

Cracking the Code: How Readiness Mediates the Environment-Adoption Relationship in Industry 4.0

(Memecahkan Kod: Bagaimana Kesediaan Memediasi Hubungan Persekitaran dan Penerapan dalam Industri 4.0)

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ABSTRACT

Industry 4.0 represents a transformative trend in the industrial sector, offering significant opportunities for improving business operations and achieving sustainability. However, small and medium-sized enterprises (SMEs) often encounter challenges in adopting these advanced technologies, underscoring the need to assess their Industry 4.0 readiness. This study explores the interplay of environmental factors and Industry 4.0 adoption, with a focus on the mediating role of Industry 4.0 readiness. A survey was administered to 157 managerial employees of Malaysian manufacturing SMEs using a quantitative methodology. Partial least squares structural equation modelling (PLS-SEM) was used to analyse the data. It was found that Industry 4.0 readiness served as a crucial mediator and environmental factors significantly and favourably influenced the adoption of Industry 4.0. These findings emphasise the importance of external environmental influences in driving technological adoption while highlighting the necessity for SMEs to develop readiness strategies to maximise the benefits of Industry 4.0. This study contributes to the understanding of Industry 4.0 integration in SMEs, offering practical insights for policymakers and business leaders to foster technological readiness and enhance competitive advantage.

Keywords: Industry 4.0; SMEs; environmental factors; industry 4.0 readiness; technology adoption

ABSTRAK

Industri 4.0 merupakan suatu trend transformasi dalam sektor perindustrian yang menawarkan peluang besar untuk meningkatkan operasi perniagaan dan mencapai kelestarian. Walau bagaimanapun, perusahaan kecil dan sederhana (PKS) sering menghadapi cabaran dalam mengadaptasi teknologi canggih ini, sekali gus menekankan keperluan untuk menilai tahap kesediaan mereka terhadap Industri 4.0. Kajian ini meneroka peranan mediasi kesediaan Industri 4.0 dalam hubungan antara faktor persekitaran dan penerapan Industri 4.0. Soal selidik terhadap 157 kakitangan pengurusan dari PKS pembuatan di Malaysia dengan menggunakan pendekatan kuantitatif. Pemodelan Persamaan Struktur Kuasa Separat (PLS-SEM) digunakan bagi menganalisis data. Hasil kajian menunjukkan bahawa faktor persekitaran memberi pengaruh positif dan signifikan terhadap penerapan Industri 4.0, dengan kesediaan Industri 4.0 bertindak sebagai perantara kritikal. Dapatan ini menekankan kepentingan pengaruh persekitaran luar dalam mendorong penerapan teknologi di samping menelusuri keperluan PKS untuk membangunkan strategi kesediaan bagi memaksimumkan manfaat Industri 4.0. Kajian ini menyumbang kepada pemahaman mengenai integrasi Industri 4.0 dalam PKS, sekali gus memberikan pandangan praktikal kepada pembuat dasar dan pemimpin perniagaan untuk menggalakkan kesediaan teknologi dan meningkatkan kelebihan daya saing.

Kata kunci: Industri 4.0; PKS; faktor persekitaran; kesediaan industri 4.0; penerapan teknologi

INTRODUCTION

Driven by cutting-edge technologies such as the Internet of Things (IoT), artificial intelligence (AI), and big data analytics, the Fourth Industrial Revolution, commonly referred to as Industry 4.0, represents a profound transformation of industrial operations worldwide (Ghobakhloo 2020). First conceptualised in Germany in 2011, Industry 4.0 integrates advanced digital and cyber-physical systems into manufacturing processes to enhance operational efficiency, reduce costs, improve quality, and enable real-time, data-driven decision-making (Almada-Lobo 2016; Khang et al. 2024).

In Malaysia, the strategic importance of Industry 4.0 has been recognised through the launch of Industry4WRD: National Policy on Industry 4.0 in 2018 to strengthen the technological competitiveness of the manufacturing sector. The policy emphasises the adoption of automation, IoT, AI, and data technologies, particularly among small and medium-sized enterprises (SMEs) (MITI 2021). Despite these initiatives, adoption rates among SMEs remain very low; fewer than 1%

have fully implemented Industry 4.0 technologies, reflecting persistent barriers in digital transformation even with substantial external support (EU-Malaysia Chamber of Commerce and Industry 2020; FMM 2022).

Although prior studies have examined Industry 4.0 adoption, several important gaps remain. Empirically, existing research has largely focused on technological and organisational factors in SMEs (Müller et al. 2018; Mittal et al. 2018; Stentoft et al. 2020), while relatively limited attention has been given to the role of environmental influences in shaping adoption decisions, particularly in the Malaysian context. Furthermore, prior studies tend to examine these factors as direct predictors of adoption (Low & Chen 2011; Gangwar et al. 2015), offering limited insight into the mechanisms through which environmental conditions may influence organisational readiness for Industry 4.0. From a theoretical perspective, many studies have applied multiple frameworks simultaneously (Gangwar et al. 2015; Amini & Javid 2023), which may obscure the underlying mechanisms within the TOE framework. In particular, the role of Industry 4.0 readiness as a mediating mechanism within TOE remains relatively underexplored in the context of Industry 4.0 adoption among manufacturing SMEs (Puklavec et al. 2018; Stentoft et al. 2020).

To explain why adoption remains limited, this study explicitly adopts the Technology–Organisation–Environment (TOE) framework as its singular theoretical foundation (Tornatzky & Fleischer 1990; Baker 2012). Within TOE, the environmental context, which includes competitive pressure, government support, external support, and business partner influences, plays a central role in shaping how organisations respond to technological change (Oliveira & Martins 2010; Zhu et al. 2006). In the SME setting, environmental forces often exert a direct effect on technology adoption because SMEs may adopt new systems in response to competitive pressure or policy incentives even when internal capabilities are limited (Iacovou et al. 1995; Low & Chen 2011). At the same time, these environmental influences can function indirectly by shaping Industry 4.0 readiness, thereby enhancing SMEs' readiness to adopt Industry 4.0 technologies (Cohen & Levinthal 1990; Teece 2007). This dual pathway is consistent with TOE-based explanations, which recognise that external conditions can both motivate adoption and stimulate the development of organisational readiness needed for implementation (Baker 2012; Zhu et al. 2006).

Based on this grounding, the present study investigates how Industry 4.0 readiness mediates the relationship between environmental influences and the adoption of Industry 4.0 technologies among Malaysian manufacturing SMEs. Readiness to change can significantly reduce challenges (Samsudin & Hanafiah 2024), highlighting its critical role in enabling firms to overcome barriers associated with digital transformation. The study aims to clarify the role of readiness as a key mechanism within the Technology–Organization–Environment (TOE) framework and extend existing literature through a mediation-focused contribution. The findings are expected to offer practical insights for SMEs navigating digital transformation and provide policymakers and industry leaders with evidence to support more effective implementation of Malaysia's Industry4WRD agenda.

