered by the SMEs to enhance overall economic growth and technological advancement in the manufacturing and production sectors is addressed in question seven. The ranking of this question is agree, strongly agree and strongly agree, which shows all three experts agree that the model incorporates all the 17 key influencing factors that can be considered by the manufacturing and production SMEs for the successful adoption of IIoT technologies.

The last question is, to what extent the expert believe that the IIoT adoption model is practical and implementable for the successful adoption of IIoT technologies in the SMEs. The findings of the last question strongly confirm the model. Almost all three experts confirm that the current study's finalised IIoT adoption model is practical and can be followed by the manufacturing and production SMEs in Malaysia in conclusion, the IIoT adoption model evaluation survey's

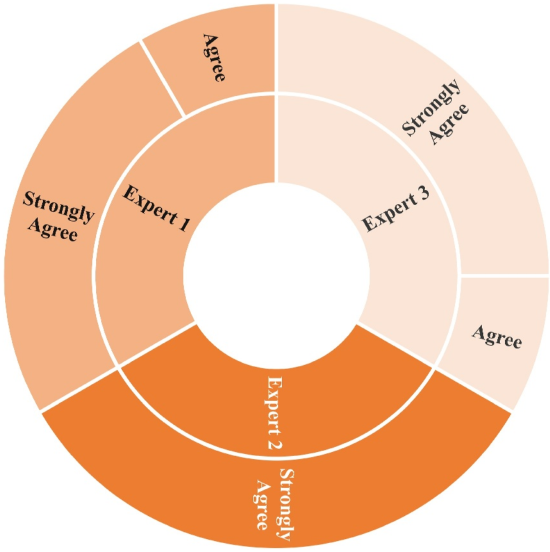

FIGURE 8 Manufacturing and production SMEs Expert's opinion results. SMEs, small medium enterprises.

findings from questions 1-8 offer evidence for validation of the IIoT adoption model.

9 | POTENTIAL ADVANTAGES OF INDUSTRIAL INTERNET OF THINGS ADOPTION MODEL FOR MANUFACTURING AND PRODUCTION SMALL MEDIUM ENTERPRISES'S

This section demonstrates the potential advantages of adoption IIoT model for the manufacturing and production SMEs. The advantages are highlighted based on the industry experts' and academicians' opinions.

1. **Increase Productivity and Operational Efficiencies:** The successful IIoT adoption will help manufacturing and production SMEs to increase productivity and overall operational efficiencies. By using IIoT technologies, manufacturing and production SMEs can reduce production processes, efficient inventory management, automate tasks, improve project management, optimal resource management, minimise downtime and efficient production via predictive maintenance that will lead to smoother and more effective business processes, higher productivity and operational efficiencies.
2. **Improved Product Quality and Consistency:** The adoption of IIoT technologies can enable manufacturing and production SMEs for real-time quality monitoring, early defects detection, quality control of the products, reduce technical issues, better adherence to industry standards and regulations, which will help SMEs to enhance product quality, consistency and customer satisfaction. Furthermore, IIoT can also help SMEs to identify and fix problems with machines faster, which would reduce downtime and keep manufacturing and production processes running smoothly.
3. **Cost Reduction and Operational Optimisation:** The IIoT adoption can help manufacturing and production SMEs to reduce operational, manufacturing and production costs by optimising resource allocation, minimising wastage, improving energy efficiency and minimise maintenance costs through predictive maintenance practices. IIoT can also help SMEs to optimise energy consumption, and automate repetitive tasks to minimise manual labour.
4. **Enhanced Customer Service and Satisfaction:** IIoT adoption can also help, manufacturing and production SMEs to improve customer service and satisfaction by offering faster order fulfillment, real-time order tracking and personalised product customisation enabled. Furthermore, customers' expectations such as shorter delivery times, higher service quality, and greater transparency in manufacturing and production processes all can be achieved through the adoption of IIoT.
5. **Improved Inventory Management and Supply Chain Visibility:** The successful adoption of IIoT technologies can provide more good visibility into inventory levels, allowing manufacturing and production SMEs just-in-time replenishment and reducing stockouts. Additionally, it can improve traceability throughout the supply chain with the help of IIoT technologies.
6. **Optimised Resource Allocation:** By adopting IIoT technologies, manufacturing and production SMEs can gain real-time data insights that will help SMEs to optimise the allocation of resources processes, including raw materials, energy and individuals' resources, which will also lead to improved efficiency and cost savings.
7. **Enhanced Worker Safety and Well-being:** Manufacturing and production SMEs by adopting the IIoT technologies can create a more safe and secure working environment for their workforce safety and privacy by enabling real-time monitoring of the equipment, delivering predictive maintenance notifications from time to time and work conditions that will reduce the risk of accidents and injuries within their environment.
8. **Improved Maintenance Practices:** Through the adoption of IIoT Technologies manufacturing and production SMEs can improve predictive maintenance abilities by reducing equipment downtime, extending machinery lifespan, early fault detection and ensuring smooth manufacturing and production execution.
9. **Enhanced Collaboration and Communication:** IIoT Technologies can help manufacturing and production SMEs to enhance the communication and collaboration through the departments, customers and with stakeholders through real-time data sharing and improved transparency.
10. **Increased Responsiveness:** The IIoT adoption will improve the ability of manufacturing and production SMEs to quickly respond to the transforming market landscape, and will allow them to easily adapt to fluctuating customer preferences or demands, and manufacture new products or provide services more rapidly.

