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Critical Factors for Implementing Smart Manufacturing: A Supply Chain Perspective

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Abstract: In a rapidly evolving technological landscape, manufacturers are increasingly pressured to undertake digital transformation, with smart manufacturing serving as a crucial milestone in this process. This study investigates the key factors influencing the implementation of smart manufacturing from a supply chain perspective, employing the analytical hierarchy process (AHP) to analyze collected data from senior managers of manufacturing firms. The findings highlight several critical factors, including the commitment of senior executives, the recruitment of skilled professionals, interdepartmental collaboration, and financial support. Moreover, this study reveals differing priorities between large and small manufacturers: large firms emphasize the importance of the Industrial Internet of Things (IIoT), while smaller firms prioritize understanding end-consumer needs and product trends. This study emphasizes that smart manufacturing is not only for optimizing the operational efficiency of manufacturing firms but also for supporting sustainability efforts through more effective use of resources and reduced environmental impact of work processes.

Keywords: smart manufacturing; Industry 4.0; critical success factors; artificial intelligence; analytic hierarchy process (AHP)

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1. Introduction

Smart manufacturing has spread globally for about a decade now. In 2012, Germany introduced the Industry Revolution 4.0 (4IR) plan, which advocates for the integration of information systems and the Internet of Things (IoT) in the manufacturing process to establish smart factories, developing the concept of smart manufacturing [1]. In 2014, the United States proposed the Advanced Manufacturing Partnership 2.0 [2]. The US government hoped that this initiative could impel US manufacturers overseas to return home so that the country would consequently regain the global manufacturing leadership. In 2015, Japan declared Industry 4.1J to develop the factory of the future, where humans and machines collaborate in harmony [3]. In 2015, China proposed "Made in China 2025" and has been vigorously developing infrastructures, such as advanced equipment and technologies required for smart manufacturing [3].

Schwab, Chairperson of the World Economic Forum, announced in 2016 that the revolution of the global manufacturing industry with a focus on smart manufacturing had arrived [4]. The global manufacturing industry is at the forefront of 4IR. The development of smart manufacturing is being realized through deploying advanced technologies and concepts, including artificial intelligence (AI), robotics, nanotechnology, 3D printing, autonomous control, connectivity systems, cloud computing, big data analytics, and Internet of Things Services (IoT/S) [5]. Leading global manufacturers have gradually been applying advanced technologies, financial resources, and market advantages to implement smart manufacturing strategies [6].

Dynamic capabilities that enable firms to respond to changing conditions of the environment, society, and customer needs with agility, flexibility, and resilience in manufacturing operations can be realized without emphasizing cost considerations. For example, Nike pays more attention to customer value than costs, as it found consumers are willing to pay higher prices for products that meet their needs [7]. Smart manufacturing, which emphasizes customer needs, can increase the eventual added value for customers. The COVID-19 pandemic has further impelled manufacturers to implement smart manufacturing, as many factories were forced to rapidly repurpose their production facilities to manufacture products that are related to pandemic prevention or treatment. For example, Lego, a well-known children's toy brand, modified several molding machines to produce more than 13,000 face masks for first-line medical staff every day [8]. Another example is Ford Motors, which has been working hard for years to develop electric cars to compete with Tesla, with little success. However, it switched some of its automobile production lines to produce medical ventilators in a matter of a few weeks during the pandemic [9]. True Value Co. also switched two of its production lines from paint to FDA-approved hand sanitizers in two weeks [10].