LITERATURE REVIEW

ENVIRONMENT

To frame these environmental factors more systematically, this study draws on the Technology–Organisation–Environment (TOE) framework, which highlights the role of external conditions in shaping technology adoption decisions (Tornatzky & Fleischer 1990). Within this lens, the environmental context encompasses the external pressures and support systems that influence an organisation's readiness, motivation, and capability to adopt Industry 4.0 technologies. Guided by this perspective, the environmental backdrop of this study (competitive pressure, business partners, external support, and government support) represents the key external forces that shape organisational adoption behaviour.

Competitive pressure reflects the influence exerted on a company by the actions and strategies of its competitors within the industry (Oliveira & Martins 2010). It is a key driver of technology adoption, with various studies highlighting its role in adopting innovations like cloud computing (Low & Chen 2011), e-business (Lin & Lin 2008), and electronic data interchange (EDI) (Chwelos et al. 2001). In highly competitive markets, businesses often feel obligated to align with industry advancements to remain competitive. Their adoption of Industry 4.0 technologies is commonly driven by the need to innovate and improve operational efficiency. Organisations that do not adapt risk losing market share or becoming obsolete. Therefore, competitive pressure acts as a crucial catalyst. Despite these challenges, the implementation of Industry 4.0 technology can improve organisational sustainability performance (Al-Swidi et al. 2023).

Another crucial element propelling the adoption of Industry 4.0 technology is business partners. Their influence is critical in a company's decision-making process regarding technological advancements, as their expertise and insights offer valuable guidance on best practices and innovative solutions (Teo et al. 2009). Collaborative relationships with suppliers, customers, and other stakeholders provide organisations with access to essential resources and knowledge (Schroeck et al. 2020). For instance, partnerships with technology providers can facilitate the acquisition of cutting-edge tools and systems necessary for Industry 4.0 implementation. Additionally, maintaining strong connections with customers allows businesses to better understand market needs, enabling them to adopt technologies that align with customer expectations and demands (Nugroho et al. 2017).

Beyond business alliances and competitive pressures, external support is essential to an organisation's ability to make the shift to Industry 4.0. When businesses are confident that vendors or third-party providers will offer them sufficient

support, they are more likely to adopt advanced technologies because this confidence lowers risks and improves implementation readiness (Premkumar & Roberts 1999). External support can come from a variety of sources, including industry associations, technology vendors, and research institutions, which provide training, expert advice, and essential resources. These forms of assistance are particularly valuable in addressing common challenges such as limited technical expertise or financial constraints (Premkumar & Roberts 1999). By leveraging this support, organisations can strengthen their innovation capabilities and better prepare to adopt Industry 4.0 technology.

One of the important factors influencing the environmental context for implementing Industry 4.0 technology is government support. Encouraging technological advancement through policies, initiatives, and funding programs is essential to fostering a business-friendly environment (Park et al. 2020). Grants, subsidies, and tax breaks are examples of financial incentives that can greatly lower the cost of implementing cutting-edge technologies, thus increasing their accessibility for businesses (Li 2018). Furthermore, regulatory frameworks that promote innovation and eliminate barriers to entry serve as catalysts for Industry 4.0 adoption. By establishing a supportive ecosystem, governments can help businesses overcome uncertainties and risks associated with technological investments (Zhou & Zheng 2023).

A comprehensive environmental framework that influences how businesses adopt and apply Industry 4.0 technology is created by the combined effects of government support, business partnerships, external support, and competitive pressure. Recognising this framework is essential for understanding the adoption dynamics and the key drivers pushing companies towards advanced industrial practices. Grounding these factors within the TOE framework strengthens the understanding that Industry 4.0 adoption is not only driven by internal readiness but also by the broader external ecosystem in which organisations operate.

In this study, the environment construct is conceptualised as a formative configuration rather than a reflective latent factor. Competitive pressure, business partner influence, external support, and government support represent distinct environmental forces that do not necessarily move together but jointly shape the external context surrounding the organisations. Following the TOE framework, these dimensions collectively form the environmental conditions influencing Industry 4.0 readiness and adoption. Together, these environmental conditions act not only as external drivers but also as capability-shaping forces, influencing how organisations prepare for and eventually adopt Industry 4.0 technology.

INDUSTRY 4.0 ADOPTION

Adopting Industry 4.0 entails integrating cutting-edge technologies like automation systems, big data analytics, artificial intelligence (AI), and the Internet of Things (IoT) strategically. In this study, Industry 4.0 adoption refers specifically to the initial adoption and implementation of key Industry 4.0 technologies within organisational processes. The focus is on whether organisations decide to adopt and integrate technologies such as automation systems, IoT, AI, and data analytics into their operations, rather than the post-adoption stages like intensity of use or long-term routinisation. These technologies are intended to transform productivity and operational efficiency in various processes. Industry 4.0 is not merely a technical improvement; it is a paradigm shift in how organisations operate, allowing for more flexibility, improved responsiveness to market dynamics, and real-time, data-driven decision-making. Additionally, it empowers manufacturers to deliver higher-quality and more efficient products (Müller et al. 2018). By streamlining production processes, these innovations promote faster, more cost-effective operations, optimise resource utilisation, and improve reliability and overall performance (Jamwal et al. 2021).

The widespread use of Industry 4.0 technology by SMEs is hampered by numerous factors. Financial constraints are a significant barrier, as adopting advanced technologies often demands substantial investment in infrastructure upgrades (Orzes et al. 2018). Furthermore, integrating Industry 4.0 solutions with existing legacy systems is technically complex and requires specialised skills that many organisations lack (Mittal et al. 2018). Limited awareness of technological advancements also hinders adoption, as SMEs often struggle with insufficient exposure to new trends, inadequate training opportunities, and a lack of effective communication about the potential benefits and applications for Industry 4.0 (Horváth & Szabó 2019). Key stakeholders, such as legislators, technology companies, and industry leaders, must work together to overcome these obstacles (Bettiol et al. 2023). Strategies like strong change management programs, industry partnerships, and government incentives are also essential for SMEs to successfully transition to Industry 4.0. These steps guarantee that businesses are equipped to handle the challenges of a rapidly changing industrial environment (Alkhazaleh et al. 2022).

In conclusion, the adoption of Industry 4.0 technology is a multifaceted process influenced by both internal capabilities and external pressures. This highlights the importance of adopting a holistic and strategic approach to successfully navigate and thrive in this era of transformative technological change.