11. **Better and Informed Decision-Making:** The adoption of IIoT technologies will help manufacturing and production SMEs to make strong informed decisions by gaining real-time insights into various aspects of their operations, such as machine performance, energy consumption, and customer preferences, through data analytics enabled by IIoT technologies.
12. **Environmental Impact and Sustainability:** The successful adoption of IIoT technologies will also help manufacturing and production SMEs to support the environmental and organisational sustainability efforts by optimising energy consumption, minimising waste, and enabling more eco-friendly manufacturing and production processes and operations.
13. **Market Demand and Competitiveness:** The adoption of IIoT can help manufacturing and production SMEs to remain competitive in a global market where the technological improvements are becoming increasingly important. Manufacturing and Production SMEs can frequently observe the pressure that motivates them to stay up with competitors that are already utilising IIoT technologies.
14. **Improved Manufacturing and Production Monitoring:** IIoT can enable manufacturing and production SMEs to enhance their ability to monitor production processes in real-time. This includes tracking machine performance, identifying bottlenecks, and optimising workflows to maximise output efficiency. With the help of IIoT, SMEs can track the inventory levels more closely and avoid running out of materials.
15. **Risk Mitigation**: The adoption of IIoT technologies can also help manufacturing and production SMEs to reduce the risks associated with manual processes and human error by automating critical tasks and providing early warnings of equipment failures. This proactive approach reduces production disruptions and ensures operational continuity.
16. **Empowered Workforce:** IIoT technologies can enable manufacturing and production SMEs to empower their workforce by automating repetitive tasks and freeing up employees to focus on more strategic and value-added activities that can lead to improve the job satisfaction and workforce engagement in the business environment.
17. **Production Monitoring Innovation:** includes data digitalisation, smart factory applications, technologies, and implementation that is beneficial for data visibility, reduction of paper consumption, digital logs, data traceability, and errors and non-conformity reduction

These are the advantages that manufacturing and production SMEs can expect from the adoption of IIoT technologies, ranging from operational efficiencies to risk mitigation, preparing manufacturing and production SMEs for long-term growth and success in an increasingly digital and competitive business landscape.

10 | RISK OF INDUSTRIAL INTERNET OF THINGS ADOPTION MODEL FOR MANUFACTURING AND PRODUCTION SMALL MEDIUM ENTERPRISE'S

This section highlights the key risks SMEs may face if they do not adopt the structured finalised IIoT adoption model validated in this study. These risks highlight the potential challenges that manufacturing and production SMEs can face by the non-consideration of the IIoT adoption model for the successful adoption of IIoT technologies.

1. **Inadequate Technological Integration:** Without following the guidance of the finalised IIoT adoption model when adopting the IIoT technologies, manufacturing and production SMEs may fail to properly adopt the IIoT technologies.
2. **Missed Operational Insights:** The model demonstrates the use of real-time data collection and analysis for improving operations. Without following the model, SMEs may miss the important insights into machine performance, production bottlenecks, and quality issues preventing their SMEs from making informed adjustments to their processes.
3. **Weak Decision-Making Framework:** The finalised IIoT adoption model provides a base for data-driven decision-making. Without adopting it appropriately, manufacturing and production SMEs could result in slower reactions to demand fluctuations or emerging opportunities.
4. **Lagging Behind Industry Standards:** By not adopting the structured guidance provided by the finalised IIoT adoption model, SMEs can be at risk of meeting industry standards. This could lead to a loss of business opportunities, as clients mostly prefer vendors with modern capabilities.
5. **Reduced Competitiveness:** Failure to adopt IIoT technologies without following the finalised IIoT adoption model may leave SMEs lagging behind competitors who have embraced modern, efficient IIoT technologies.
6. **Inability to Scale:** The neglection of the finalised IIoT adoption model may restrict SMEs from expanding their operations or adapting to the latest modern technologies.
7. **Loss of Strategic Focus:** Without the finalised IIoT adoption model, SMEs may struggle to align their operations with long-term strategic goals, leading to fragmented efforts and wasted resources.
8. **Reputational Damage:** By ignoring the necessary steps and guidance of the finalised IIoT adoption model the operational inefficiencies, missed deadlines, or quality issues caused by outdated IIoT technologies may harm the SME's reputation in the market.
9. **Dependency on Manual Processes:** Without the adoption of IIoT technologies according to the IIoT adoption model guidelines, SMEs may remain fully dependent on manual operations that can increase the likelihood of human error and inefficiencies.

Each of the above-mentioned risks demonstrates the potential challenges SMEs face when they do not adopt a structured IIoT adoption model validated in this study that emphasises the importance of systematic planning and execution for successful IIoT adoption.

11 | ASSUMPTIONS ABOUT INDUSTRIAL INTERNET OF THINGS ADOPTION MODEL FOR MANUFACTURING AND PRODUCTION SMALL MEDIUM ENTERPRISE'S

This section demonstrates the key assumptions about the finalised IIoT adoption model. These assumptions outline the necessary conditions and expected outcomes for a successful adoption of IIoT technologies, emphasising the IIoT adoption model's potential to transform the manufacturing and production SMEs processes and operations.

1. **Improved Operational Efficiency:** It is assumed that the finalised IIoT adoption model will help the manufacturing and production SMEs to streamline their manufacturing and production processes reducing inefficiencies, and improving the overall productivity.
2. **Enhanced Decision-Making:** The finalised IIot adoption model will enable manufacturing and production SMEs SMEs to make faster and better decisions by providing actionable insights through advanced IIoT technologies and tools.
3. **Cost Optimisation:** The finalised IIoT adoption model will help manufacturing and production SMEs optimise operational costs by reducing energy consumption, minimising downtime through predictive maintenance and improving resource utilisation.
4. **Scalability for Future Growth:** It is assumed that the finalised IIoT adoption model will allow for scalable IIoT technologies adoption, allowing manufacturing and production SMEs SMEs to expand their operations and adopt new technologies without significant disruptions.
5. **Improved Quality Control:** The finalised IIoT adoption model will enhance quality assurance processes by enabling continuous monitoring and real-time feedback during production leading to higher-quality products and reduced defects.
6. **Increased Competitiveness:** It is assumed that following the finalised IIoT adoption model will make manufacturing and production SMEs more competitive by aligning their operations with industry standards and leveraging advanced IIoT capabilities to meet market demands effectively.
7. **Government and Policy Support:** The model assumes that governments will offer necessary regulations, policies, and incentives that facilitate IIoT adoption in manufacturing and production SMEs, such as tax breaks, subsidies, or grants.
8. **Scalability of IIoT Solutions:** The finalised IIoT adoption model assumes that IIoT technologies will be scalable and flexible enough to grow with the needs of manufacturing and production SMEs over time. This assumption presumes that SMEs will be able to easily expand or upgrade their systems as their operations evolve.
9. **Employee Willingness to Adopt Change:** The model assumes that employees and management in manufacturing and production SMEs will be willing to embrace the changes brought by IIoT adoption.
10. **Sufficient Training and Knowledge Transfer:** The model assumes that adequate training programs will be available to upskill the workforce and enable employees to operate and maintain IIoT systems effectively. Without sufficient training, employees may struggle to adapt, leading to inefficiencies or errors in the adoption process.