Smart manufacturing is not just for improving operational efficiency and product quality [11]. The critical outcome of smart manufacturing should be customized services to consumers [11]. In the past, manufacturers sought to maximize profits through economies of scale-oriented business models [12]. In contrast, today, manufacturers focus on customer-oriented business strategies that emphasize customer service capabilities as the primary source of comparative advantage [13]. The core of Industry 4.0 is smart manufacturing [14], which has been embraced by many global firms, such as Audi's networked digital factory and Robert Bosch GmbH's smart factory in Germany [15]. Smart manufacturing not only enhances operational efficiency and product customization but also plays a crucial role in promoting sustainable development by optimizing resource use and reducing environmental impact, aligning with global sustainability goals. Implementing smart manufacturing practices, such as reducing waste through real-time data analytics and enhancing energy efficiency, supports long-term sustainability by minimizing the environmental footprint of manufacturing operations. As smart manufacturing can bring numerous benefits to enterprises, an increasing number of firms are investing in implementing the system [16]. However, there is a paucity of research on critical success factors for implementing smart manufacturing, especially from a supply chain management perspective. Smart manufacturing implementation requires major changes in supply chain management [17]. Previous studies discussed the impact of certain factors on smart manufacturing, but few investigated the critical factors and their relative importance [18]. This study explores the key factors for the successful implementation of smart manufacturing through the Analytic Hierarchy Process (AHP) based on the opinions of senior managers, scholars, and experts in manufacturing and supply chain management. This study also conducted a comparative analysis of the key factors of implementing smart manufacturing based on the size of manufacturers, such as large vs. small and medium-sized enterprises (SMEs). Such comparative analyses can shed additional information about differences in smart manufacturing strategies based on the scale of operations.

The remainder of this paper is organized as follows. Section 2 presents the literature review to provide theoretical support to the study. In Section 3, we discuss the AHP framework to explore the key factors for implementing smart manufacturing. Section 4 provides the research results. In Section 5, we present the discussion and conclusions, including theoretical implications, practical implications, and limitations and future research.

2. Literature Review

2.1. Evolution of Manufacturing Automation

Human history has gone through several significant revolutions to improve the quality of life. Each revolution has focused on how to overcome the limited capabilities of human labor [19]. In modern times, technology-enabled automation has been the focus of the revolution process. In the Second Industrial Revolution, at the beginning of the 19th century, electricity-driven machines, such as looms, were developed to operate invariable tasks that required considerable human labor. At that time, machines could support mass production, but the system was generally referred to as automated production [20]. As the age of computers arrived in the 20th century, some simple service tasks began to be performed by machines. Automated telephone answering systems, for example, were gradually deployed to service industrial applications. In the 21st century, machines began to take over some tasks that require cognitive judgment and complex procedures [19]. The application examples of such automatic systems include smart factories [21], robot hotels [22], and automatic food delivery robots [23]. During this period, machines became smarter due to the development of AI. AI-enabled smart robots, equipped with smart sensors, can perform tasks that require rapid, accurate, and complex judgments and actions, and human workers only need to learn how to collaborate or augment the work of robots [24,25].

Traditionally, manufacturers have adopted cost reduction as one of their main goals. Mass standardized production, such as lean production [26], helps achieve economies of scale, thereby reducing production costs and increasing profits. However, enterprises using cost minimization as a competitive advantage can easily be surpassed by competitors that offshore or outsource their manufacturing operations to countries or regions with lower labor costs. Manufacturing has gradually transformed into flexible [27] and agile operations [28] to respond to the needs of downstream customers. Today, manufacturing has gradually evolved into a production model that focuses on ultimate customer value, which emphasizes the service supply chain [29]. The supply chain is no longer limited to the management of back-end supplier integration and front-end customer integration but has been extended to managing the entire business process [30]. Smart manufacturing is an efficient and ideal production model that focuses on customer value. To implement smart manufacturing, the production system needs to be both flexible and efficient to mass-produce personalized products at reasonable costs [31].

Schwab (2017) [32] suggested that cyber–physical systems of 4IR should be characterized by the integration of various technologies, thereby blurring the boundaries between the physical, digital, and biological fields. Application-pull and technology-push have become the driving forces of 4IR [33,34]. Companies faced with the impact of 4IR need to implement digital transformation to face and win future competition [35,36]. The success of digital transformation depends on people, organization, technology, and processes. Manufacturing firms use open, collaborative innovation, enterprise systems, and organizational adjustments to achieve digital transformation and the goal of smart manufacturing, essential milestones of 4IR. Recent studies emphasize the importance of sustainable practices and efficient resource utilization in digital transformation initiatives [37,38].

2.2. Smart Manufacturing

Customized products have gradually become a market trend [39], and manufacturers must respond to the needs of rapid product development, flexible production, and dynamic environments [40]. Thus, manufacturing systems should be designed to meet the individual needs of customers [41]. To gain a sustained competitive advantage, enterprises must provide highly customized products. A high degree of customization affects the method of production, requiring special tools, specific steps, and frequent changes in machine settings in the production process. Recent studies indicate that system flexibility, alongside technical capabilities, is pivotal for Industry 4.0 adoption, as it allows for rapid response to changing production demands and enhances sustainable implementation [42]. Such frequent realignments of the production system result in increased production costs. Zuehlke (2008) [43] claimed that smart factories that can respond quickly to product change requirements need transformation to smart manufacturing to stay abreast in the era of 4IR. Compared with traditional production systems, smart manufacturing systems have many advantages, including improved service standards [44] and performance [11,16].

