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Enhancing Competitiveness: Driving and Facilitating Factors for Industry 4.0 Adoption in Thai Manufacturing

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Abstract: Adopting Industry 4.0 (I4.0) is inevitable for Thailand's manufacturing sector to remain competitive because global markets increasingly demand higher quality, faster delivery, and greater customization. While firms need to enhance productivity and optimize resource utilization, they also need to reduce operation costs, which require advanced technologies and data-driven operations. However, successful adoption requires skilled human resources, which is challenging for small and medium-sized enterprises (SMEs). This research explores factors driving and facilitating the implementation of Industry 4.0 (I4.0) in Thai manufacturing firms among SMEs and large firms. We employed qualitative analysis using semi-structured interviews with SMEs and large manufacturing firms in Thailand. Five key factors emerged as crucial for I4.0 adoption: awareness of I4.0, strong and proactive support from top management, self-funding capabilities, and effective human resource development strategies. While large multinational enterprises (MNEs) possess more significant resources and capabilities to adopt I4.0 technologies, SMEs face considerable challenges. They require a strategic approach tailored to their unique needs and resources to develop a feasible I4.0 roadmap. Additionally, governments and industry associations can play a significant role by providing training, funding, and other resources to empower SMEs to embrace I4.0.

Keywords: digital transformation; human resource development strategy; top management support; Industry 4.0; capability building

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1. Introduction

The shift to Industry 4.0 (I4.0) has been a catalyst for significant transformation in the manufacturing sector, driven by technologies like the Internet of Things (IoT), Artificial Intelligence (AI), and big data analytics. This change is crucial for maintaining global competitiveness, especially for countries like Thailand. Traditional production methods, which rely heavily on manual processes and basic automation, have not met the increasing demand for efficiency, customization, and quality. Therefore, researching the factors that drive and support I4.0 adoption in Thai manufacturing firms is essential to help them make this transition effective.

Thai manufacturing firms are actively pursuing I4.0 adoption to maintain their global competitiveness. However, the successful adoption of I4.0 entails a complex endeavor with several factors, especially for small and medium-sized enterprises (SMEs). The extent and manner of I4.0 adoption in developing countries, such as Thailand, remain underexplored. While previous studies have investigated the concept of I4.0 and its potential benefits, a gap exists in the literature between the conceptual approach to I4.0 and the reality of its adoption regarding the specific local context of the Thai manufacturing sector, which is robust to the unique challenges faced by Thai firms (Jeenanunta et al. 2017; Jermsittiparsert et al. 2020). The specific research goal is to identify key factors driving and facilitating I4.0

adoption in Thai manufacturing firms through an in-depth qualitative case study approach, providing actionable insights for industry stakeholders and policymakers.

Recent studies have explored various aspects of I4.0 adoption in different regions. For example, research on Malaysian SMEs found that leadership and organizational flexibility are critical to I4.0 adoption, but many firms lack strategic flexibility (Hossain et al. 2023). In Italian Micro, Small, and Medium Enterprises (MSMEs), adopting I4.0 technologies increased labor productivity by 7%, yet there were challenges related to cost efficiency and knowledge creation (Bettiol et al. 2023). In Bangladesh, the main barrier was a lack of technical knowledge about I4.0, which slowed its adoption (Hossain et al. 2023). Miah et al. (2024) proposed the Skills and Employability Framework for I4.0, focusing on the South Asian region. They mentioned that training and development, financial constraints, and regulatory issues are significant challenges to I4.0 technology adoption.

While our analysis references global trends in I4.0, to establish a comparative framework, it is crucial to understand how these global patterns can be adapted to the Thai context. Studies from other countries offer valuable insights into the challenges and best practices of implementing I4.0, which is crucial for tailoring strategies specific to Thailand. Recent studies have highlighted significant strides in adopting Industry 4.0, within Thailand. Jeenanunta et al. (2017) also highlighted the challenges in human resource development for technological upgrades in Thailand, pointing out the significant gaps in skills and innovation capabilities. Sureeyatanapas et al. (2023) found that despite the potential benefits, Thai sugar producers are still at a low readiness level to adopt I4.0 technologies due to high investment costs. Small businesses struggle to find qualified employees, collaborate with reliable technological partners, and adapt to new working methods. Rauch et al. (2021) emphasized that Thailand needs to build a robust foundation for I4.0 implementation.

Previous studies on drivers and obstacles of I4.0 adoption have been conducted in developed countries, especially Western countries (Castelo-Branco et al. 2019). Such studies in Asian developing countries, especially, are still limited (Bellantuono et al. 2021). Furthermore, many studies have shown contradictory and different conclusions about the driving factors and challenges of I4.0 adoption (Bellantuono et al. 2021; Delera et al. 2022; Himang et al. 2020; Khin and Kee 2022). Miah et al. (2024) also identify six challenges, such as training and development, financial constraints, and regulatory issues, that must be addressed to grab maximum potential. Stentoft et al. (2021) conducted a mixed-method analysis to examine the drivers and barriers to I4.0 readiness and practice among Danish small and medium-sized manufacturers. Based on the qualitative results of four firms, the most perceived drivers were cost reduction, legal requirement (only for low technology intensity firms), customer requirements, and conscious strategy on I4.0 (for medium-high and high technology intensity firms). The most acknowledged obstacles were a lack of management's understanding of the strategic importance of I4.0 (only for low and medium-low technology intensity firms), lack of employee knowledge about I4.0 (except for a high-intensity firm), and lack of employee readiness (only for a high-intensity firm). However, the quantitative findings (190 firms) contradicted the results of other studies (Vuksanović Herceg et al. 2020) stating that barriers (e.g., lack of knowledge, lack of employee readiness) did not significantly influence the I4.0 technology adoption.

Despite these insights, there is still a significant gap in the understanding of the specific challenges and support needed for Thai manufacturers. While there are distinct differences between SMEs and large firms in their approach to I4.0, there are also notable similarities. Large firms typically possess more robust financial resources, established technological infrastructure, and access to skilled labor, which facilitate the adoption of advanced technologies. In contrast, SMEs often struggle with financial constraints and a lack of technological expertise. However, SMEs and large firms share common objectives, such as cost reduction, improving operational efficiency, increasing competitiveness, and adapting to market changes. Both face challenges related to integrating new technologies with existing systems and the necessity for ongoing employee training. Understanding

these similarities and differences is crucial for developing tailored strategies to support the implementation of I4.0 across different types of firms. This study aims to fill this gap by focusing on the unique socioeconomic conditions of Thai manufacturing firms, especially SMEs, which face different challenges compared to larger enterprises. Our study seeks to bridge this gap by analyzing the factors driving and supporting I4.0 adoption in Thai manufacturing firms. Unlike other studies that offer broad regional analyses, our research focuses on the Thai context. We conducted semi-structured interviews with crucial SMEs and large-firm stakeholders to gather detailed insights. By identifying critical factors such as top management support, financial challenges, and human resource capabilities, our research offers practical recommendations for policymakers and industry leaders to better support the I4.0 transition.