Each of the above assumptions demonstrates a specific way the finalised IIoT adoption model provides benefits to manufacturing and production SMEs, emphasising its potential to transform their operations effectively.

12 | DISCUSSION OF FINALISED INDUSTRIAL INTERNET OF THINGS ADOPTION MODEL

In terms of technological factors, efficiency is considered the most important influencing factor in the industrial sectors due to streamlining their operations, reduce waste, and increase productivity. IIoT technologies can help to increase the efficiency of the manufacturing and production SMEs by maximising resource utilisation, minimising downtime and improving overall profitability. Moreover, user-friendly IIoT technologies along with an easy understanding interface and less training requirements can encourage manufacturing and production SMEs to adopt IIoT technologies more smoothly. By providing the IIoT technologies that are easy to use in manufacturing and production SMEs can be utilised, configured and managed these technologies in terms of interface, complexity and testing without any difficulty. Additionally, a reliable and secure Internet connectivity is very important for the manufacturing and production SMEs to ensure that their current infrastructure or any planned upgrades facilitate the communication criteria of the IIoT technologies before adopting it. A reliable and secure Internet connectivity will help manufacturing and production SMEs to support the exchange of data, information and instructions within the manufacturing and production settings as well as with external parties, such as distributers, stakeholders and suppliers while making a good and strong relationship with their customers.

Privacy and security are also very important influencing factor for any industry, including manufacturing and production SMEs. In order for the manufacturing and production SMEs to adopt long-term safe and secure IIoT technologies, they should prioritise IIoT technologies with robust security features to protect their sensitive data, information and systems from any potential threats or breaches. By implementing strong cybersecurity measures, access control and utilising protection protocol can make sure the integrity and confidentiality of the information assets within the manufacturing and production SMEs. Furthermore, IIoT technologies can enable real-time monitoring and tracking of operations, assets and resources to provide SMEs with valuable insights for informed decision-making and process optimisation. It can help SMEs to track up-to-the-moment products, information and data for fast response to issues while optimisation of operations.

In the context of organisational factors, cost plays a significant role in any organisation including manufacturing and production SMEs. IIoT technologies can help SMEs to reduce operational cost and maintenance cost, labour cost, inventory cost, waste cost and avoid unplanned downtime cost. Affordable and cost-effective IIoT technologies that demonstrate a clear return on investment can encourage the adoption of IIoT technologies in manufacturing and production SMEs. Furthermore, SMEs need to analyse and assess their existing infrastructure and ensure necessary upgrades or investments to support the successful adoption of IIoT technologies. This may include upgrading IT systems, networks, or acquiring compatible hardware and software that are required for the adoption and implementation of IIoT technologies within the manufacturing and production SMEs.

Industrial IoT technologies that have the potential to improve their operational performance, improve quality, and increase competitiveness in the market. It can also help SMEs meet demanding quality standards and improve customer satisfaction. Moreover, proper training and skill development opportunities for the workforce can help SMEs overcome the learning challenges associated with new IIoT technologies and ensure successful adoption and utilisation of IIoT technologies. In order to make the efficient manufacturing and production processes, SMEs should invest in educating their workforce on the principles, operation, maintenance, configurations and utilisation of IIoT technologies. This can include hands-on training sessions, online courses or partnering with technology providers or educational institutions. A good IIoT technologies' training programme can ensure that employees at all levels understand the benefits and are equipped to effectively utilise the IIoT technologies.

Regarding the environmental factors, the financial incentives, regulations, rules, standards and initiatives such (taxation, trading agreements, environmental standards and regulations, labour laws, and incentives or subsidies) provided by the government to the manufacturing and production SMEs can facilitate the successful adoption and implementation of IIoT. Government should make proper polices and standards to provide more initiatives to support the SMEs in adopting IIoT Technologies. Small medium enterprises must ensure compliance with any industry-specific regulations or standards related to data privacy, cybersecurity, or environmental considerations set by the government. Similarly, legal and ethical concerns ensure the regulatory compliance, maintain consumer security and privacy and improve SMEs reputation. Manufacturing and production SMEs should consult legal experts and develop robust policies and procedures to address these concerns. This may involve obtaining necessary licenses, ensuring data anonymisation, and establishing clear guidelines for data usage and sharing. Small medium enterprises also have to set a legal frameworks and ethical standards when using IIoT. Adhering to these guidelines develop trust with customers and stakeholders, supporting long-term business sustainability.

For the successful IIoT adoption and implementation, SMEs must ensure to explore the available resources such as finance, guidelines, individuals, potential technologies, raw materials, equipment, labour and energy. The majority of the SMEs are lacking the internal resources to invest and adopt IIoT technologies. External resources such as government grants, subsidies, and financial incentives can offer the SMEs with the initial funds to prepare the initial cost for adopting IIoT technologies. Overall, the resources can motivate SMEs to adopt IIoT technologies to optimise operations, improve efficiency, and stay competitive in their industry. Similarly, the availability of specialised tools such as software, hardware, communication technologies, equipment and integration support play an important role within the manufacturing and production environment for facilitating SMEs towards the adoption of IIoT technologies. Tools can support real-time monitoring of production processes, predictive maintenance, and data-driven decision-making. Moreover, tools also have advanced analytics and visualisation capabilities that motivate SMEs to execute actionable insights, reduce resource allocation and improve the overall efficiency. Manufacturing and production SMEs need to ensure that they have all the required tools within their environment that can be utilised for the successful adoption of IIoT technologies.