A smart factory is defined as a production system with context awareness [45]. Context awareness means that the system can analyze contextual information (such as the location or the status of items) in a cloud system through continuous analysis of substantial amounts of data during the production process [45]. A smart factory can independently and continuously operate through the networked interaction among people, machines, raw materials, and systems [34,46]. A smart factory combines IIoT, big data analytics, and autonomous operation technology with the support of connected machines and equipment that communicate with each other and make smart decisions. The smart factory provides flexible and automated production through the combination of software, hardware, and machines to optimize manufacturing while reducing unnecessary labor and waste of resources [21]. Zuehlke (2010) [47] suggested that the prerequisite for implementing smart factories is to embed smart technology in all devices involved in production operations. These integration levels help address the inherent complexity in coordinating various actors in Industry 4.0, including people, data, and machines, facilitating seamless information flow and improved decision-making within smart manufacturing environments [48]. The supply chain system formed by connecting smart factories can facilitate smart manufacturing. Both logistics and information flow are integrated into the supply chain, and production decisions can occur simultaneously [49]. Smart manufacturing deploys AI-supported machines and equipment to increase the productivity of the manufacturer and its supply chain partners [50]. Recent studies have further explored the application of IIoT and advanced data analytics in smart factories, highlighting the critical role of secure and reliable decision-making processes in enhancing operational efficiency [51,52].

The architecture of 4IR facilitates the implementation of smart manufacturing as it can make manufacturing more flexible and agile [53]. Javaid et al. (2020) [54] proposed that 4IR is a smart system. During the entire production process, information is provided instantaneously by AI, IoT, and other advanced digital technologies to enhance the flexibility of the production system. 4IR helps transform traditional manufacturing into highly efficient and fully automated factories and construct a new type of supply chain network [39]. The value of smart manufacturing is to continuously optimize all production-related operations in the dynamic demand environment [55]. The application of AI has enabled manufacturers to make smart decisions through continuous real-time analysis of numerous manufacturing data. AI not only helps improve the performance of smart manufacturing, but it also enables timely decision-making while using the least amount of human labor [56].

SMEs and large enterprises often face different challenges when implementing smart manufacturing. SMEs face unique challenges in implementing smart manufacturing, particularly due to resource limitations and insufficient technical expertise [57]. These constraints hinder SMEs from fully capitalizing on advancements in Industry 4.0 technologies, such as the Industrial Internet of Things (IIoT) and big data analytics, which are critical for automation and process optimization [58]. Studies have shown that while larger firms often integrate these technologies to achieve substantial efficiency gains, SMEs struggle with high adoption costs and a lack of skilled labor to manage complex systems [59]. Emerging markets, however, are increasingly adopting smart manufacturing practices, as they present significant growth opportunities and enable local industries to enhance competitiveness on a global scale [60]. These differences highlight the need for tailored strategies that address the specific resource and capability constraints of SMEs, as well as the opportunities for growth and competitiveness in emerging markets.

Recent research emphasizes the importance of integrating supply chain management perspectives into smart manufacturing implementation, highlighting how interconnected supply chains can enhance agility, resilience, and sustainability in Industry 4.0 environments [58,61]. Studies indicate that digital integration, real-time data sharing, and collaborative networks across supply chains are critical for successful smart manufacturing, allowing firms to respond dynamically to market demands and disruptions [62,63]. This supply-chain-centered approach underscores that effective smart manufacturing adoption requires robust data analytics and cross-functional coordination to maximize scalability, responsiveness, and sustainable competitive advantage.