This research adds valuable insights to both the academic literature and practical applications. Academically, it enriches our understanding of I4.0 adoption by providing evidence from the small-, medium-, and large-sized Thai manufacturing sector, offering a localized perspective. The findings highlight the different and similar driving and facilitating factors for I4.0 adoption across different firm sizes and types. Our findings provide an initial exploration into the driving and facilitating factors for I4.0 adoption in Thailand, which can serve as a foundation for broader, more comprehensive studies. We aim to contribute to the ongoing discussion and provide preliminary insights rather than definitive conclusions regarding the Thai manufacturing sector. Additionally, this study contributes empirical data on Thai firms' specific challenges and opportunities, enriching the literature on industrial modernization in developing economies.

Practically, our findings can serve as a guide for policymakers, industry associations, and manufacturing firms. The insights can help develop strategies and policies that address the specific needs of Thai manufacturing firms, particularly SMEs, improving their readiness and capability to adopt I4.0 technologies. It recommends targeted policy interventions, such as increasing financial support for SMEs, developing comprehensive skill enhancement programs, and improving technological infrastructure. These recommendations are based on empirical findings and aim to address the unique challenges identified in the study.

To understand the Thailand approach to I4.0, Section 3 conducts a systematic literature review to identify the driving and facilitating factors of I4.0 implementation in varied contexts. Section 4 describes the methodology used to understand the driving and facilitating factors in the Thai manufacturing context. Section 5 presents the results. Section 6 concludes this study.

2. The Adoption of I4.0 in Thailand in the Context of Neighboring Countries

In this section, we explore the adoption of Industry 4.0 in Thailand, contextualized within the experiences of neighboring Asian countries. This comparative analysis highlights Thai manufacturers' unique challenges and opportunities and the broader regional trends influencing Industry 4.0 adoption. By examining the strategies and outcomes in Malaysia, Vietnam, and Indonesia, we aim to comprehensively understand the regional dynamics and how they impact Thailand's I4.0 adoption efforts.

The Thai government has launched many projects in cooperation with the Japanese government, such as the Automotive Human Resource Development Project (AHRDP) in 2006–2011, to support and cultivate knowledge and the technological development of manufacturing firms, especially among SMEs, to improve their productive activities. The Thai government has also accelerated industrial upgrading and structural change by promoting digital transformation of existing manufacturing and automation-related businesses since it announced new policies such as Thailand 4.0 in 2016 (Wongwuttiwat and Lawanna 2018) and the development of new S-curve industries in the Eastern Economic Corridor (EEC) in 2016 (Kohpaiboon 2020). The Lean Automation System Integrator (LASI) training program launched in 2018 is one of the international cooperation programs for capacity building among the Thai and Japanese governments and private and educational

sectors to promote the understanding and adoption of I4.0. However, many firms struggle to develop sustained digital transformation and I4.0 implementation. In 2015, the Office of Industrial Economics reported that about 25% of the firms' production process is entirely manual, 35% is a combination of computer numerically controlled (CNC) and manual, 25% is a combination of CNC and automated handling system, 10% is CNC and robot, and only 5% of the firms were fully automated (OIE 2015). The Federation of Thai Industries (FTI) developed the self-assessment 4.0 model to assess a manufacturing firm's readiness for I4.0. Of 1335 firms, only 2% reached I4.0, 28% are in I3.0, 61% are in I2.0, and 9% are in I1.0 (FTI 2021). Comparatively, other Southeast Asian countries have progressed in adopting I4.0 technologies at varying paces (Miah et al. 2024). The adoption of key Industry 4.0 technologies is still in its early stages in Vietnam. About 6.9% of firms use cloud computing for business tasks, 1.5% use Big Data or AI for marketing purposes, only 6.1% of firms use advanced methods for manufacturing, 5.9% use robots, and 1.8% of manufacturing firms use additive manufacturing technologies (Cirera et al. 2021). There are still hesitant applications for these new technologies, as represented by their low readiness levels (Le et al. 2023). The Vietnamese government's support and the increasing presence of multinational companies have been crucial drivers of this adoption. In Malaysia, production efficiency and cost reduction were the strongest drivers for I4.0 adoption in the electrical and electronics industry. However, the most significant obstacles were the talent shortage and skilled workforce, limited financial support, and a lack of substantial business evidence to support such investment (Wong and Kee 2022; Yeap et al. 2024). De Marchi et al. (2022) discussed the network architecture of Education and Training for Automation 4.0 (ETAT) centers, which aims to develop a skilled workforce equipped for Automation 4.0. These studies underscore the importance of tailored educational frameworks for fostering industry readiness and competitiveness. The diversified situation of I4.0 adoption among Thai firms and the gap among countries suggests unexplored untapped country, sector, and firm-specific driving and hindering factors of I4.0 adoption. Therefore, more studies should be conducted to determine the antecedent factors of I4.0 implementation in different contexts and industry characteristics (Khin and Kee 2022; Stentoft et al. 2021).

3. Literature Review

A literature review was conducted using a comprehensive search of peer-reviewed scholarly articles written in English from several databases. The databases used were Web of Science, Emerald, IEEE, Taylor & Francis, Science Direct, and the Thai Journal Citation Index (TCI). The leading search phrases were digital transformation, I4.0, I4.0 implementation, I4.0 technology, factors affecting I4.0 implementation, human resource development toward I4.0, organizational strategy for I4.0, case study, and qualitative. Articles were selected based on their relevance to the study's objectives. The process for identifying driving and facilitating factors involved analyzing the findings and discussions of the selected articles. Key themes and factors were extracted and categorized to ensure comprehensive coverage of the literature and reliability of the results. As a result, we identified three driving factors and six facilitating factors as shown in Table 1.

Table 1. Driving and facilitating factors for Industry 4.0.

Themes	Sub-Themes	Source(s)
Driving factors	I4.0 Awareness	Awodele et al. (2024); Ersoz et al. (2018); Sarı et al. (2020)
	Expected benefits and opportunities	Horváth and Szabó (2019); Khin and Kee (2022); Kiel et al. (2017); Müller et al. (2018); Stentoft et al. (2021)
	Customer pressure	Khin and Kee (2022); Vuksanović Herceg et al. (2020)

Table 1. *Cont.*

Themes	Sub-Themes	Source(s)
Facilitating factors	Top management support	Khin and Kee (2022); Vuksanović Herceg et al. (2020)
	Financial support	Awodele et al. (2024); Khin and Kee (2022); Vuksanović Herceg et al. (2020)
	I4.0 communication channel	EDB (2020)
	Inter-company collaboration	Khin and Kee (2022); Vuksanović Herceg et al. (2020)
	Stakeholders support	
	Digital skill development	Khin and Kee (2022); Moktadir et al. (2018); Vuksanović Herceg et al. (2020)

3.1. Driving Factors

The three driving factors include I4.0 awareness (Awodele et al. 2024; Ersoz et al. 2018; Sarı et al. 2020), expected benefits and opportunities (Khin and Kee 2022), and customer pressure (Khin and Kee 2022; Vuksanović Herceg et al. 2020).