INDUSTRY 4.0 READINESS

Industry 4.0 readiness is the capacity of an organisation to successfully integrate emerging technologies. Past research indicates that better-prepared organisations are more likely to successfully implement Industry 4.0 innovations. Similarly, countries prioritising efforts to close the digital divide are achieving significant progress in implementing these technologies (Castelo-Branco et al. 2019). Various frameworks have been designed to evaluate an organisation's readiness for adopting innovations and technologies, including Industry 4.0. These models identify critical factors that influence readiness, which

have been extensively investigated. For instance, a study found that SMEs can more easily adopt Industry 4.0 technology and experience digital transformation when they prioritise 15 crucial readiness factors (Sriram & Vinodh 2020). In this study, Industry 4.0 readiness is defined as an organisational capability rather than an intention. Readiness reflects the organisation's technological, human, and organisational capacities that enable the adoption of Industry 4.0 technology. This distinction is important because intention captures a motivational state, whereas readiness represents the structural conditions required for adoption to occur.

Research indicates that organisations are more likely to adopt and integrate technologies effectively when these innovations are perceived as highly relevant to their business operations (Stentoft et al. 2020). Nonetheless, there is currently no widely recognised or uniform framework for evaluating Industry 4.0 readiness (Rajnai & Kocsis 2018). This highlights the importance of reviewing the literature on Industry 4.0 readiness to better understand the factors influencing an organisation's capacity to adopt these innovative technologies (Sony & Naik 2019). Although numerous Industry 4.0 readiness frameworks exist, they differ in scope and emphasis, with some highlighting technological maturity, while others focus on organisational processes, culture, skills, or integration practices. Despite these variations, the literature shows that most frameworks share several recurring themes: technological readiness, human competencies, and organisational processes that support digital transformation. Aligned with these commonly recurring readiness dimensions, this study adopts the organisational readiness construct from Puklavec et al. (2018), as it captures technological, human, and organisational readiness; elements that are consistently emphasised across existing Industry 4.0 readiness frameworks. Although originally applied in the context of business intelligence systems, their construct reflects these widely shared readiness dimensions (i.e., technological, human, and organisational readiness), making it suitable and theoretically consistent for conceptualising readiness in the Industry 4.0 context used in this study.

HYPOTHESES DEVELOPMENT

ADOPTION OF INDUSTRY 4.0 AND ENVIRONMENT

The decision to adopt new technologies is heavily influenced by both internal and external factors. Organisations are typically attuned to the dynamics of their industry and the broader external environment. Internally, they must evaluate their strengths and weaknesses to maintain competitiveness. Externally, the environment presents opportunities for growth alongside potential challenges that must be managed. The adoption of Industry 4.0 technology is greatly influenced by important factors like government support, external support, business partner collaboration, and competitive pressure.

The adoption of Industry 4.0 technology is significantly influenced by competitive pressure, which pushes businesses to increase productivity, encourage innovation, and satisfy customer demands in order to stay competitive. Research has shown that such pressures strongly impact the adoption of technologies like RFID and Blockchain, especially among SMEs striving to stay relevant in dynamic markets (Shahzad et al. 2023; Paydar et al. 2014; Wong et al. 2019). Similarly, business partners are essential to the adoption of Industry 4.0 because they offer resources, technological solutions, and expertise that can improve organisational capabilities. Collaborative efforts in areas like innovation, supply chain integration, and research further accelerate digital transformation, helping organisations maintain their competitive edge (Schroeck et al. 2020).

Government support also plays a pivotal role, with policies, funding initiatives, research programs, and public-private partnerships creating an enabling environment for technological adoption and business growth (Lin et al. 2018; Fontana et al. 2023). Additionally, external support mechanisms, such as training opportunities and industry networks, help organisations address challenges and advance digital transformation (Jayashree et al. 2022). Therefore, it is essential to examine how these variables interconnect. Consequently, the following hypothesis is put forth in this study.

H₁ Environment has a positive significant relationship with Industry 4.0 adoption.

ENVIRONMENT AND INDUSTRY 4.0 READINESS

Because the environment presents businesses with both opportunities and challenges, there is a strong interdependence between the environment and Industry 4.0. To remain competitive and sustainable, organisations must adapt their operations to meet environmental demands and adopt practices that align with sustainability goals. This dynamic interaction between a business and its internal and external environments significantly influences both organisational sustainability and the broader advancement of Industry 4.0 initiatives (Wong & Kee 2022).

Previous research has highlighted the critical influence of environmental factors on the readiness of businesses, particularly SMEs, to adopt Industry 4.0. Addressing these environmental dynamics is vital for facilitating the transition to this advanced industrial framework (Maria et al. 2019). Governments also play a crucial role in this process through initiatives for technology adoption, management training, and education (Sari & Santoso 2020). As external environmental factors lie beyond their control, businesses must constantly assess and adjust to these changes in order to successfully implement new strategies and guarantee a smooth transition.

Competitive pressure is one of the key elements affecting Industry 4.0 readiness in the environmental context. The need for constant innovation, spurred by competition from both established players and new entrants, pushes organisations

to adopt advanced technologies and optimise operational efficiency (Wong & Kee 2022). This pressure motivates businesses to increase agility, meet evolving customer expectations, and stand out in the marketplace by leveraging Industry 4.0 solutions. These innovation-focused initiatives are essential for sustaining competitiveness and fostering long-term growth in an ever-changing business environment.

Collaboration with business partners and the availability of external support are critical in enhancing Industry 4.0 readiness. Partnerships with business stakeholders offer access to advanced technologies, specialised expertise, and shared knowledge, enabling organisations to adopt best practices while minimising potential risks (Purnomo et al. 2018). Similarly, external support from governments, including financial assistance, tax incentives, and research initiatives, helps lower economic barriers and facilitates the adoption of new technologies (Zhou & Zheng 2023; Shahzad et al. 2023). These collaborative efforts strengthen stakeholder relationships, promote strategic partnerships, and help organisations to effectively manage the complexities of Industry 4.0 transformation, setting the stage for sustainable success. Based on these considerations, it is essential to examine the interconnectedness of these variables. Consequently, the following hypothesis is put forth in this study.

H₂ Environment has a positive significant relationship with Industry 4.0 readiness.

READINESS AND ADOPTION OF INDUSTRY 4.0 TECHNOLOGY

The readiness of an organisation is a crucial determinant in its decision to adopt new technologies. Readiness represents the interplay of various factors and plays a critical role in facilitating adoption by examining how these dimensions interact to enable successful implementation. For example, Kee et al. (2023) emphasised that SMEs' readiness in managerial, operational, and technological domains strongly influences their capacity to adopt Industry 4.0 technology. Furthermore, readiness significantly impacts the adoption process, shaping decisions and ensuring smoother implementation. For instance, Denmark is recognised as one of the most ICT-intensive countries among OECD nations. However, research indicates that many OECD countries exhibit low levels of readiness, suggesting that SMEs in these regions often need additional resources to adequately prepare for digital transformation (Stentoft et al. 2019). The adoption of Industry 4.0 technology is typically more successful in nations that place a high priority on digitisation. This emphasises the importance of promoting readiness, especially among SMEs, in order to guarantee the successful adoption of cutting-edge technologies (Sriram & Vinodh 2020).