2.3. Application of AHP in Operation Management

AHP has been applied extensively in studies dealing with various aspects of operation management [64–71]. The AHP model can support manufacturing firms in selecting the best decisions and operational plans regarding workforce management, products/services, supply chains, and organizational change. Kim and Whang (1993) [64] used AHP to determine the weights and rankings of new technology elements for their contributions to products. To optimize manufacturing operations, Weber (1993) [65] applied AHP to solve the decision-making problem regarding production machines, such as whether to improve the existing machines, buy a new computerized numerical control (CNC) system, or explore other alternatives. Tummala et al. (1997) [66] applied AHP to evaluate the success factors, benefits, and costs of different operational programs. Akarte et al. (2001) [67] used AHP to evaluate suppliers as strategic outsourcing partners. Fogliatto and Albin (2003) [68] applied AHP to evaluate new methods to manufacture products in food processing operations. Subramoniam et al. (2013) [69] employed AHP to make effective decisions regarding remanufacturing. Govindan et al. (2014) [70] examined the importance of assessing barriers in a green supply chain through AHP. Because all barriers could not be removed simultaneously, AHP was applied to identify critical barriers that should be overcome before implementing a green supply chain. Karaşan et al. (2018) [71] integrated AHP with TOPSIS to find the most appropriate production strategy for a manufacturing plant, illustrating the robustness of AHP in multi-criteria decision-making. AHP has proven to be an invaluable decision-making tool in various fields of operations and production management. Its versatility in handling both qualitative and quantitative factors allows for optimal decision-making in areas such as project management, production strategy, and supplier selection.

3. Methods

3.1. Research Sample

This study is focused on the manufacturing industry in Taiwan because the country is known for its many world-class enterprises that compete globally with smart manufacturing. We first selected several firms that have successfully introduced smart manufacturing and applied the snowball method to search for additional firms that implemented smart manufacturing to develop the research sample. The data collection through a questionnaire-based survey was targeted at senior managers of the selected large enterprises and SMEs. Large enterprises typically have more resources available for innovation, whereas SMEs can afford limited resources but have greater agility flexibility [72]. This study intends to perform a comparative analysis of differences in the critical factors for introducing smart manufacturing between large and SME groups. According to the definition of industrial classifications in Taiwan, SMEs are those with less than NT$100 million paid-in capital or less than 200 employees [73]. All enterprises that have greater paid-in capital or more employees are classified as large manufacturers. This study collected data from large enterprises such as TSMC and Foxconn. Additionally, the manufacturing sector of Taiwan's SMEs has demonstrated an ability to adapt to environmental changes. Therefore, the sample in this study is representative.

AHP was chosen because of its ability to systematically prioritize factors in multi-criteria decision-making, which aligns well with our goal of identifying and ranking critical factors for smart manufacturing. According to Melillo and Pecchia (2016) [74], AHP studies typically range from a few experts to hundreds of participants, depending on the specific research context. The precision and reliability of AHP do not heavily depend on large sample sizes because the method prioritizes the quality of judgments over quantity. This is supported by research suggesting that smaller sample sizes in AHP can still yield robust and reliable results if the participants are well-chosen and knowledgeable in their fields [74].

Additionally, a key advantage of AHP over other multi-criteria decision-making methods is its ability to produce reliable and statistically robust results without requiring a statistically significant sample size [75,76].

Before the official release of the AHP questionnaire, it was pretested by a senior industry manager and a professor of operations management to ensure there were no further issues. The AHP questionnaire collection period was from March to April 2021, during which 23 questionnaires were distributed. Table 1 presents the profile of the respondents to the AHP questionnaire. After excluding invalid questionnaires, we collected 18 valid questionnaires. Among the respondents, senior managers, including General Managers, CEOs, and Chief Executives, accounted for 28%. Upper-middle managers, such as Vice Presidents and Directors of manufacturing departments, made up 33%. Managers of manufacturing departments constituted 39%. Additionally, 44% of the respondents had over 10 years of service experience.

Table 1. Respondents' profile.

Classification	Items	Number of Respondents	Percentage
Title	Top manager	5	28%
	Upper-middle manager	6	33%
	Manager	7	39%
Years of experience	Fewer than 3 years	4	22%
	3 to 10 years	6	34%
	More than 10 years	8	44%

Remarks: The sample size is 18.

3.2. Research Process

The literature on the implementation of 4IR emphasizes the importance of effective management, processes, technologies, partnerships, and human resources [77,78]. These critical factors can be categorized into three broad aspects: organization, management, and environment. In this study, we adopted the technology-organization-environment (TOE) viewpoint as the analysis framework to categorize the critical factors for implementing smart manufacturing, identified through literature analysis and interviews of industry experts. AHP was applied to extract experts' opinions about the importance of the identified critical factors for introducing smart manufacturing. As the critical factors are complex, the experts' intrinsic knowledge can play important roles in assessing the factors.