3.1.1. I4.0 Awareness

Understanding I4.0 is the first step before firms implement or adopt it (Awodele et al. 2024). Awareness of the potential advantages of I4.0 opens opportunities for firms to embrace and invest in I4.0 technologies (Sarı et al. 2020). Understanding the benefits motivates companies to explore I4.0 solutions and consider their potential impact on their operations. In the Czech Republic and Kazakhstan, many firms had not implemented I4.0 because they had a low awareness (Basl 2017; Dikhanbayeva et al. 2021; Horváth and Szabó 2019; Stentoft et al. 2021). Many firms have only adopted and used technologies with a clear and demonstrably high-value proposition for their specific needs and existing processes (Awodele et al. 2024; Sarı et al. 2020). In South India, firms with less information on the I4.0 concept and its components had inadequate future actions and expectations (Safar et al. 2020). In contrast, firms with a high awareness of the benefits of I4.0 technologies and competitive advantages had already moved toward I4.0 with concrete strategic plans and actions (Ersoz et al. 2018; Sarı et al. 2020). However, some studies argued that even though the firms were aware of the potential advantages of I4.0, only a few used these concepts in particular activities, such as monitoring industrial processes (Mittal et al. 2018; Moeuf et al. 2018).

3.1.2. Expected Benefits and Opportunities

I4.0 involves significant investments in technology, infrastructure, and workforce training (Horváth and Szabó 2019; Khin and Kee 2022). Moreover, it also changes how businesses operate. If firms clearly understand and perceive the potential benefits opportunities, such as increased productivity, cost reduction, or improved product quality, they might consider moving toward I4.0 (Horváth and Szabó 2019; Khin and Kee 2022; Müller et al. 2018; Vuksanović Herceg et al. 2020). Khin and Kee (2022) proposed a list of benefits firms expect from I4.0 implementation, such as production and cost efficiency, traceability, flexibility, productivity, and better quality. They also showed a list of opportunities, such as customers' confidence in quality, more export markets, more high-end customers, and more significant market share.

3.1.3. Customer Pressure

Customer pressure forces firms to continuously improve their efficiency and performance. I4.0 technologies allow firms to adapt to changes faster and be more responsive to customers' demands quickly. Customers expect a wider variety of products, faster customization, and shorter delivery times. Firms that embrace I4.0 can gain a competitive edge by offering more innovative and efficient products and services. Vuksanović Herceg et al. (2020) found that customers' requirements dominated the decision to adopt I4.0 compared with employees' requirements. Firms prioritize customer satisfaction over the company's

profitability (Vuksanović Herceg et al. 2020). Furthermore, firms with I4.0 technologies can be perceived as leaders in adopting I4.0 and perceived as an image of innovation and forward-thinking, which can attract more customers.

3.2. Facilitating Factors

The six facilitating factors consist of top management support (Khin and Kee 2022; Vuksanović Herceg et al. 2020), financial support (Awodele et al. 2024), expected benefits and opportunities (Awodele et al. 2024; Khin and Kee 2022; Vuksanović Herceg et al. 2020), I4.0 communication channel, inter-company collaboration, stakeholder support (Khin and Kee 2022; Vuksanović Herceg et al. 2020), and digital skill development (Khin and Kee 2022; Moktadir et al. 2018; Vuksanović Herceg et al. 2020).

3.2.1. Top Management Support

Several studies have highlighted the importance of top management support in driving I4.0 implementation (Miah et al. 2024; Srivastava et al. 2022). The top management's perception of opportunities and challenges obtained from I4.0 drives I4.0 implementation (Müller et al. 2018). Realizing that I4.0 can maintain and expand its opportunities to be more competitive in the market, increasing operational efficiencies, and improving quality are crucial motivators for its adoption. Management's understanding and assessment of these benefits are essential for overcoming the inherent challenges and uncertainties associated with I4.0. Moreover, studies indicate that acknowledging challenges like organizational and production fit, competitiveness, and future viability are pivotal in shaping the decision-making process for I4.0 implementation (Fettermann et al. 2018; Moktadir et al. 2018; Müller et al. 2018; Veile et al. 2020). Therefore, top management's dual recognition of opportunities and challenges drives the strategic direction and ensures a balanced and informed approach to I4.0 adoption. Market uncertainty of business significantly drove I4.0 adoption in the short, medium, and long term (Prause 2019). Top management support is required to achieve a long-term strategy for I4.0 implementation, especially (Prause 2019).

Top management also plays a crucial role in handling the resistance from employee and middle management levels, which significantly hinders the adoption of I4.0 technology (Bellantuono et al. 2021). Dynamic leadership is also required to convince resistant individuals of the benefits of embracing a change toward I4.0 and build an innovative mindset among employees and an organizational culture (Parhi et al. 2022).

Such influences of top management leadership should be strengthened by concrete gains from digital transformation to make I4.0 strategies successful. Top management can support and facilitate a team to develop a successful pilot I4.0 project, showing employees the benefits of utilizing digital technologies and demonstrating how technologies will help them improve their work performance, not replace them. If the benefits of adopting I4.0 are not clear, it will create more barriers to I4.0 initiation (Horváth and Szabó 2019).

3.2.2. Financial Support

Financial support is also essential for developing and improving I4.0 systems. Financial resources are indispensable to secure I4.0 technologies, hardware, software, and other resources. However, firms can start an I4.0 pilot project using the existing resources available within the firms and avoid new investments as much as possible. Firms must constantly update and improve technologies to catch up with fast-paced technological changes and stay competitive. Even so, the lack of financial support limits organizations' ability to acquire or develop I4.0 technologies and makes hiring a skilled workforce to manage and maintain the new technologies difficult. SMEs with limited financial capability needed financial support to facilitate I4.0 adoption (Veile et al. 2020). However, financial constraints are not always a major hindrance. Khin and Kee (2022) showed contradicting findings suggesting that some SMEs proactively initiated the I4.0 project without any support from the government because I4.0 was worth starting.