Businesses that are not adequately prepared often possess a hindered ability to adopt Industry 4.0 technology. A survey on Industry 4.0 Adoption Journey (2021) revealed that 32.3% of businesses did not commence Industry 4.0 adoption due to the lack of readiness. Many businesses feel unprepared to adopt the innovations and changes brought about by Industry 4.0, prompting them to frequently put off adoption until they are sufficiently prepared. This emphasises the importance of readiness for successful adoption. Therefore, the following hypothesis is put forth in this study.

H₃ Industry 4.0 readiness has a positive significant relationship with Industry 4.0 adoption.

THE ROLE OF INDUSTRY 4.0 READINESS AS A MEDIATOR BETWEEN ENVIRONMENTAL FACTORS AND INDUSTRY 4.0 ADOPTION

The environment has a major impact on whether or not a business decides to implement Industry 4.0. This study examines various factors, including competitive pressure, business partnerships, external support, and government support. Since some of these environmental factors are within an organisation's control, Industry 4.0 technology adoption requires readiness. The mediation logic in this study is grounded in capability-building and IS adoption literature, which shows that environmental signals trigger organisational investment in readiness, and this readiness enhances the organisation's absorptive capacity for new technologies (Cohen & Levinthal 1990; Teece 2007). In this mechanism, the external environment provides pressure, resources, or legitimacy cues (Iacovou et al. 1995); organisations respond by strengthening readiness capabilities, and these internal capabilities, in turn, enable the effective adoption and assimilation of Industry 4.0 technology (Zhu et al. 2006).

A study by Maria et al. (2019) found that environmental factors greatly enhance businesses' readiness for Industry 4.0. Meanwhile, Rakibul and Bhuiyan (2024) investigated how Industry 4.0 readiness functions as a bridge between the adoption of Industry 4.0 technology and government support. Their findings imply that although government regulations and assistance initiatives can promote Industry 4.0 adoption, the company's internal readiness plays a major role in successful adoption. Therefore, businesses must adapt to and build on these environmental changes to effectively transition to Industry 4.0. However, the constantly evolving nature of the environment presents challenges, requiring companies to remain agile and proactive. Consequently, readiness could act as a mediator, addressing the gap between the external environment and Industry 4.0 adoption. Based on these insights, this study proposes the following hypothesis.

H₄ Industry 4.0 readiness mediates the relationship between the environment and Industry 4.0 adoption.

The concepts of adoption, Industry 4.0 readiness, and the environment are all integrated into the suggested theoretical framework. It implies that Industry 4.0 readiness is influenced by the environment, and that readiness serves as a mediator that eventually propels Industry 4.0 adoption. A graphic representation of the framework is shown in Figure 1.

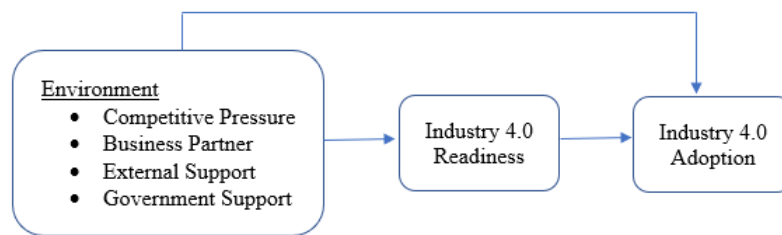


FIGURE 1. Conceptual framework

METHODOLOGY

This study employed a quantitative approach that primarily entailed collecting data through a questionnaire. The target population consisted of manufacturing SMEs in Malaysia. A purposive sampling approach was used to identify managerial personnel involved in strategic, technological, or operational decision-making. A total of 500 questionnaires were distributed via email using a Google Forms online survey link, allowing respondents to complete the questionnaire electronically. Responses from these managers serve as the unit of analysis at the organisational level. This single-informant approach is appropriate because managers possess direct knowledge of their organisation’s strategic, technological, and operational activities. However, the use of one respondent per organisation is acknowledged as a limitation, as it may introduce perceptual bias, though this method is common in SME studies where access to multiple informants is limited (Lyon et al. 2000).

PLS-SEM was selected as the data analysis method because it is suitable for prediction-oriented research, able to handle complex models with multiple constructs and mediation paths, and performs well with smaller sample sizes and non-normal data distributions (Chin 1998; Hair et al. 2019; Hair & Alamer 2022; Ringle et al. 2023). These conditions align with the exploratory nature and sample characteristics of this study. Two stages of data analysis were conducted using SmartPLS 4: the measurement model evaluation phase and the structural model analysis phase. Established reliability and validity thresholds were used to assess the measurement model. Following Hair et al. (2017, 2022), the outer loadings of ≥ 0.708 , composite reliability (CR) ≥ 0.70 , and average variance extracted (AVE) ≥ 0.50 were adopted as benchmarks for reflective constructs. These criteria ensured that all retained items demonstrated sufficient indicator reliability, internal consistency, and convergent validity.

All 24 items in the questionnaire were intended to investigate the connections among the variables in the study. The questionnaire was developed based on validated measurement items from prior studies listed in Table 1. To ensure clarity, contextual relevance, and content validity in the Malaysian SME setting, the instrument underwent pilot testing with 30 managerial respondents from manufacturing SMEs. All measurement items were adapted from established scales listed in Table 1. Minor wording adjustments were made to suit the Malaysian SME context, such as simplifying terminology and aligning examples with manufacturing settings. To ensure content validity, two academic experts in technology adoption reviewed the items for clarity, relevance, and cultural appropriateness. A cognitive pre-test was also conducted during the pilot study, where respondents were asked to explain their interpretation of selected items. Feedback was used to refine wording, improve flow, and confirm item comprehension. During the assessment process, no items were removed, as all indicators met the recommended reliability and validity thresholds. Retaining all items preserved the completeness of the original measurement constructs and ensured full comparability with prior studies. A response rate of 32.4% was obtained from the distribution of 500 questionnaires, of which 157 were completed. Only fully completed questionnaires were retained for analysis, while incomplete or unusable responses were excluded. To improve participation, follow-up procedures were conducted after the initial email invitation. A courtesy call was made one day after the email was sent to the respective companies. In cases where no response was received, a follow-up call was conducted one week later, followed by a reminder email to encourage participation. These follow-up calls and reminder emails were conducted periodically until an adequate number of responses was obtained, resulting in the final sample of 157 usable responses.

In this study, the environment variable is modelled as a second-order formative construct composed of four reflective first-order dimensions: competitive pressure, business partners, external support, and government support. This study specifies a reflective–formative hierarchical component model, where the first-order constructs (competitive pressure, business partners, external support, and government support) are reflective and the second-order construct (Environment) is formative. Following the two-stage approach, the first stage estimated the reflective first-order constructs and generated latent variable scores, which were then used as formative indicators of the second-order environment construct in the second stage.