To conduct interviews with industry experts, we selected three manufacturers in Taiwan, ranging from SMEs to large. The first interview was conducted with the business manager of a small-scale manufacturer of transformers and reactors. The second interviewee was the general manager of a middle-scale firm that produces clothing labels with an annual turnover of TWD 1 billion (approximately USD 32 million). The third interviewee was the deputy plant director of a large original design manufacturer for international consumer electronics brands with an annual turnover of more than TWD 10 billion (approximately USD 320 million). While the interviews were structured, they were supplemented by unstructured conversations. The first two interviews and the literature review were used to develop the initial AHP framework, while the third interview was conducted to verify the feasibility of the AHP framework.

AHP is a systematic decision modeling approach used mainly for analyzing problems under uncertainty conditions with multiple evaluation criteria [79]. Many AHP-related studies have dealt with decision-making issues in economic, social, and management fields. AHP solves complex decision problems by evaluating judgment criteria among alternative options or factors with their associated priorities [80]. AHP derives the priority weight of each factor through the pairwise comparison matrix. To ensure the consistency of the comparison results, the consistency index (CI) and the consistency ratio (CR) are used. If the

CR value is less than or equal to 0.1, then the consistency of the matrix is satisfactory [80,81]. After the weights of the factors at each level are computed, the weight of the overall level is determined, and the final decision is made based on the weight values of alternative plans. To extract the experts' opinions for the study, Expert Choice 11.5 software was used. The research process is shown in Figure 1.

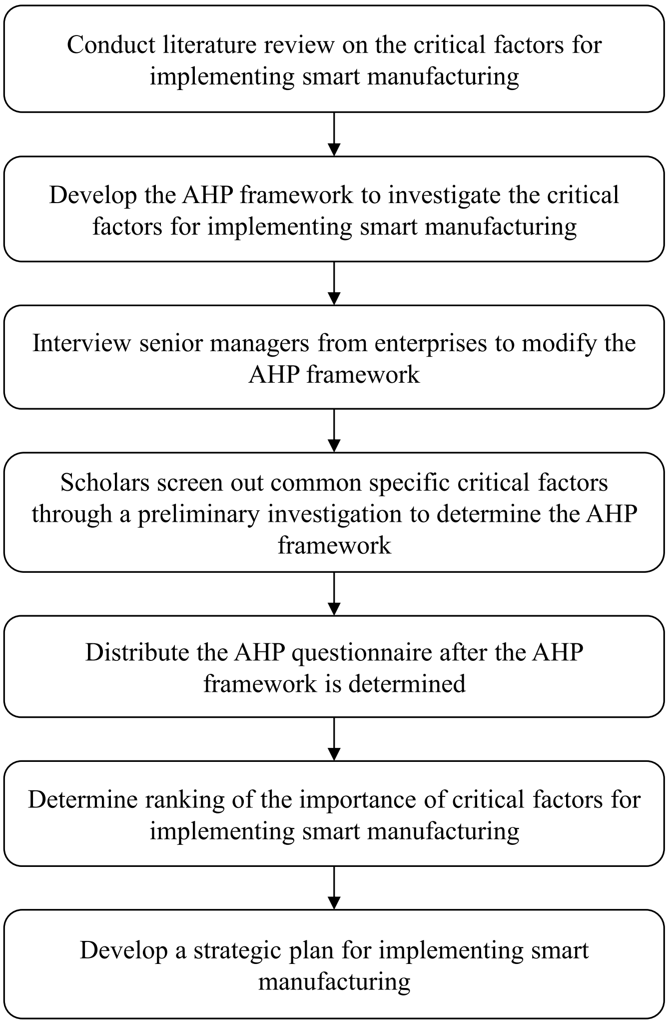

Figure 1. Research flow chart.