3.2.3. I4.0 Communication Channels

To facilitate the transition to I4.0, management should communicate regularly with employees. This includes showing a clear vision and mission of I4.0 adoption, explaining the benefits of I4.0, and the "why" behind the changes. Regular discussions help employees understand how their roles contribute to this vision and to the company's success. To our knowledge, previous studies have not included this factor in their analyses. However, this factor is used as an assessment criterion for the Smart Industry Readiness Index developed by Singapore (EDB 2020). This criterion includes the organization's building block, structure, management pillar, and inter- and intra-company collaboration dimensions. It focuses on internal and external collaborations with partners to achieve a shared vision and purpose. Current studies have mainly focused on the infrastructure of communication systems, such as sharing data through the IoT or advanced technologies (Mourtzis et al. 2016; Mourtzis et al. 2018; Zhao et al. 2020). Therefore, investigating the influence of establishing formal communication channels for information sharing on I4.0 adoption can reveal new practices that SMEs can easily adopt.

3.2.4. Inter-Company Collaboration

Inter-company collaboration is critical in enhancing I4.0 readiness and adoption (Bettiol et al. 2023; Li et al. 2022; Veile et al. 2024). Effective collaboration between companies can lead to shared resources, knowledge transfer, design new product features and functionality, and enhanced innovation capabilities (Ganotakis et al. 2013; Müller et al. 2020; ul zia et al. 2023). Collaborative networks facilitate the exchange of knowledge, expertise, and best practices about I4.0 technologies and business cases, allowing SMEs to leverage larger firms' expertise and capabilities (Camarinha-Matos et al. 2017). This collective knowledge pool can accelerate learning curves and shorten the time it takes for each firm to achieve its I4.0 goals. Firms can also collaborate to develop a new I4.0 solution for existing or potential problems. Firms engaged in collaborative efforts with partners are better positioned to exploit I4.0 technologies and successfully implement I4.0 (Bettiol et al. 2023; Müller et al. 2018).

3.2.5. Stakeholder Support

According to Vuksanović Herceg et al. (2020), manufacturing firms in Serbia need different support from each stakeholder. Suppliers and users of I4.0 technologies play the most critical role in resolving technical issues. Financial support from the government is essential. On the other hand, support from universities and research institutions is needed to educate human resources about I4.0 and provide knowledge regarding technical issues (Vuksanović Herceg et al. 2020).

3.2.6. Digital Skills Development

Digital technologies are constantly evolving, and employees need to be able to adapt and learn new skills quickly to stay current. This can be a significant challenge for organizations, particularly in industries where technology is rapidly changing and skills that were once in demand can quickly become obsolete (Li 2022; Nambisan et al. 2017). The quality of human capital positively affects the I4.0 technologies adoption, and most of them are highly educated and highly skilled workers (Corò and Volpe 2020). Employees need to develop domain-related competencies, develop analytical ability, and learn new digital knowledge and skill sets related to automation and the Internet of Things (IoT) to efficiently utilize and configure advanced I4.0 technologies (Alam and Dhamija 2022; Cooke et al. 2022; da Silva et al. 2022; Ghobakhloo 2020). Parhi et al. (2022) also showed that workforce empowerment and technical capabilities played a significant role in the success of I4.0 implementation in India. The findings from Veile et al. (2020) also emphasized that financial resources, employees' skills, education, and training support were also crucial factors for I4.0 adoption. Nevertheless, the lack of a skilled workforce is a significant challenge and obstacle to I4.0 implementation, especially in developing countries (Kiel et al. 2017; Müller

et al. 2018; Vuksanović Herceg et al. 2020). Kapoor and Kabra (2014) found that budget and other resource allocation were major challenges organizations face in building the workforce's digital skills. The lack of internal capabilities to design, implement, and monitor the effectiveness of a capability-building program is another challenge for organizations in human resource development (HRD).

4. Methodology

We employed qualitative analysis, specifically a multiple-case study approach (Gustafsson 2017; Stake 2013), using semi-structured interviews with manufacturing firms in Thailand to capture insights, explore, and analyze the driving and facilitating factors and barriers that affect their decision to adopt I4.0. Qualitative analysis allows us to develop unique insights and in-depth understanding that are difficult to obtain from a closed-ended survey questionnaire. Moreover, broader perspectives can be explored during the interviews through interviewees' perceptions (Horváth and Szabó 2019; Miles and Huberman 1984).

We focus on the manufacturing sector because it is significantly affected by I4.0 (Arnold et al. 2016; Butt 2020; Felsberger et al. 2022; Johnson et al. 2008; Sarı et al. 2020). The sample was carefully selected using a non-random approach with purposive sampling techniques to guarantee comprehension of the studied phenomenon and gain deep insight from top-level management regarding the important driving and facilitating forces and barriers behind I4.0 adoption of the companies (Onwuegbuzie and Collins 2007; Strauss and Corbin 1994; Vuksanović Herceg et al. 2020). We used the directory of the Federation of Thai Industries (FTI), the National Electronics and Computer Technology Center (NECTEC), and the Department of Industrial Works, Ministry of Industry to contact and invite manufacturing firms in many manufacturing subsectors to participate in the research.

Seven interviewee firms included one small-sized firm (employed less than 51 employees) from the automotive parts industry, two medium-sized firms (those with 51–200 employees) from the automotive parts and electronics industry, and three large-sized firms (those with more than 200 employees) from the automotive, textile, and footwear industries (Saunders et al. 2018). The selection of these companies carefully considered various factors, including Thailand's representative industries, diversity in firm size and production engineering, their known engagement with I4.0 technologies, and their willingness to participate in detailed interviews. Their diversity allows for capturing broader perspectives and experiences in I4.0 adoption. The interviews were conducted from different viewpoints, including factory owners, CEOs, and managers at various levels, to avoid bias from a high degree of differing opinions from various job positions. We ensured the interviewees had at least a senior management level (Phillips 1981; Seidler 1974). Interviews were conducted both face-to-face and via the online channel from August 2022 to February 2023. The interview duration was between 60 and 90 min per interview. Each firm has one participant from at least the senior management level. A list of questions was provided to the interviewees before the interview date. All interviews were recorded, coded, and transcribed. We treated the interviewees' information as confidential and anonymous.

The interview questions were adapted from the literature (Awodele et al. 2024; Ersoz et al. 2018; Horváth and Szabó 2019; Khin and Kee 2022; Kiel et al. 2017; Moktadir et al. 2018; Müller et al. 2018; Stentoft et al. 2021; Vuksanović Herceg et al. 2020). The interview consisted of three main parts. The first part collected general information about the firm, such as establishment information, main customers and suppliers, and the firm's activities and movement toward I4.0. The second part discussed their current status of I4.0, technology adoption, and readiness to adopt I4.0. The third part focused on the driving and facilitating factors, barriers, and challenges in adopting I4.0. Table 2 exemplifies the questions.

Table 2. Example of questions for the proposed themes and sub-themes.