Furthermore, the environment variable is modelled as a second-order formative construct composed of four reflective first-order dimensions: competitive pressure, business partners, external support, and government support. This specification is consistent with the conceptualisation of the environmental context within the Technology–Organisation–Environment (TOE) framework, where the environment represents a combination of distinct external forces that collectively shape organisational responses to technological change. These dimensions capture different aspects of the external environment and are not expected to be interchangeable. Instead, each dimension contributes uniquely to forming the overall environmental conditions faced by organisations. Aligned with prior methodological guidance, a formative specification is deemed appropriate when indicators represent distinct facets that jointly define a construct (Jarvis et al. 2003; Hair et al. 2022).

Moreover, this study specifies a reflective–formative hierarchical component model, where the first-order constructs (competitive pressure, business partners, external support, and government support) are reflective, and the second-order construct (Environment) is formative. Following the two-stage approach, the first stage estimated the reflective first-order constructs and generated latent variable scores, which were then used as formative indicators of the second-order environment construct in the second stage (Becker et al. 2012; Hair et al. 2022). The sources of the items used in this study are listed in Table 1.

TABLE 1. Sources of the Items used

Variable	No. of Items	References
Competitive Pressure	4	Arnold et al. (2018)
Business Partner	4	Teo et al. (2019)
External Support	3	Arnold et al. (2018)
Government Support	3	Ifinedo (2011)
Industry 4.0 Readiness	5	Puklavec et al. (2018)
Industry 4.0 Adoption	5	Ifinedo (2011) and Gangwar et al. (2015)

Basic demographic information was also collected to provide context for the sample. The results revealed that the respondents were mainly male (58.6%) and belonged to the age group of 30–39 years (53.5%). The largest subsectors represented were food and beverages (29.9%), chemicals (22.9%), and basic metals (14%). Most firms were medium-sized (63.7%) and had been established for 6–10 years (28%) or 1–5 years (24.2%).

RESULTS

Convergent and discriminant validity were evaluated to ensure the validity and reliability of the model. Cronbach's alpha was used to measure the internal consistency with a threshold of 0.7 (Sekaran & Bougie, 2016), while item reliability was evaluated with a minimum loading of 0.708 (Hair et al. 2019). Composite reliability (CR) was also taken into account with a threshold of 0.7. Furthermore, average variance extracted (AVE) values greater than 0.50 were deemed acceptable (Hair et al. 2019).

The indicator reliability of all reflective first-order constructs (competitive pressure, business partners, external support, government support, Industry 4.0 readiness, and Industry 4.0 adoption) was examined through outer loadings. Most items exceeded the recommended loading of 0.708 (Hair et al. 2017), with values ranging from 0.724 to 0.933. One item (A5 = 0.653) recorded a value slightly below the threshold, but was retained because the construct still met the AVE requirements and the indicators were important for content validity.

Internal consistency reliability was also supported, with Cronbach's alpha values ranging from 0.796 to 0.920 and composite reliability (CR) values between 0.802 and 0.921, both exceeding the recommended minimum of 0.70. Convergent validity was also established, with AVE values above 0.50 (0.620–0.829). Table 2 shows the outcome of the measurement model.

TABLE 2. Outcome of the measurement model

Construct/Item	Loading	Cronbach's alpha	CR	AVE
Competitive Pressure (CP)		0.796	0.802	0.620
CP1	0.831			
CP2	0.755			
CP3	0.763			
CP4	0.799			
Business Partner (BP)		0.920	0.921	0.807
BP1	0.898			
BP2	0.885			
BP3	0.915			
BP4	0.896			
External Support (ES)		0.897	0.897	0.829
ES1	0.902			
ES2	0.909			
ES3	0.921			
Government Support (GS)		0.858	0.858	0.780
GS1	0.854			
GS2	0.902			
GS3	0.892			

Construct/Item	Loading	Cronbach's alpha	CR	AVE
Industry 4.0 Readiness (R)		0.911	0.913	0.739
R1	0.859			
R2	0.907			
R3	0.887			
R4	0.795			
R5	0.844			
Industry 4.0 Adoption (A)		0.893	0.904	0.700
A1	0.892			
A2	0.933			
A3	0.866			
A4	0.724			
A5	0.653			

Discriminant validity describes the degree to which a construct differs from other constructs (Hair et al. 2022). The discriminant validity of all constructs in the model (competitive pressure, business partner, external support, government support, Industry 4.0 readiness, and Industry 4.0 adoption) was assessed using the Fornell–Larcker criterion and HTMT ratio. According to the Fornell–Larcker criterion, the square root of the AVE for each construct was greater than its correlations with other constructs, indicating satisfactory discriminant validity (Chin, 2010). The results for the Fornell–Larcker criterion are shown in Table 3.

TABLE 3. Discriminant validity analysis (Fornell–Larcker criterion)

	BP	CP	ES	GS	R	A
Business Partner (BP)	0.898					
Competitive Pressure (CP)	0.788	0.795				
External Support (ES)	0.730	0.661	0.911			
Government Support (GS)	0.808	0.700	0.785	0.883		
Industry 4.0 Readiness (R)	0.785	0.742	0.715	0.830	0.902	
Industry 4.0 Adoption (A)	0.710	0.685	0.660	0.760	0.845	0.918

HTMT values were examined to provide a more stringent assessment of discriminant validity (Henseler et al. 2015). The majority of construct pairs demonstrated HTMT ratios below the recommended threshold of 0.90, including CP–ES (0.775), CP–GS (0.840), BP–ES (0.803), and ES–GS (0.894). Several pairs, namely BP–CP (0.921), BP–GS (0.908), GS–R (0.915), and R–A (0.902), slightly exceeded the threshold. However, these constructs represent theoretically related dimensions within the broader environmental context and the sequential relationship between Industry 4.0 readiness and Industry 4.0 adoption, where some degree of conceptual overlap is expected. Such proximity can naturally result in marginally higher HTMT values.

Furthermore, the Fornell–Larcker criterion was fully satisfied, cross-loadings were consistent with the expected construct structure, and all VIF values were within acceptable limits, indicating no multicollinearity concerns. Taken together, these results indicate that discriminant validity remains satisfactory. The HTMT results are presented in Table 4.