From the perspective of individual factors, adaptability helps individuals in SMEs to adapt to new situations and environments for rapid processes adjustments, systems, optimisation, improved productivity and operations to support the adoption of IIoT technologies seamlessly within the manufacturing and production SMEs. IIoT requires the manufacturing and production SMEs to adapt processes, workflow and adaptable mindset among their workforce to facilitate their openness to the changes and support the adoption of IIoT technologies into their daily operations. Additionally, developing a strong knowledge potential about IIoT technologies is very important for SMEs. This includes conducting research, organising seminars or workshops, consulting with experts, or partnering with academic institutions or technology providers. When manufacturing and production SMEs gain a deeper understanding of the benefits, capabilities, and adoption considerations of the IIoT technologies. Therefore, the SMEs are required to invest more in building their knowledge based and understanding of IIoT technologies through workshops, seminars, trainings programs, research, consultations or partnerships with experts in the field.

The prioritisation of SMEs towards safety measures and minimising the risk that is associated with the adoption and implantation of IIoT technologies ensure a more safe and secure work environment, reduce operational risks, potential attack, accident, physical hazards, risks to personnel or threat and protect individuals and their assets. Implementing robust safety measures and practices can mitigate potential hazards, enhance workplace safety, and improve a culture of employee well-being. Moreover, building potential skills among the workforce to develop the capacity for the adoption and implantation of IIoT technologies improves operational efficiency and supports SMEs growth. Small medium enterprises are required to identify skill gaps within their workforce and provide relevant training or hire skilled professionals to effectively manage and maintain IIoT technologies. Small medium enterprises should also be in skills development programs or initiatives for the workforce to troubleshoot, innovate, and maximise the benefits of IIoT technologies within manufacturing and production SMEs. A skilled workforce can ensure that IIoT systems are effectively managed, maintained, and configured to their full potential.

Each factor of the IIoT adoption model has its own advantages for manufacturing and production SMEs. If the manufacturing and production SMEs consider each factor properly, they can take the advantages offered by IIoT technologies and facilitate a smoother transition towards digital transformation. Furthermore, the final IIoT adoption model will serve as a roadmap and strategic guide for the manufacturing and production SMEs in Malaysia to adopt IIoT technologies within their business environment. The final IIoT adoption model developed in this research study will not only facilitate manufacturing and production SMEs in the adoption process but will also encourage the SMEs to enhance and improve their overall global market competitiveness, speedup their business process, reduce costs and optimise their operation, efficient operations, improve product quality, reduce environmental impact and sustainability of manufacturing and production SMEs in Malaysia. By following the final IIoT adoption model for adopting IIoT technologies SMEs can prepare themselves for long-term growth and success in a digitalised economy.

13 | SUGGESTIONS AND RECOMMENDATIONS

In order to adopt IIoT technologies seamlessly, SMEs in developing countries, including decision and policymakers, stakeholders need to take a unique approach and follow some suggestions and guidelines along with the IIoT adoption model to ensure the smooth adoption and implementation of IIoT. Firstly, SME owners and top management must have to acknowledge the importance and significance of IIoT technologies including executing the operational excellence, improving product quality, and enhancing overall competitiveness etc. They should invest in educating themselves and their workforce about the advantages of IIoT technologies and how it can be adopted, implemented and utilised to take its advantages, such as streamlining processes, reduce costs, and increase profitability. IIoT technologies should be available for supporting and encouraging production scheduling managers, quality inspectors and line operators to integrate and implement them into the manufacturing and production phases.

1. **Industries and Academics Collaborations:** SMEs should actively do collaborations with educational institutions and technology providers to gain a deeper understanding of IIoT technologies for their specific industry and requirements. Such collaborations, partnerships and communications can provide access to expert knowledge, training programmes and potentially co-develop industry-specific IIoT applications. Well-established knowledge-sharing platforms among SMEs can also improve the exchange of the best practices, successful implementation strategies and lessons learnt. Furthermore, educational institutions should improve collaborations with industry partners, particularly with SMEs, to gain insights into the specific challenges and requirements faced by these manufacturing and production SMEs. These collaborations will lead to the development of industry-relevant IIoT curriculum and research projects, ensuring that the knowledge and skills imparted are directly applicable to real-world scenarios.
2. **Training and Skill Development Programs:** Educational institutions, including universities, colleges, and vocational training centres, should prioritise the development and incorporation of IIoT-related courses and programmes into their curriculum. These courses should cover theoretical aspects as well as hands-on training in IIoT technologies, applications, and implementation strategies. By equipping students with the necessary skills and knowledge, educational institutions can contribute to building a workforce that is well-prepared IIoT adoption and implementation in the industrial sector. Additionally, educational institutions should actively engage in organising workshops, seminars, and training programs specifically designed for SME owners, managers and employees. These programmes can help raise awareness about IIoT benefits, address common concerns and misconceptions, and provide practical guidance on implementation strategies. By offering these resources in accessible formats, educational institutions can empower SMEs to make informed decisions about IIoT adoption and overcome potential barriers.
3. **Government Financial Support:** The government should provide financial incentives, such as tax breaks, subsidies, and grants for the manufacturing and production SMEs stakeholders to make IIoT technologies more accessible and affordable for them, as a majority of the SMEs face financial challenges when adopting IIoT technologies. The government should support the adoption of IIoT in manufacturing and production SMEs by providing funded training opportunities, partnering with educational institutions to build relevant programmes, and building industry-academia collaboration platforms.
4. **Industrial Financial Solutions:** Financial organisation should also contribute by offering attractive loan packages and financing options to SMEs investing in IIoT technologies. These financing solutions should account for the potential long-term benefits and return on investment associated with IIoT adoption, making it more accessible for SMEs with limited capital resources.