Themes	Sub-Themes	Key Interview Questions
Driving factors	I4.0 Awareness	- Why would you decide to adopt I4.0? - What are the driving factors for adopting it?
	Expected benefits and opportunities	- What are the benefits you expect from I4.0 adoption? - What opportunities do you foresee by adopting I4.0?
	Customer pressure	- Does your customer request that you adopt I4.0?
Facilitating factors	Top management support	- What kind of support do you receive from top management? - Have you implemented I4.0 strategy?
	Financial support	- Do you receive financial support from a firm or government?
	I4.0 communication channel	- Do you have a formal channel to communicate about I4.0?
	Inter-company collaboration	- Do you collaborate with customers/suppliers? - Do you collaborate with other partners?
	Stakeholders support	
	Digital skill development	- Do you have a training program to upskill and/or reskill regarding I4.0 technologies? - How do you invest in employee training and development programs for I4.0 technologies and skills?

The data were analyzed using thematic analysis, which involves identifying patterns, themes, and categories within the interview transcripts to systematically explore the interviewees' responses (Nowell et al. 2017). The transcripts were read and re-read to gain an understanding of the data. The data were coded, labeled, and categorized based on their content to capture key concepts and ideas. In the theme development process, codes were organized into themes and sub-themes representing patterns or commonalities across the data, guided by existing literature or research questions. Then, themes were reviewed, refined, and validated through discussions among authors and participant feedback to ensure that they accurately represented the data. The last step was summarizing the results to show the key themes and findings (Braun and Clarke 2006; Nowell et al. 2017).

5. Results

This research aims to explore the driving factors, facilitating factors, and obstacles to I4.0 adoption in the manufacturing sector in Thailand to gain insight into I4.0. This section summarizes the findings of the interviews by driving and facilitating factors.

5.1. General Information of Firms

Table 3 shows the manufacturing firms' profiles and their readiness toward I4.0. There is one small-sized firm (Firm G), two medium-sized (Firms E and F), and four large-sized firms (Firms A, B, C, and D) from various manufacturing sectors, such as the automotive industry (Firms B, F, and G), textile (Firms B, C, and D), and electronics and electrical sectors (Firms A and E). The average firm age is 27 years. Four (Firms A, B, C, and G) are Tier-1 suppliers directly providing complete components, sub-assemblies, or modules to the original equipment manufacturer (OEM) that assembles the final product. Firms D, E, and F are Tier-2 suppliers that supply raw materials, parts, or sub-components directly to Tier-1 suppliers. Firms A and B are the Original Brand Manufacturers (OBM), while Firms D to G are the Original Equipment Manufacturers (OEM). Firm C is both an OEM and an OBM. For the capital structure, Firms A and B are Multinational Enterprise (MNE) from Switzerland and Germany, respectively. Firms C, D, and G are 100% Thai-owned companies. Firm F is a joint venture (JV) with Japan. For the transactional relationship with suppliers, Firms A, B, E, and F have significant local and international suppliers, while Firms C, D, and G have only local suppliers. For market orientation, Firms A, B, and E

have the main customers in many countries. Firm C exports only to Asian countries. Firm D's primary customers are in Europe and Asia. Firm F's primary customers are Thailand and Japan. Firm G's main customers are in Thailand and Europe.

Table 3. Profile of the firms.

	Firm A	**Firm B**	**Firm C**	**Firm D**	**Firm E**	**Firm F**	**Firm G**
Product	Sewing machine	Automobiles	Leather and shoes	Yarn dyeing, fabric dyeing, and finishing	Plastic injection molding, parts	Automotive parts	Automotive parts
Age (years)	33	25	29	32	24	27	21
Tier	1	1	1	2	2	2	1
Size	Large	Large	Large	Large	Medium	Medium	Small
No. of employees	700+	1000+	1054	300+	190	152	25
OEM/OBM	OBM	OBM	OBM/OEM	OEM	OEM	OEM	OEM
Capital structure	MNE (Switzerland)	MNE (Germany)	100% Thai owned	100% Thai owned	100% Thai owned	JV with Japan	100% Thai owned
Major suppliers	Local and International	Local and International	Local	Local	Local and International	Local and International	Local
Major customers	Multinational	Multinational	Asia	Europe, Asia	Multinational	Local and Japan	Local and Europe
Main market	Export	Export	Export	Export	Domestic	Domestic	Domestic
Technology adoption	80% adopted automation and technology replaced with I4.0	Fully adopted automation	CNC and automation	Manual	Initiate cloud-based software, data storage, and analysis	CNC and semi-automation	CNC and manual
Readiness of I4.0	Very high	Very high	High	Very low	Medium	Medium	Very low
Adopt I4.0	Yes	Yes	Yes	No	Yes	No	No

In 2023, Firm A adopted automation and I4.0 technologies for about 80% (self-estimation) of the factory, such as autonomous robots, big data applications, cloud computing, simulation, IoT, and system integration. Firm B's production was fully automated. Firm C also integrated an automation system with high-performance CNC machines, while Firm F had a semi-automation system. Firm E was in the phase of implementing I4.0 technologies, such as the installation of sensors and robots, to increase productivity as a pilot project. The production of Firm G was mainly manual, and CNC was used for specific processes. Firm D also operated manually and had used the machines since the factory started. Firms A to C were highly ready to adopt I4.0. Firms E and F had medium readiness to adopt. In contrast, Firms D and G had not initiated any I4.0 activities and were not ready to adopt. In summary, Firms A, B, C, and E have implemented I4.0, while Firms D, F, and G have not implemented.

5.2. Driving Factors

Table 4 shows a comparison of the driving factors for each firm.

Table 4. Thematic analysis of driving factors.

Themes	Sub-Themes	Firm A	Firm B	Firm C	Firm D	Firm E	Firm F	Firm G
Driving factors	**I4.0 awareness**	Fully aware			Aware		Somewhat aware	
	Expected benefits				Productivity Cost efficiency			
		Production efficiency Transparency Supply chain integration Traceability Flexibility Better quality		Production efficiency		Better quality	Production efficiency	
	Expected opportunities	Customers' confidence in quality More supply to meet higher demand					Customers' confidence in quality	
		Bigger market share More high-end customers			More export market			Better-imaged products
					More high-end customers New market with better margin			
	Customer pressure	No				Yes	No	

5.2.1. I4.0 Awareness

This study measures I4.0 awareness into four levels: fully aware, aware, somewhat aware, and low. Fully aware means firms deeply understand I4.0 concepts, technologies, and potential benefits. They are likely actively exploring or implementing I4.0 solutions in manufacturing processes by having dedicated teams or resources focused on I4.0 adoption. Aware means firms have a general understanding of I4.0 and its potential impact. They are interested in adopting I4.0 technologies but may lack a clear understanding of how to implement them or the specific benefits of their operations. They are actively seeking information and exploring options for I4.0 adoption. Somewhat aware refers to firms with limited knowledge of I4.0 and no idea about its implications. Low refers to firms that have heard about the term but are still confused about the definitions and complexity of the concept. It is difficult for them to identify the real scope and objectives of I4.0 (Awodele et al. 2024; Dikhanbayeva et al. 2021; Ersoz et al. 2018; Sarı et al. 2020). Table 4 presents the awareness level of each interviewed firm.