TABLE 4. Discriminant Validity Analysis (Heterotrait–Monotrait (HTMT))

	BP	CP	ES	GS	R	A
Business Partner (BP)						
Competitive Pressure (CP)	0.921					
External Support (ES)	0.803	0.775				
Government Support (GS)	0.908	0.840	0.894			
Industry 4.0 Readiness (R)	0.885	0.820	0.810	0.915	0.885	
Industry 4.0 Adoption (A)	0.810	0.780	0.750	0.840	0.902	

To address potential common method bias (CMB), procedural remedies such as ensuring respondent anonymity and separating construct sections were implemented. Statistically, full collinearity VIF values were all below the threshold of 5.0 (highest = 4.1), indicating that CMB is unlikely to be a concern (Kock 2015). Although Harman’s single-factor test indicated that the first factor accounted for 60.55% of the total variance, this method has been widely criticised for its limited sensitivity (Podsakoff et al. 2012). Taken together with the acceptable VIF and HTMT results, the findings suggest that common method bias does not significantly affect the study.

Discriminant validity was assessed comprehensively for all constructs in the measurement model, including competitive pressure, business partner, external support, government support, Industry 4.0 readiness, and Industry 4.0 adoption. HTMT values were complemented with 95% bootstrapped confidence intervals derived using a nonparametric resampling procedure (500 samples). Due to the higher-order construct specification, HTMT inference was primarily assessed for the first-order constructs representing the environmental dimensions. The results showed that none of the confidence intervals included the value of 1.00, indicating that the constructs are empirically distinct (Henseler et al. 2015). Although the BP–CP pair exhibited the highest HTMT value (0.921), its confidence interval (0.858 to 0.986) remained below unity. When taken together with the satisfactory Fornell–Larcker results, cross-loadings, and collinearity diagnostics, these findings indicate that discriminant validity is considered acceptable. Table 5 summarises the HTMT confidence interval results.

TABLE 5. HTMT 95% bootstrapped confidence intervals

Construct Pair	HTMT	95% CI Lower	95% CI Upper
CP – BP	0.921	0.858	0.986

CP – ES	0.775	0.676	0.863
CP – GS	0.840	0.758	0.914
BP – ES	0.803	0.711	0.884
BP – GS	0.908	0.843	0.959
ES – GS	0.894	0.836	0.951

Model fit was further assessed using the Standardised Root Mean Square Residual (SRMR), which is an approximate fit measure for PLS-SEM (Henseler et al. 2014). The SRMR value for both the saturated and estimated models was 0.083, which fell below the commonly accepted threshold of 0.10 for acceptable fit and the more conservative 0.08 threshold in some guidelines. These results indicate that the model demonstrates an adequate overall fit. The confirmation of reliability, validity, CMB checks, model fit, and predictive accuracy was followed by an evaluation of the structural model.

Meanwhile, predictive validity was assessed using PLSpredict with 10-fold cross-validation and one repetition. The Q^2_{predict} values were above zero for all endogenous constructs (Industry 4.0 Adoption = 0.700; Industry 4.0 Readiness = 0.651; Environment = 0.994), indicating meaningful predictive relevance (Shmueli et al. 2019). A comparison between PLS-SEM prediction errors with the linear model (LM) benchmark showed that PLS-SEM produced lower RMSE and MAE values for the majority of the manifest variables related to Adoption (e.g., A1–A5) and Readiness (R1–R5), demonstrating superior out-of-sample predictive performance. For example, A1 exhibited lower RMSE (0.698 vs. 0.723) and MAE (0.515 vs. 0.530) under PLS-SEM compared to the LM benchmark. Similar patterns were observed for CP, BP, ES, and GS items, confirming medium to high predictive power. Because most indicators showed PLS errors lower than or comparable to LM errors and Q^2_{predict} values were all well above zero, the model was deemed to demonstrate strong predictive performance, thus satisfying the criteria recommended by Shmueli et al. (2019) and Hair et al. (2022). A summary of the predictive performance is presented in Table 6.

TABLE 6. PLSpredict results for construct-level predictive performance

Construct	Q^2_{predict}	PLS RMSE	LM RMSE	Predictive Power
Industry 4.0 Adoption	0.700	0.555	Higher	High
Industry 4.0 Readiness	0.651	0.598	Higher	Medium–High
Environment	0.994	0.080	Higher	Very High

The Environment construct was modelled as a second-order formative construct comprising four reflective first-order dimensions: competitive pressure, business partner support, external support, and government support. A two-stage approach was applied in SmartPLS 4. In Stage 1, all first-order reflective constructs were assessed and latent variable scores were generated. In Stage 2, these latent scores served as formative indicators to estimate the higher-order Environment construct.

Multicollinearity was assessed using outer VIF values, which ranged from approximately 1.5 to 4.1. These values were well below the commonly accepted threshold of 5, indicating that collinearity among the formative indicators was not problematic. Bootstrapping results further showed that three dimensions made significant contributions to the Environment construct: Business Partner \rightarrow Environment ($\beta = 0.292$, $p < 0.001$), Competitive Pressure \rightarrow Environment ($\beta = 0.235$, $p = 0.019$), and External Support \rightarrow Environment ($\beta = 0.549$, $p < 0.001$). Although government support exhibited a nonsignificant weight ($\beta = 0.024$, $p = 0.787$), it was retained due to its strong theoretical relevance in Industry 4.0 adoption research. Overall, these assessments confirm that the formative higher-order specification of the Environment construct is valid.

Bootstrapping with 5,000 subsamples was used to evaluate the hypothesised structural relationships. The results showed a strong positive effect of the Environment construct on Industry 4.0 adoption ($\beta = 0.566$, $t = 6.043$, $p < 0.001$), supporting H₁. The Environment construct also demonstrated a substantial positive influence on Industry 4.0 readiness ($\beta = 0.829$, $t = 24.241$, $p < 0.001$), supporting H₂. Similarly, Industry 4.0 readiness significantly predicted Industry 4.0 adoption ($\beta = 0.356$, $t = 3.907$, $p < 0.001$), supporting H₃. Figure 2 presents the standardised path coefficients and R² values.

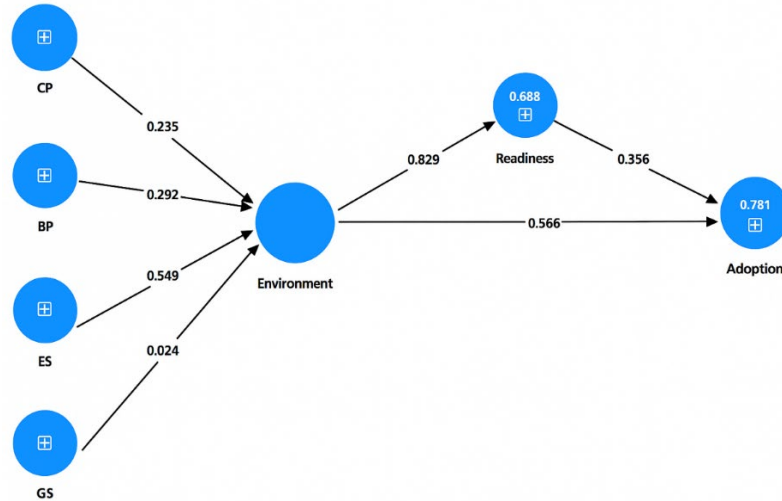


FIGURE 2. Structural model with standardised path coefficients and R² values

The R² value for Industry 4.0 adoption was 0.781, indicating that 78.1% of its variance was explained by the model. Industry 4.0 readiness recorded an R² value of 0.688, demonstrating strong explanatory power. Both values exceeded the threshold of 0.19 suggested by Chin (1998), indicating robust model performance. The effect size analysis further reinforced these findings. Environment demonstrated a large effect on Industry 4.0 adoption ($f^2 = 0.456$) and a very large effect on Industry 4.0 readiness ($f^2 = 2.203$). Industry 4.0 readiness showed a medium effect on Industry 4.0 adoption ($f^2 = 0.181$), indicating a meaningful but comparatively smaller contribution. The hypothesis testing results are displayed in Table 7.