5. **Awareness Campaigns:** The government should also arrange some public awareness campaigns with the help of educational institutions that highlight the advantages of IIoT which will help to increase understanding and encourage adoption among SMEs. Moreover, large corporations and multinational companies should engage in knowledge-sharing and mentorship programmes with SMEs, sharing their experiences and best practices in IIoT adoption.
6. **Government Policies and Regulations:** The government must support the IIoT adoption by providing supportive policies, regulations, rules, standards and initiatives including developing regulatory frameworks for the successful IIoT adoption and implementation in SMEs, while ensuring data protection, and establishing national IIoT standards. Governments should also support the public–private collaborations and partnerships to facilitate the IIoT technologies-based research and adoption and create dedicated funds to support manufacturing and production SMEs in their IIoT technologies adoption. Additionally, SMEs also have to stay informed regarding relevant government policies, incentives, or regulation that may be announced by the government that may impact the adoption of IIoT technologies.
7. **Customers' Satisfaction and Requirements:** SMEs should leverage the IIoT technologies that have the capabilities of fulfilling the satisfaction of customers and requirements, such as product customisations, improving the quality of the product, offering data-driven insights, reducing lead times and optimise the manufacturing and production processes. SMEs should prioritise the usage of IIoT-enable insights to gain a better view of customers' behaviours and preferences. They should also focus on exploring new ways to utilise the IIoT technologies to build unique value-added services such as predictive maintenance or optimisation of the performance that can give them an edge in the global competitive market.
8. **Sustainability:** Manufacturing and production SMEs should adopt and implement the IIoT technologies that have the capabilities to contribute in sustainable manufacturing and production practices including the reducing energy consumption, waste and optimising the overall environmental impact. SMES should seek for the technologies that can offer real-time resources management and utilisation and environmental insights to enable SMEs to make informed decisions for improving the sustainability [67–70]. SMEs should also support the economic initiatives for instance monitoring manufacturing and production life cycle for better reuse and recycling. They should also ensure to adhere with the environmental secure and safety standards and regulations.
9. **Predictive Maintenance:** For better maintenance manufacturing and production SMEs should adopt the IIoT technologies that provide fast and robust predictive maintenance abilities. The IIoT technologies must have built in advanced machine learning and analytics models to predict equipment failure before it occurs, minimise downtime, detect anomalies, reduce operational costs, reduce maintenance schedules and prolong the lifespan of the equipment and machinery. SMEs should seek for IIoT technologies that can easily integrate and accommodate data from various multiple resources for instance weather conditions.
10. **Technological Support:** Technology providers, innovators and developers should focus on developing user-friendly, affordable, and industry-specific IIoT technologies that address the unique challenges faced by SMEs. Additionally, they should provide comprehensive technical support, guidance, step-by-step clear instructions and consultation services to assist SMEs in navigating the difficulties of IIoT adoption and implementation. SMEs should choose the IIoT technologies that require less effort for the integration or upgrades with the existing systems.
11. **Strong Network and Communication:** For the safe and reliable adoption of IIoT technologies, the manufacturing and production SMEs must ensure about a strong network and communication setting including fast Internet connection, dependable warless network, secure data transmission protocol and communication etc [71]. The government should provide high-bandwidth Internet access in industrial areas and subsidies for SMEs to upgrade their networking capabilities. Additionally, SMEs should explore 5G technology adoption and implementation for enabling the faster and more reliable communication between devices and systems.
12. **Real-Time Tracking and Monitoring Systems:** The IIoT technologies should have the capability of providing real-time tracking and monitoring. These IIoT technologies should provide SMEs with fast and instant insights into manufacturing and production operations, including allowing SMEs for frequent tracking and monitoring of inventory levels, manufacturing and production processes, supply chain movements and equipment performance and failure. Real-time tracking and monitoring of IIoT technologies can enhance decision-making speed and accuracy by removing the need for manual tracking. SMEs should also seek foe the IIoT technologies that can provide real time notifications and alerts that will allow SMEs to respond fatly to the failure or possibilities of difficulties. Real-time tacking and monitoring based on IIoT technologies can also enable SMEs to monitor product quality and performance after delivery, which can lead to increasing customer satisfaction and product development.
13. **Privacy and Security:** Manufacturing and Production SMEs should prioritise robust privacy and security standards and measures, including workforce safety and data security to secure their SMEs based on IIoT technologies. It can be possible by implementing strong encryption mechanisms, enabling multi-factor authentication, and constantly updating all software and firmware. SMEs should also conduct regular security checks and vulnerability assessments to identify and track the vulnerabilities [72–75]. The technology providers or innovators must ensure that built-in security mechanisms and continuing maintenance services are resilient to emerging cyber

threats. Additionally, manufacturing and production SMEs should create and implement effective data handling policies, train employees on cybersecurity best practices, and consider collaborating with cybersecurity professionals to build a strong defence against future attacks.

14 | CONCLUSION AND FUTURE WORKS

The Industrial IoT has transformed the industrial sector especially the manufacturing and production SMEs due to its potential advantages for the SMEs, such as increasing efficiencies, providing real-time tracking capabilities, improving predictive maintenance and customer experience. The aims of the research have been achieved by developing the finalised IIoT adoption model based on TOEI framework. The model has contained 17 key influencing factors for the successful adoption and implantation of IIoT technologies in the manufacturing and production SMEs. Furthermore, the research has adopted comprehensive quantitative statistical analysis methods and the final IIoT adoption model has been assessed using Smart PLS in terms of reliability and validity using the validation methods, including the Construct Reliability, Internal Consistency Reliability, Cronbach's Alpha, Composite Reliability, Rho_a and Rho_c, Construct Validity, Convergent Validity and AVE. The result of the analysis shows that all the influencing factors from each category, including technological, organisational, environmental and individual have a positive impact and fulfilled the required criteria for the adoption of IIoT technologies for the manufacturing and production SMEs that show the final IIoT adoption model is valid and reliable and can be utilised by the manufacturing and production SMEs. Moreover, this research study also demonstrates a comprehensive comparison of IIoT versus IoT technologies, this comparison will help SMEs in developing countries to clearly understand the concept of both IoT and IoT technologies and will also guide them to make informed decisions related to the technological advancement. Furthermore, this research study also proposes potential advantages, suggestions and recommendations for the manufacturing and production SME stakeholders, owners, government, policies and decision makers and educational institutions that need to be followed in order to ensure the smooth adoption of IIoT technologies in the SMEs.