Firm A and Firm B are large-sized MNEs. Their top management and employees fully know the I4.0 concept and how it can increase its competitive advantage and business performance. Their overseas headquarters force every factory to adopt I4.0 technologies. Firm B introduced I4.0 to the Thai factory in 2018, using the concept of "Operational Excellence and Digitalization" as set up by the CEO. The strategies and roadmap are well-organized and align with the business mission. More than 80% of all employees clearly understand and embrace I4.0. Firm A's Thai factory has transformed toward I4.0 since 2012 by implementing Kaizen and lean manufacturing and using the latest technologies to solve their problems in the supply chain. Top management set up a policy for digital transformation and focused on setting the same high standards for all factories. Most of the employees are aware of the I4.0 concept and benefits. Firm C is also fully aware of and understands I4.0 technologies and implementation. Top management recognizes the potential for increased productivity and enhanced quality through implementing Industry 4.0 technologies by visiting many exhibitions and show cases in Thailand and overseas. Top management launched a clear roadmap and policies to support the company's digital transformation.

In contrast, Firms D and F suggest that firm size and capital structure are insufficient conditions to reach the highest awareness level. These two firms have not implemented I4.0 because their top management has not understood the I4.0 concept. The top management of Firm D somewhat understood the basic concept of I4.0. They informally talked about it in a few meetings with employees but did not seriously consider adopting it soon. This firm considered implementing IoT in production lines, such as sensors and RFID. However, the investment costs were very high, and its organizational structure, strategies, and human resources were not ready for digital transformation. Therefore, the top management decided not to invest in the new technologies, and the I4.0 project was not initiated. The top- and middle-level management did not clearly understand what I4.0 meant for Firm F. It attended many I4.0 seminars organized by the public sector. However, many factories are still confused and question what I4.0 is, which degree of technology adoption needs to be called I4.0, and how many robots or machines they must use to be called I4.0. Firm F is studying I4.0, conducting a cost/benefit evaluation, and considering the potential to use robots to replace the workforce in the production line. Firm G is considering adopting I4.0 because the automotive market shift focuses on electronic vehicles within 5–10 years.

5.2.2. Expected Benefits and Opportunities

(1) Benefits. Firms A and B (large MNEs) fully aware of I4.0 are expected to gain productivity, cost efficiency, production efficiency, transparency, supply chain integration, traceability, flexibility, and high quality. Firms C and F are expected to increase their productivity, costs, and production efficiency. Firm G only aimed for productivity and cost efficiency, while Firm E expected to increase productivity, cost efficiency, and better quality. Firm D only expected productivity and cost efficiency. In other words, all firms expect

quality and cost control improvements, whereas Firms A and B expect additional benefits that improve their entire supply chain operation and governance.

(2) Opportunities. Firm A and Firm B (large MNEs), who are fully aware of I4.0, believed that I4.0 adoption might lead to opportunities to gain customers' confidence in quality, improved people and culture, more significant market share, more supply to meet higher demand, and having more high-end customers. Large Thai-owned firms (Firm C) that exported to the Asian market expected customers' confidence in quality, more supply to meet higher demand, and more export market. Firm D was highly confident about its product quality. Therefore, the expected opportunities from I4.0 are more export markets, more high-end customers, and new markets with better margins. Firm E expected that I4.0 could increase customers' confidence in quality, increase export markets, increase high-end customers, and create new markets with better margins. In contrast, Firm F expected customers' confidence in the quality and more export market. Firm G needed customers' confidence in the quality and better-imaged products because it was a small-sized OEM with a limited understanding of I4.0.

The two large MNEs with full awareness of I4.0 expected benefits and opportunities other than improvements in daily operational performance. However, the findings from the rest of the firms suggest that these expectations will depend on various factors, such as strategic orientations and operational priorities.

5.2.3. Customer Pressure

Contrary to the results of the literature review, only Firm E has received pressure from its main customers to adopt I4.0. Firm E must satisfy the increasing demand for high-quality and precise products from its customers. Firm E's business field of plastic injection and molding is machine-intensive. Therefore, the firm needs to invest in sensors and robots to increase productivity and improve quality. The rest of the firms did not receive any pressure to adopt I4.0.

However, only large firms with the highest awareness levels proactively implemented I4.0, as discussed in Section 5.1. Firm D and Firm F, who are not proactive and do not have any support from top management, still use existing technologies to operate because their productivity is adequate. These findings imply that top management awareness and customer-supplier relationships will affect the role of customer pressure in I4.0 implementation.

5.3. Facilitating Factors

Table 5 shows a comparison of the facilitating factors for each firm.

5.3.1. Top Management Support

After the concept of I4.0 was recognized and introduced in the organization, top management played a crucial role in facilitating the planning and implementation of I4.0 projects and activities. The top management of Firm A set up an organizational strategy that facilitates the adoption of I4.0. Moreover, to sustain I4.0 implementation, the top management has to regularly monitor and evaluate the project's progress. Top management of Firm B set digitalization strategy and mission for every department, starting from routine tasks. Managers must present monthly progress on digitalization and I4.0, projects, and success cases and share the best practices of their departments. A key performance indicator (KPI) was set to evaluate the performance. The CEO also offers appreciation rewards such as the project of the Week/Month, an IMotion activity that promotes innovative ideas from employees, and monetary rewards. Firm C proactively invested in I4.0 technology and collaborated with its partner, specializing in IoT and smart factory technologies. The top management supported the I4.0 projects and worked with consultants to launch pilot projects to reduce waste in the production system. Sensors and IoT devices were installed on the shop floor to monitor production. The top management monitored the project closely through a monthly report. Firm E is developing the policy and strategies of I4.0, with full support from the top management.

Table 5. Thematic analysis of facilitating factors.

Themes	Sub-themes	Firm A	Firm B	Firm C	Firm D	Firm E	Firm F	Firm G
Facilitating factors	**Top management support**	Proactive, fully supportive, involved, and committed to I4.0 projects. Initiated and driven by top management with clear goals, directions, roadmap, action plan, and strategies.			No	Reactive and involve	No	No
	Financial support	Self-investment					Need funding and support from the government	Self-investment
	I4.0 communication channel	Formal communication channels are established with the official record			Informal communication			
	Inter-company collaboration	Whole supply chain		Main customers and suppliers	No	Main customers and suppliers		
	Stakeholder support	Customer Supplier		Customers Suppliers Universities Research institutions	No	Customer Supplier		No
	Digital skill training program	Innovative and adaptive training program for future skill		Structured training programs	Basic program for specific job function	Structured training programs	Basic program for specific job function	Informal mentorship and apprenticeship

5.3.2. Financial Support

Firms A, B, C, and E allocated their budget to invest, especially in I4.0 projects and activities, because they knew that investing in I4.0 needed a high upfront budget. All large firms mentioned that I4.0 provides new opportunities for the firm to digitalize the production system and fulfill customer-specific requirements more effectively and efficiently.