TABLE 7. Results of hypothesis testing

Hypothesis	Path	Std. β	t-value	R ²	f^2	p-value	Decision
H ₁	Environment → Industry 4.0 Adoption	0.566	6.043	0.781	0.456	0.000	Supported
H ₂	Environment → Industry 4.0 Readiness	0.829	24.241	0.688	2.203	0.000	Supported
H ₃	Industry 4.0 Readiness → Industry 4.0 Adoption	0.356	3.907	—	0.181	0.000	Supported

To evaluate the mediating role of Industry 4.0 readiness, the indirect effect of Environment → Industry 4.0 Readiness → Industry 4.0 Adoption was examined using a bootstrapping procedure with 5,000 subsamples following the approach recommended by Hair et al. (2022). The indirect effect was significant ($\beta = 0.296$, $t = 4.093$, $p < 0.001$). Bootstrapped 95% bias-corrected confidence intervals further confirmed its significance, as the interval did not include zero (95% CI = 0.133 to 0.453). Because the direct and indirect effects of Environment on Industry 4.0 Adoption ($\beta = 0.566$, $p < 0.001$) were positive, the results indicate complementary partial mediation (Hair et al. 2022). The Variance Accounted For (VAF) was calculated as:

$$VAF = \frac{0.296}{0.566 + 0.296} = 0.343$$

This showed that 34.3% of the total effect of the Environment on Industry 4.0 adoption is transmitted through Readiness, supporting partial mediation. Table 8 summarises the mediation results.

TABLE 8. Results of mediation effect

Hypothesis	Relationship	Std. β	Std. Dev	t-value	p-value	LL (95% CI)	UL (95% CI)	Decision
H ₄	Environment → Industry 4.0 Readiness → Industry 4.0 Adoption	0.296	0.072	4.093	0.000	0.133	0.453	Supported

DISCUSSION

This study investigated the interplay of environmental factors, Industry 4.0 readiness, and Industry 4.0 adoption in the context of manufacturing SMEs in Malaysia. The environmental construct is modelled as a second-order construct comprising competitive pressure, business partners, external support, and government support. Therefore, the results reflect the combined effect of these environmental dimensions and do not allow the identification of the individual contribution of each specific factor. Four hypotheses were tested: the direct influence of the environmental construct on Industry 4.0 adoption; the relationship between the environment and Industry 4.0 readiness; the influence of readiness on Industry 4.0

adoption; and the mediating role of Industry 4.0 readiness towards the relationship between the environmental construct and Industry 4.0 adoption.

In the Malaysian SME context, the strong influence of environmental factors on both Industry 4.0 readiness and Industry 4.0 adoption can be understood through several local characteristics. Malaysian manufacturing SMEs are highly embedded in supplier–buyer networks, and collaboration norms encourage organisations to respond quickly to expectations from dominant customers and business partners. Government initiatives such as Industry4WRD, automation grants, and tax incentives also create a policy environment that signals the urgency of digital transformation, heightening both perceived pressure and support. Competitive pressure is especially salient in Malaysia’s export-oriented sectors, where SMEs must meet the digital and automation requirements of multinational buyers to remain competitive. These contextual features help explain why environmental forces exert both a strong direct effect and an indirect effect through Industry 4.0 readiness: organisations respond to external expectations by upgrading their capabilities, which then enable Industry 4.0 adoption.

To align the discussion with the corrected structural estimates, it is important to interpret the relationships according to their observed magnitudes. The environment exerted a very large effect on readiness ($f^2 = 2.203$), but a smaller yet still substantial direct effect on Industry 4.0 adoption ($f^2 = 0.456$). This pattern suggests that, in Malaysian SMEs, environmental pressure primarily triggers capability building activities that enhance readiness, which then partly translates into Industry 4.0 adoption. Readiness itself showed a medium effect on Industry 4.0 adoption ($f^2 = 0.181$), indicating that while internal readiness is important, external influences continue to play a central role in shaping Industry 4.0 adoption decisions.

These dual pathways can be explained by Malaysia’s supplier-driven industrial structure, where multinational buyers impose digital requirements that prompt SMEs to develop skills, training, and process improvements that constitute readiness. In line with the TOE framework and capability-based perspectives, environmental conditions act as external drivers that stimulate organisational capability development, which in turn facilitates the adoption of Industry 4.0 technology (Zhu et al. 2006; Teece 2007). This supports the significant relationship between the environment and Industry 4.0 readiness, as well as the positive effect of Industry 4.0 readiness on Industry 4.0 adoption. The mediating role of Industry 4.0 readiness further indicates that environmental pressures are translated into Industry 4.0 adoption outcomes through internal capability development, which is consistent with prior studies on technology adoption and organisational readiness (Puklavec et al. 2018; Stentoft et al. 2020).

As the environmental construct is modelled as a higher-order construct, the discussion focuses on its overall effect rather than the individual contribution of specific dimensions. Nevertheless, the findings remain consistent with prior research highlighting the importance of environmental influences in technology adoption. Studies on RFID (Paydar et al. 2014), blockchain (Wong et al. 2019), cloud computing (Low & Chen 2011), supply chain systems (Lin 2013), and artificial intelligence (Chen et al. 2021) similarly report strong environmental effects. Evidence from Malaysian SMEs further supports the role of environmental pressures in shaping Industry 4.0 adoption decisions (Amini & Javid 2023).

Additionally, this study found that Industry 4.0 readiness mediates the relationship between environmental factors and Industry 4.0 adoption. Environmental elements such as business partners, external support, government support, and competitive pressure influence an organisation’s readiness to adopt Industry 4.0 technology. This suggests that organisations with adequate digital infrastructure, skilled workers, and supportive internal processes are better positioned to implement Industry 4.0 technology. It aligns with broader literature noting that countries and organisations with stronger technological capacity achieve smoother transitions into Industry 4.0 (Castelo-Branco et al. 2019). Recent studies further indicate that organisational mechanisms, such as top management support, can also mediate the relationship between environmental pressures and the adoption of Industry 4.0 technology (Zhou & Zheng 2023), suggesting that internal readiness factors play an important bridging role. In another study, Ng et al. (2021) showed that Industry 4.0 adoption helps reduce information asymmetry by improving transparency and data quality, which strengthens management’s intention to address such issues. This supports the view that readiness to change plays a crucial role in overcoming challenges and enabling successful adoption.