Additionally, this research study opens avenues for future research to explore the integration of IIoT within various sectors beyond manufacturing and production SMEs. It suggests examining the scalability of the IIoT adoption model in larger enterprises and across different industries. Additionally, it encourages investigating the long-term impacts of IIoT on business performance, workforce dynamics, and economic growth. Future studies could also focus on the development of sector-specific IIoT frameworks and the role of government policies in facilitating IIoT adoption. Moreover, there is a potential to delve into the ethical implications and cybersecurity challenges associated with IIoT deployment.

AUTHOR CONTRIBUTIONS

Sajid Shah: Conceptualisation; data curation; formal analysis; investigation; methodology; software; visualisation; writing–original draft; writing–review & editing. **Syed Hamid Hussain Madni**: Conceptualisation; formal analysis; methodology; project administration; software; supervision; validation; writing–review & editing. **Siti Zaitoon Mohd Hashim**: Supervision; validation. **Muhammad Faheem**: Investigation; resources; review and editing. **Hafiz Muhammad Faisal Shahzad**: Data curation; project administration; software.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

ORCID

Sajid Shah https://orcid.org/0009-0006-9980-101X
Syed Hamid Hussain Madni https://orcid.org/0000-0002-3816-1382
Muhammad Faheem https://orcid.org/0000-0003-4628-4486

REFERENCES

1. Alsharif, M.H., et al.: Green IoT: a review and future research directions. Symmetry 15(3), 757 (2023). https://doi.org/10.3390/sym15030757
2. Khang, A., et al.: Advanced IoT Technologies and Applications in the Industry 4.0 Digital Economy. CRC Press (2024)
3. Babayigit, B., Abubaker, M.: Industrial internet of things: a review of improvements over traditional SCADA systems for industrial automation. IEEE Syst. J. 18(1), 120–133 (2023). https://doi.org/10.1109/jsyst.2023.3270620
4. Zhang, J., et al.: Smart industrial IoT empowered crowd sensing for safety monitoring in coal mine. Digit. Commun. Networks 9(2), 296–305 (2023). https://doi.org/10.1016/j.dcan.2022.08.002
5. Bodlaj, M., Kadic-Maglajlic, S., Vida, I.: Disentangling the impact of different innovation types, financial constraints and geographic diversification on SMEs' export growth. J. Bus. Res. 108, 466–475 (2020). https://doi.org/10.1016/j.jbusres.2018.10.043
6. Peter, O., Pradhan, A., Mbohwa, C.: Industrial internet of things (IIoT): opportunities, challenges, and requirements in manufacturing businesses in emerging economies. Procedia Comput. Sci. 217, 856–865 (2023). https://doi.org/10.1016/j.procs.2022.12.282
7. Li, H., et al.: How an industrial internet platform empowers the digital transformation of SMEs: theoretical mechanism and business model. J. Knowl. Manag. 27(1), 105–120 (2023). https://doi.org/10.1108/jkm-09-2022-0757