Moreover, I4.0 can trace and track the processes throughout supply chains in real-time to achieve higher flexibility and quality of production processes (Khin and Kee 2022) and higher supply chain efficiency. Therefore, most large firms, which are influential in operating their entire supply chains, anticipate a significant benefit from I4.0, and are well-prepared for investment in new technologies. SMEs recognized the benefits of I4.0, but perceived that investment cost was higher than the expected return on investment after exploring the feasibility of I4.0 investment. It is a considerable risk for SMEs to invest without any support or funding from the government. Therefore, Firms D, F, and G need funding and support from the government to initiate I4.0 projects.

5.3.3. I4.0 Communication Channel

Firms A, B, and C established formal communication channels within the firms and officially recorded the I4.0 activities and technologies that they adopted. They also addressed concerns about employees' fear of losing their jobs or being replaced by automation. This transparency fosters understanding, reduces resistance, and encourages employee buy-in for a successful transition. Firms D to G had no formal communication channels. They relied on informal channels such as discussing I4.0 in some meetings, personal chat, or hallway discussions. Communication through these channels could lead to misunderstanding or misinformation about I4.0. Moreover, information across different informal channels could create confusion and make it difficult for employees to grasp the company's overall I4.0 vision and strategy.

5.3.4. Inter-Company Collaboration

Firms A and B collaborated with their partners across the supply chain by integrating I4.0 technologies and cloud computing with enterprise resource planning (ERP) systems and supply chain management (SCM) systems. This transparent collaboration facilitated improved communication, data sharing, better coordination, real-time visibility of production processes, and faster response times to disruptions among different partners in the supply chain. Firms C, E, F, and G only collaborated with their primary customers and suppliers in specific activities, such as product development, problem-solving, and sharing production status. Firm D had no inter-company collaboration.

5.3.5. Digital Skill Training Program

Firms A and B have proactively developed training programs to identify and incorporate innovative learning and development practices and training for future skill sets. The program is robust and adaptive to keep up with the pace of technology changes. The training programs are regularly reviewed, refreshed, and customized based on the insights provided by key stakeholders through feedback loops. These firms also organized in-house training through internal and external experts from universities and the private sector. The internal experts can organize training in I4.0 technologies for their employees. They also have internal training facilities and knowledge management systems that allow employees to access e-learning platforms anywhere and anytime. Firms D and F only provided basic training programs for specific job functions. Firms C and E had structured training programs designed to run continuously and expand employees' digital skill sets. They developed a continuous training program aligned with the organization's needs and HR functions. Firm G only had informal mentorship and apprenticeship. Since Firms D and G did not see the urge to implement I4.0 technology, they focused mainly on training specific technical skills in necessary job functions.

5.4. Discussions on Conditions of I4.0 Adoption

What are the critical factors that determine the level of readiness for I4.0 (hereafter, I4.0 adoption)? To identify key elements from the interviews, we focus on the firms at a very high level of readiness of I4.0 (i.e., Firms A and B) and those at a deficient level (i.e., Firms D and G).

Firms A and B share common characteristics. These two firms have the same driving and facilitating factors. However, they only have different technological adoption attributes (i.e., Firm A is 80% automated and replaced with I4.0, and Firm B has fully adopted automation). Among the firm attributes, only these two firms have the capital structure of MNE, suggesting MNE as a sufficient condition of the very high level of I4.0 in this case study, which aligns with Horváth and Szabó (2019), who mentioned that MNEs were more flexible in allocating financial resources to invest in new technologies for new developments. Although we do not conclude that this finding is robust, it does, in combination with comparisons with other firms, provide rich insights into the condition of I4.0. For example, Firm C has characteristics similar to those of Firms A and B, such as large size, full awareness, proactive support from top management, and formal communication channels. However, unlike Firms A and B, Firm C is 100% owned by Thai and expects a narrower scope of benefits to its own productivity, production, and cost efficiency. This evidence suggests that some Thai firms are still focusing on the limited interests of their stakeholders and their supply chains, which makes the adoption of I4.0 at a lower level satisfactory.

In the same way as the analysis, Firms D and G, with a deficient level of I4.0 and high dependence on manual processes, do not receive any stakeholder support, which is a uniqueness of these two firms. This finding implies that the lack of stakeholder support can be a sufficient condition for the deficient level of I4.0 adoption. Although these two firms are different in size (i.e., Firm D is large and Firm G is small), their top management does not support I4.0 projects, which may discourage Firms D and G from accessing stakeholder support. This finding also suggests the importance of competitive environments, leadership style, and other determinants of firm strategies for I4.0, in understanding I4.0 adoption. These findings support the hypothesis that management issues are a crucial obstacle to I4.0 adoption if top management can neither identify opportunities from I4.0 adoption nor recognize the importance of I4.0 technology (Horváth and Szabó 2019; Khin and Kee 2022; Vuksanović Herceg et al. 2020).

Productivity and cost efficiency are expected benefits from I4.0 for all interviewed firms, irrespective of their size and capital structure. In addition, all the interviewed local firms are OEMs. The findings in this subsection indicate that firm- and factory-level efficiencies are fundamental motives for attempting I4.0, especially for local firms in Thailand and probably for other developing countries focusing on manufacturing activities in supply chains.

The barriers and challenges of the studied firms can be summarized as two main issues. First, management issues, lack of initiative, and support from top management (Firms D, F, and G) hinder I4.0 adoption. Top management fails to recognize the importance or potential opportunities of I4.0 technologies in the long term. Firms with proactive leadership that provides a supportive working environment are more likely to achieve I4.0 adoption. Second, there is a lack of stakeholder support for firms with low levels of I4.0 adoption, such as Firms D and G. This suggests that stakeholder support is crucial for successful I4.0 implementation. The absence of stakeholder support can be a significant barrier, especially for firms that are heavily reliant on manual processes.

6. Conclusions

The qualitative analysis of this study investigated the driving and facilitating factors of Thai manufacturing firms toward I4.0. The findings of this study contribute to the literature on I4.0 adoption among Thai manufacturing firms, offering valuable insights into the driving factors and facilitating conditions. The different levels of awareness and understanding of I4.0 concepts among firms, with larger MNEs exhibiting a more

profound comprehension and proactive approach than smaller, local firms, are consistent with Horváth and Szabó (2019); Sarı et al. (2020). This variance also reflects the critical role of top management in fostering awareness and creating a favorable environment for I4.0 adoption. Top management in MNEs has clear strategies, well-organized roadmaps, and a strong leadership commitment to digital transformation initiatives. However, smaller firms often face challenges in grasping the implications and benefits of I4.0, particularly when top management lacks a comprehensive understanding or fails to prioritize its adoption. Additionally, SMEs may lack the organizational capacity and infrastructure to drive I4.0 initiatives effectively, leading to slower progress and limited innovation compared to their larger counterparts.