In summary, this study provides insights for Malaysian manufacturing SMEs aiming to implement Industry 4.0 by highlighting the important roles played by internal readiness and environmental drivers. To maximise the likelihood of successful Industry 4.0 implementation, SMEs should not only enhance their internal readiness but also leverage favourable external conditions and respond strategically to environmental pressures.

IMPLICATIONS

The findings provide several actionable implications for manufacturing SMEs seeking to advance their Industry 4.0 transformation. Given that environmental forces, particularly business partners, external support, government support, and competitive pressure, exert both strong direct and indirect effects on Industry 4.0 adoption, SMEs must strategically align their capability-building efforts with the external pressures they encounter.

First, SMEs should conduct structured Industry 4.0 readiness audits based on the dimensions applied in this study. Such audits enable organisations to identify capability gaps systematically and create targeted digital transformation roadmaps. Readiness assessments are consistent with recommendations in the Industry4WRD Readiness Assessment framework, which emphasises benchmarking existing capabilities before adopting advanced technologies (MITI 2018). Recent evidence suggests that while many Malaysian SMEs have the strategic vision, a critical gap remains in workforce competency, which

remains the lowest-scoring dimension in national assessments (Techanamurthy et al. 2025). Furthermore, readiness is now tied to the New Industrial Master Plan 2023 (NIMP 2030), which mandates digital infrastructure as a prerequisite for global supply chain participation.

Second, SMEs should pursue targeted capability investments that correspond to the intensity of the environmental pressures they face. Under highly competitive pressure, investments in automation, real-time visibility systems, and process integration may be necessary to maintain supply chain relevance. When external support or partner expectations are dominant drivers, SMEs should prioritise foundational digital skills, cybersecurity readiness, and interoperability solutions. This aligns with prior findings that capability development is essential for SMEs to convert environmental pressures into strategic technological adoption (Castelo-Branco et al. 2019; Wong et al. 2019). Recent research shows that pressure from institutions and stakeholders, especially for sustainability reporting and tracking emissions, stands as the main reason prompting companies to adopt IoT and Big Data Analytics in supply chains (Pervez et al. 2026).

Third, SMEs can significantly reduce Industry 4.0 adoption risks by engaging in partner-led enablement. Large buyers, MNCs, and upstream partners increasingly provide shared platforms, digital templates, and technical guidance. Such collaborative arrangements help SMEs overcome financial and knowledge constraints, which is consistent with previous research emphasising the role of network-based support in reducing technological uncertainty (Lin 2013; Chen et al. 2021). Fourth, although government support displayed a nonsignificant formative weight in the model, SMEs may still benefit from available incentives if approached strategically. Organisations should utilise grants, automation programs, and advisory services conditional upon readiness milestones, such as achieving basic digitalisation or workforce upskilling.

Moreover, the results also yield important insights for policymakers designing interventions under Malaysia's Industry4WRD national agenda. The relatively weak empirical contribution of government support suggests gaps in program awareness, accessibility, or alignment with SME needs. Policies should therefore prioritise simplified procedures, targeted outreach, and sector-specific communication, particularly for micro and small manufacturers. Given the significant mediating role of readiness, policymakers should design tiered incentives aligned with organisations' capability levels. For instance, foundational programs (e.g., digital skills training, basic automation) could precede advanced Industry 4.0 adoption grants. Conditional incentives tied to readiness scores can encourage progressive transformation and avoid premature or ineffective technology investments.

This study also contributes to Industry 4.0 and digital transformation research in several important ways. First, it empirically validates a mediated TOE framework by demonstrating that readiness serves as a complementary mediator between environmental factors and Industry 4.0 adoption in an emerging economy SME setting. This extends prior work by clarifying how external pressures translate into internal capability development, consistent with TOE-based theorisation (Baker 2012; Oliveira & Martins 2011) and more recent SME digital adoption studies (Sangosanya et al. 2025). Second, the study offers a methodological contribution by modelling the environment as a formative higher-order construct. The assessment of indicator weights, significance, and VIF values demonstrates when such aggregation is defensible and provides an example of rigorous validation using PLS-SEM, an approach encouraged in recent methodological literature (Hair et al. 2022). Third, the study adds contextual insight into emerging economies by showing that in Malaysia, partner ecosystems and competitive forces play stronger roles in shaping Industry 4.0 readiness and Industry 4.0 adoption than government support. These findings highlight the importance of supply chain-driven transformation and provide boundary conditions for the generalisability of Industry 4.0 frameworks in resource-constrained organisations.

Overall, these implications highlight the need for Malaysian manufacturing SMEs to pursue capability development that aligns with their environmental conditions, while policymakers must refine support structures to better match firms' readiness levels. Together, these insights offer a practical and theoretically grounded pathway for advancing Industry 4.0 adoption in the sector.

CONCLUSION

This study examined the relationships between environmental factors, Malaysian manufacturing SMEs' readiness for Industry 4.0, and their adoption of Industry 4.0. It suggests a theoretical framework that scholars can further investigate and refine. Both the direct and indirect effects of environmental factors on Industry 4.0 adoption, which are mediated by Industry 4.0 readiness, are empirically supported by the study. In a practical sense, the study seeks to educate SMEs on the importance of environmental considerations and Industry 4.0 adoption and readiness. It allows SMEs to more effectively manage challenges associated with Industry 4.0 adoption, ensuring that they are ready to successfully implement Industry 4.0 and obtain a competitive edge by concentrating on these external factors when planning for Industry 4.0 integration.

However, this study has some limitations. It excluded sectors like agriculture and services, which could be greatly impacted by Industry 4.0, and instead concentrated on Malaysian manufacturing SMEs. Additionally, the quantitative data collection approach used in this study has potential drawbacks, such as limited sample size, omitted variable bias, and environmental factors affecting respondent participation. Future research may consider qualitative methods or mixed-methods approaches to address these limitations. Moreover, although mediation was examined in this study, the use of cross-sectional data limits the ability to draw causal conclusions. As temporal ordering cannot be established, the findings should be interpreted as statistical mediation rather than temporal mediation. Cross-sectional mediation is common in PLS-SEM research (Hair et al. 2021), but causal inferences require longitudinal or experimental designs. Therefore, future studies

should employ time-separated data collection to validate the temporal sequence among the environment, Industry 4.0 readiness, and Industry 4.0 adoption. Future studies could also incorporate additional factors and variables to expand the scope of the framework.

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