8. Shah, S., et al.: Factors influencing the adoption of industrial internet of things for the manufacturing and production small and medium enterprises in developing countries. IET Collab. Intell. Manuf. 6(1), e12093 (2024). https://doi.org/10.1049/cim2.12093
9. Dora, M., et al.: Critical success factors influencing artificial intelligence adoption in food supply chains. Int. J. Prod. Res. 60(14), 4621–4640 (2022). https://doi.org/10.1080/00207543.2021.1959665
10. Dachyar, M., Ilahiyyah, E.: Determining the importance factors of financial technology adoption in hospital using fuzzy analytical network process (FANP). In: IOP Conference Series: Materials Science and Engineering. IOP Publishing (2019).012047
11. Ramos, P.N., Enteria, M.L.B., Norona, M.I.: Readiness model development in the adoption of Internet of Things (IoT) among Philippine manufacturing SMEs using force field analysis approach and structural equation modelling. In: Proceedings of the Second Asia Pacific International Conference on Industrial Engineering and Operations Management, Surakarta, Indonesia, pp. 14–16 (2021)
12. Rajbhandari, S., et al.: Assessing the industrial readiness for adoption of industry 4.0 in Nepal: a structural equation model analysis. Heliyon 8(2), e08919 (2022). https://doi.org/10.1016/j.heliyon.2022.e08919
13. Patil, K.P., Pramod, D.: Adoption of IIoT-based smart manufacturing systems by MSMEs-A TOE-TAM approach. In: 2023 3rd Asian Conference on Innovation in Technology (ASIANCON), pp. 1–6. IEEE (2023)
14. Mukherjee, S., et al.: Achieving organizational performance by integrating industrial Internet of things in the SMEs: a developing country perspective. TQM J. 36(1), 265–287 (2024). https://doi.org/10.1108/tqm-07-2022-0221
15. Kumar, A., et al.: A framework for assessing social acceptability of industry 4.0 technologies for the development of digital manufacturing. Technol. Forecast. Soc. Change 174, 121217 (2022). https://doi.org/10.1016/j.techfore.2021.121217
16. Mittal, S., et al.: A smart manufacturing adoption framework for SMEs. Int. J. Prod. Res. 58(5), 1555–1573 (2020). https://doi.org/10.1080/00207543.2019.1661540
17. Narwane, V.S., et al.: Mediating role of cloud of things in improving performance of small and medium enterprises in the Indian context. Ann. Oper. Res. 329(1-2), 69–98 (2023). https://doi.org/10.1007/s10479-019-03502-w
18. Shahzad, A., et al.: Adoption of fourth industrial revolution 4.0 among Malaysian small and medium enterprises (SMEs). Human. Soc. Sci. Commun. 10, 1–14 (2023). https://doi.org/10.1057/s41599-023-02076-0
19. Jayashree, S., et al.: Testing an adoption model for Industry 4.0 and sustainability: a Malaysian scenario. Sustain. Prod. Consum. 31, 313–330 (2022). https://doi.org/10.1016/j.spc.2022.02.015
20. Abd Shukor, R., Mooi, W.K., Ahmad, M.N.: Small and medium enterprises' business sustainability based on the Industry 4.0 internet of things adoption: a Malaysian Bumiputera case study. Serb. J. Manag. 17(1), 99–110 (2022). https://doi.org/10.5937/sjm17-35505
21. Yi, L.Y., et al.: Readiness for and adoption of Industry 4.0 among small and medium sized enterprises in the Malaysian Furniture industry. Bioresources 16(4), 8289–8308 (2021). https://doi.org/10.15376/biores.16.4.8289-8308
22. Abdulaziz, Q.A., et al.: Developing an IoT framework for Industry 4.0 in Malaysian SMEs: an analysis of current status, practices, and challenges. Appl. Sci. 13(6), 3658 (2023). https://doi.org/10.3390/app13063658
23. Won, J.Y., Park, M.J.: Smart factory adoption in small and medium-sized enterprises: empirical evidence of manufacturing industry in Korea. Technol. Forecast. Soc. Change 157, 120117 (2020). https://doi.org/10.1016/j.techfore.2020.120117
24. Jung, S., Kim, D., Shin, N.: Success factors of the adoption of smart factory transformation: an examination of Korean manufacturing SMEs. IEEE Access 11, 2239–2249 (2023). https://doi.org/10.1109/access.2022.3233811
25. Madhavan, M., Sharafuddin, M.A., Wangtueai, S.: Measuring the Industry 5.0-readiness level of SMEs using Industry 1.0–5.0 practices: the case of the seafood processing industry. Sustainability 16(5), 2205 (2024). https://doi.org/10.3390/su16052205
26. Nguyen, X.T., Luu, Q.K.: Factors affecting adoption of industry 4.0 by small-and medium-sized enterprises: a case in Ho Chi Minh city, Vietnam. J. Asian Fin., Econ. Bus. 7(6), 255–264 (2020). https://doi.org/10.13106/jafeb.2020.vol7.no6.255
27. Parra-Sánchez, D.T., Talero-Sarmiento, L.H., Guerrero, C.D.: Assessment of ICT policies for digital transformation in Colombia: technology readiness for IoT adoption in SMEs in the trading sector. Digit. Policy, Regul. Govern. 23(4), 412–431 (2021). https://doi.org/10.1108/dprg-09-2020-0120
28. Marcon, É., et al.: Sociotechnical factors and Industry 4.0: an integrative perspective for the adoption of smart manufacturing technologies. J. Manuf. Technol. Manag. 33(2), 259–286 (2022). https://doi.org/10.1108/jmtm-01-2021-0017
29. Ghafari, F., Shourangiz, E., Wang, C.: Cost effectiveness of the Industrial Internet of Things adoption in the US manufacturing SMEs. Intell. Sustain. Manuf. 1, 10008 (2024). https://doi.org/10.35534/ism.2024.10008
30. Khushbu, G., et al.: Internet of things in manufacturing. A Review. Mater. Today Proc. 46, 6775–6780 (2021). https://doi.org/10.1016/j.matpr.2021.04.337
31. Ahmed, S.F., et al.: Industrial Internet of Things enabled technologies, challenges, and future directions. Comput. Electr. Eng. 110, 108847 (2023). https://doi.org/10.1016/j.compeleceng.2023.108847
32. Ahmad, S., et al.: Qualitative v/s. quantitative research-a summarized review. Population 1(43), 2828–2832 (2019). https://doi.org/10.18410/jebmh/2019/587
33. Plonsky, L.: Quantitative research methods. In: The Routledge Handbook of Instructed Second Language Acquisition. Routledge (2017)
34. Shah, S., et al.: Assessing the prioritization of key influencing factors for industrial IoT readiness in SMEs. In: International Conference of Reliable Information and Communication Technology, pp. 252–262. Springer (2023)
35. Khan, W.Z., et al.: Industrial internet of things: recent advances, enabling technologies and open challenges. Comput. Electr. Eng. 81, 106522 (2020). https://doi.org/10.1016/j.compeleceng.2019.106522
36. Sari, A., Lekidis, A., Butun, I.: Industrial networks and IIoT: now and future trends. In: Industrial IoT: Challenges, Design Principles, pp. 3–55. Applications, Security (2020)
37. Gebremichael, T., et al.: Security and privacy in the industrial internet of things: current standards and future challenges. IEEE Access 8, 152351–152366 (2020). https://doi.org/10.1109/access.2020.3016937
38. Behnke, I., Austad, H.: Real-time performance of industrial IoT communication technologies: a review. IEEE Internet Things J. 11(5), 7399–7410 (2023). https://doi.org/10.1109/jiot.2023.3332507
39. Li, K., et al.: Framework and capability of industrial IoT infrastructure for smart manufacturing. Standards 3, 1–18 (2023). https://doi.org/10.3390/standards3010001
40. Hazra, A., et al.: A comprehensive survey on interoperability for IIoT: taxonomy, standards, and future directions. ACM Comput. Surv. 55, 1–35 (2021). https://doi.org/10.1145/3485130
41. Dhirani, L.L., et al.: Ethical dilemmas and privacy issues in emerging technologies: a review. Sensors 23(3), 1151 (2023). https://doi.org/10.3390/s23031151
42. Abuhasel, K.A., Khan, M.A.: A secure industrial internet of things (IIoT) framework for resource management in smart manufacturing. IEEE Access 8, 117354–117364 (2020). https://doi.org/10.1109/access.2020.3004711
43. Xu, H., et al.: A survey on digital twin for industrial internet of things: applications, technologies and tools. IEEE Commun. Surv. Tutorials 25(4), 2569–2598 (2023). https://doi.org/10.1109/comst.2023.3297395
44. Yarmilko, A., Datsenko, D.: Increase of the dependability and adaptability of critical infrastructure' IIoT systems. In: Проблеми зняття з експлуатації об'єктів ядерної енергетики та відновлення навколишнього середовища (INUDECO 23): збірник матеріалів VIII Міжнародної конференції (27–28 квітня 2023, м. Славутич), pp. 117–121 (2023)