Financial resources emerge as a crucial facilitator of I4.0 adoption, particularly for smaller firms with limited budgets. Larger firms are better positioned to access the financial and non-financial resources crucial for I4.0 implementation, giving them an advantage over SMEs (Sarı et al. 2020). While larger MNEs are willing to invest in I4.0 technologies, recognizing their long-term benefits and competitive advantages, smaller firms struggle to justify the high upfront costs without external support or funding. This finding shows the importance of tailored strategies to communicate the potential benefits and opportunities of I4.0 in different types of firms, considering their size, sector, and market position. Moreover, the study highlights the significance of top management support in driving I4.0 initiatives within organizations, with proactive leadership playing a pivotal role in setting clear strategies, providing resources, and supporting technological change.

Moreover, collaboration and communication within supply chains present contrasting scenarios for large MNEs and SMEs. MNEs leverage their global networks and resources to foster collaboration between suppliers and customers, facilitating enhanced transparency, data sharing, and coordination. In contrast, due to limited resources and organizational capabilities, SMEs may face challenges in establishing formal communication channels and inter-company collaboration. Horváth and Szabó (2019) also confirmed that a lack of network-level collaboration and technology integration at the supply chain level is a key hindrance to I4.0 implementation.

Another crucial aspect is the importance of training and skill development programs to prepare employees for the challenges and opportunities presented by I4.0. Large MNEs invest significantly in comprehensive training programs to upskill and reskill their workforce and ensure they can effectively utilize I4.0 technologies. These findings are consistent with Di Sabato and Savov (2023), who show that large firms provide more support to employee training programs than SMEs, especially for MNEs. However, SMEs face challenges in providing adequate training and skill development opportunities, limiting their ability to harness the full potential of I4.0.

Furthermore, most manufacturing SMEs operate as OEMs, catering to the specific requirements of their customers. When their current skills, knowledge, and experiences suffice to meet customer demands, these firms may struggle to recognize the critical importance of reskilling or upskilling in the context of I4.0 technologies. The obvious example is Firm G, which hesitated to initiate I4.0 adoption due to uncertainty regarding the potential shift in automotive production from combustion engines to electric vehicles within the next 5–10 years. If such a transition occurs, Firm G would need to adapt its production processes, technologies, and human resource capability to manufacture parts for electric vehicles. However, if this transition does not occur as expected, investing in new technologies could result in unnecessary costs for the company. Firms need to consider the uncertainties from government policies, charging infrastructure development, and consumer preferences for electric vehicles, which might affect the transition in the future.

To assist Thai manufacturing firms, especially SMEs, experts from the public sector, such as government agencies, the private sector, and the academic sector, should educate them to understand the I4.0 implementation steps and benefits clearly. Ensure that they have a clear direction and confidence to move toward I4.0. The absence of a cohesive digitalization strategy is an obstacle to I4.0 adoption for SMEs. Firms should know how

to acquire and disseminate up-to-date technological knowledge and reflect on the shared goals and collaborative efforts of all stakeholders within the firm and between partners in supply chains.

This study demonstrates that all firms share common goals, such as cost efficiency and productivity. Moreover, they encounter challenges related to integrating new technologies with existing systems and the need for ongoing employee training. The factors influencing I4.0 adoption among Thai manufacturing firms range from awareness and understanding to financial resources, top management support, and skill development. Thai SMEs encounter distinct challenges due to several factors, including limited financial resources, a lack of economies of scale, lower technological advancement, and insufficient skilled labor compared to large firms. These constraints can hinder their ability to invest in new technologies and the training required for I4.0. SMEs often have less access to government support than large firms do, while SMEs and large firms strive to implement I4.0. As a result, their approaches to common challenges can vary significantly. Larger firms can adopt advanced technologies rapidly, with more robust financial resources, established technological infrastructure, and access to skilled labor.

Addressing these challenges and creating an enabling environment for I4.0 adoption requires concerted efforts from policymakers, industry associations, and organizational leaders to tailor strategies, provide support mechanisms, and foster collaboration within supply chains. By doing so, Thailand's manufacturing sector can harness the transformative potential of I4.0 to enhance competitiveness, drive innovation, and secure sustainable growth in the digital age.

The limitation of this paper is that the results are based on human perception, which can introduce subjective biases. Specifically, the findings reflect the views of individuals at different managerial levels within the studied firms. Top management support, for instance, was assessed by individuals in top managerial positions, which might have introduced self-assessment bias. Therefore, the results might differ in different industries, firm sizes, and countries. Despite these insights, the sample size is relatively small and may not capture the full diversity of the Thai manufacturing sector. We acknowledge that a sample size of seven companies cannot fully represent the entire industry. This could potentially limit the generalizability of the findings to a broader population of Thai manufacturing firms.

Additionally, the sample may not fully represent the diversity of manufacturing subsectors or company sizes within the country. As the study relies on qualitative analysis of semi-structured interviews, there may be inherent subjectivity and bias in the interpretation of the data. The perspectives and experiences of participants may vary, and the findings may not capture the full spectrum of views on I4.0 adoption among Thai manufacturing firms. The study's cross-sectional design provides a snapshot of the current state of I4.0 adoption among Thai manufacturing firms. However, it does not capture longitudinal changes or trends over time.

Future research should consider more extensive and varied samples to validate these findings. Additionally, longitudinal studies can provide a deeper understanding of the adoption process over time. Moreover, comparative designs could provide deeper insights into the dynamics of I4.0 adoption and its impact on firm performance. To address subjective biases, we included additional respondents from middle management and operational levels to provide a broader perspective and reduce potential bias. However, we acknowledge that this approach does not eliminate bias, as perceptions can vary widely within a firm. Future studies could benefit from including a more significant number of respondents from each company to further enhance the reliability and validity of the findings. These findings can be used as a basis for benchmark analyses in countries that share similarities with Thailand. A quantitative cross-country empirical study is recommended for future research.

Moreover, other external factors, such as economic conditions, government policies, and technological advancements, could impact the adoption and implementation of I4.0 technologies in ways that are not fully captured or accounted for in the study. Investi-

gating the impact of specific I4.0 technologies, such as IoT, AI, and robotics, on different industry sectors can provide more detailed insights. Furthermore, comparative studies of Thailand and other countries with similar economic profiles can offer valuable lessons and best practices.

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