45. Straub, L., et al.: Employee skills for circular business model implementation: a taxonomy. J. Clean. Prod. 410, 137027 (2023). https://doi.org/10.1016/j.jclepro.2023.137027
46. Taherdoost, H.: Validity and reliability of the research instrument; how to test the validation of a questionnaire/survey in a research. In: How to Test the Validation of a Questionnaire/survey in a Research (August 10, 2016) (2016)
47. Boparai, J.K., Singh, S., Kathuria, P.: How to design and validate a questionnaire: a guide. Curr. Clin. Pharmacol. 13(4), 210–215 (2018). https://doi.org/10.2174/1574884713666180807151328
48. Corp, S.: SME Corporation Malaysia. [Online]. http://www.smecorp.gov.my (2023). [Accessed]
49. Joshi, A.P., Patel, B.V.: Data preprocessing: the techniques for preparing clean and quality data for data analytics process. Orient. J. Comput. Sci. Technol. 13(0203), 78–81 (2020). https://doi.org/10.13005/ojcst13.0203.03
50. Jane, V.: Survey on iot data preprocessing. Turk. J. Comput. Math. Educ. (TURCOMAT) 12, 238–244 (2021)
51. Fan, C., et al.: A review on data preprocessing techniques toward efficient and reliable knowledge discovery from building operational data. Front. Energy Res. 9, 652801 (2021). https://doi.org/10.3389/fenrg.2021.652801
52. Wan, X., et al.: Estimating the sample mean and standard deviation from the sample size, median, range and/or interquartile range. BMC Med. Res. Methodol. 14, 1–13 (2014). https://doi.org/10.1186/1471-2288-14-135
53. Hair, J.F.: Multivariate Data Analysis (2009)
54. Black, W., Babin, B.J.: Multivariate data analysis: its approach, evolution, and impact. In: The Great Facilitator: Reflections on the Contributions of Joseph F. Hair, Jr. To Marketing and Business Research. Springer (2019)
55. Kimberlin, C.L., Winterstein, A.G.: Validity and reliability of measurement instruments used in research. Am. J. Health Syst. Pharm. 65(23), 2276–2284 (2008). https://doi.org/10.2146/ajhp070364
56. Hajjar, S.: Statistical analysis: internal-consistency reliability and construct validity. Int. J. Quant. Qual. Res. Methods 6, 27–38 (2018)
57. Agbo, A.A.: Cronbach's alpha: review of limitations and associated recommendations. J. Psychol. Afr. 20(2), 233–239 (2010). https://doi.org/10.1080/14330237.2010.10820371
58. Amirrudin, M., Nasution, K., Supahar, S.: Effect of variability on Cronbach alpha reliability in research practice. Jurnal Matematika, Statistika dan Komputasi 17(2), 223–230 (2021). https://doi.org/10.20956/jmsk.v17i2.11655
59. Lai, M.H.: Composite reliability of multilevel data: it's about observed scores and construct meanings. Psychol. Methods 26(1), 90–102 (2021). https://doi.org/10.1037/met0000287
60. Carlson, K.D., Herdman, A.O.: Understanding the impact of convergent validity on research results. Organ. Res. Methods 15(1), 17–32 (2012). https://doi.org/10.1177/1094428110392383
61. Chin, C.-L., Yao, G.: Convergent validity. In: Encyclopedia of Quality of Life and Well-Being Research. Springer (2021)
62. Dos Santos, P.M., Cirillo, M.Â.: Construction of the average variance extracted index for construct validation in structural equation models with adaptive regressions. Commun. Stat. Simulat. Comput. 52(4), 1639–1650 (2023). https://doi.org/10.1080/03610918.2021.1888122
63. Peterson, R.A.: A meta-analysis of variance accounted for and factor loadings in exploratory factor analysis. Market. Lett. 11(3), 261–275 (2000). https://doi.org/10.1023/a:1008191211004
64. Farrell, A.M., Rudd, J.M.: Factor analysis and discriminant validity: a brief review of some practical issues. In: Australia and New Zealand Marketing Academy Conference 2009. Anzmac (2009)
65. Rönkkö, M., Cho, E.: An updated guideline for assessing discriminant validity. Organ. Res. Methods 25(1), 6–14 (2022). https://doi.org/10.1177/1094428120968614
66. Ab Hamid, M.R., Sami, W., Sidek, M.M.: Discriminant validity assessment: use of Fornell & Larcker criterion versus HTMT criterion. In: Journal of Physics: Conference Series. IOP Publishing (2017).012163
67. Butt, R.A., et al.: A survey of dynamic bandwidth assignment schemes for TDM-based passive optical network. J. Opt. Commun. 41(3), 279–293 (2020). https://doi.org/10.1515/joc-2017-0186
68. Al-Khasawneh, M.A.S., et al.: A MapReduce based approach for secure batch satellite image encryption. IEEE Access 11(5), 62865–62878 (2023). https://doi.org/10.1109/ACCESS.2023.3279719
69. Faheem, M., et al.: Cyberattack patterns in blockchain-based communication networks for distributed renewable energy systems: a study on big datasets. Data Brief 53(5), 110212 (2024). https://doi.org/10.1016/j.dib.2024.11021250.66
70. Ashraf, M.W., et al.: Disaster-resilient optical network survivability: a comprehensive survey. Photonics 5(4), 35 (2018). https://doi.org/10.3390/photonics5040035
71. Chen, Y., et al.: Evaluation of machine learning models for smart grid parameters: performance analysis of ARIMA and Bi-LSTM. Sustainability 15(11), 8555 (2023). https://doi.org/10.3390/su15118555
72. Faheem, M., et al.: A multiobjective, lion mating optimization inspired routing protocol for wireless body area sensor network based healthcare applications. Sensors 19(23), 5072 (2019). https://doi.org/10.3390/s19235072
73. Al-Khasawneh, M.A., et al.: A secure blockchain framework for healthcare records management systems. Healthc. Technol. Lett. 11(6), 461–470 (2024). https://doi.org/10.1049/htl2.12092
74. Faheem, M., Mahmoud Ahmad, A.-K.: Multilayer cyberattacks identification and classification using machine learning in Internet of BlockChain (IoBC)-based energy networks. Data Brief 54(5), 110461 (2024). https://doi.org/10.1016/j.dib.2024.110461
75. Faheem, M., et al.: A blockchain-based resilient and secure framework for events monitoring and control in distributed renewable energy systems. IET Blockchain 4(S1), 1–15 (2024). https://doi.org/10.1049/blc2.12081

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