3.3. Developing the Initial AHP Framework

The development of the AHP questionnaire involved two steps. First, we developed a list of critical factors for implementing smart manufacturing from the TOE perspective based on the literature review and expert interviews, as described earlier. A total of 24 key factors were identified in this step. This study identifies 24 specific critical factors categorized into four main critical factor groups: internal management of the enterprise, manufacturing technology, supplier participation, and customer participation. From a supply chain perspective, this research examines the significance of these critical factors in the implementation of smart manufacturing. Existing literature reveals that these four specific factor categories correspond to the roles of internal and external members within the supply chain [33]. The second step is to conduct a preliminary investigation to determine common critical factors to ensure the number of key factors would not be too large to perform the pairwise comparison in the AHP analysis. We invited seven university faculty members who have conducted extensive teaching and research on operations management and smart manufacturing to evaluate the identified 24 key factors. They were asked to assess whether the 24 critical factors are indeed key factors for introducing smart manufacturing.

Each respondent was requested to select three common key factors in each critical factor category. Table 2 presents the result of this step. As two items in the category of "Internal management of enterprises" had the same score, a total of 13 common key factors were selected for inclusion in the AHP questionnaire.

The relevant technologies required for introducing smart manufacturing are explained from the technological perspective. Smart manufacturing technologies include AI, robotics, nanotechnology, additive manufacturing, cloud computing, big data analytics, and IIoT [82]. Smart manufacturing can communicate among machines, systems, and/or between them, requiring limited human control for factory operations [83]. IIoT facilitates communications between machines and systems that are embedded with smart manufacturing technologies [47,83]. Smart manufacturing requires an enormous amount of real-time data for process optimization and control of abnormal situations based on big data analytics [84,85]. Improvements in IT and manufacturing technology applications (e.g., the use of industrial robots) have promoted customization capabilities [43] that enhance the competitiveness of enterprises [44]. In addition, the digitalization of manufacturing expertise and production experience to transform them into parameters or programs is also one of the key factors in the implementation of smart manufacturing. In the interviews, industry experts also mentioned, "In addition to advanced manufacturing technology in the process of introducing smart manufacturing, the readiness for the input of systems and programs is also very important, such as introducing experience and process technology to the program". Based on the initial investigation and analysis, this study selected big data analysis technology, IIoT, and digitalization of expertise to form the "manufacturing technology" category.

The organizational aspect refers to the key factors that companies encounter internally when developing smart manufacturing, such as financial support and compliance with government policies. Before introducing smart manufacturing, enterprises should properly plan for and arrange the key factors at the organizational level. The introduction of new projects requires key decision makers' support and conviction for innovative ideas [77,86]. The implementation of smart manufacturing also entails cooperation among various departments within the firm [87,88]. The recruitment of smart manufacturing professionals is also a requirement [19]. Smart manufacturing is a large-scale project requiring many financial resources [21]. The initial investigation results show that financial factors are critical for the implementation of smart manufacturing. As a result, this study included the following factors in the "Internal management of enterprises" category in the AHP questionnaire: financial support, senior managers' determination, interdepartmental cooperation, and recruitment of relevant talents.

The external environment category includes the participation of the supplier and customer, indicating the support of these two supply chain partners is imperative for the implementation of smart manufacturing. Industry experts also stated during the interviews that "In addition to customers, enterprises also need to establish close relationships with suppliers as external partners when they implement smart manufacturing". Today, end-consumers' demand for products is quite diverse. This trend affects the supply chain of brand owners, original equipment manufacturers, and suppliers. When manufacturers and suppliers work closely together, the risk of misunderstanding can be minimized in product design and change processes [89]. As poor product design could lead to difficulties in production and service activities, designers must work closely with manufacturers to determine the manufacturability of the designs [90]. Suppliers' flexibility in response to manufacturers' needs [91] and the degree of strategic coordination [92] during the collaboration process are important factors in selecting suppliers. Thus, the flexibility of suppliers in response to manufacturers' needs is important when manufacturers implement smart manufacturing. In addition, information sharing is a key element of effective supply chain management [29] as it promotes flexible responses in the supply chain. According to our initial investigation and analysis, the category of "supplier participation" includes suppliers' flexibility in response to demand dynamics, support of the smart manufacturing project, and information integration with the manufacturer.

Table 2. Initial survey to identify common key factors.

Critical Factor Category	Specific Critical Factor	Proportion Identified as Key Factors	As a Critical Factor in the AHP Questionnaire	References
Internal management of enterprises	1. Determination of senior executives to implement smart manufacturing	7/7	✓	[19,29]
	2. Following the strategy of downstream customers	2/7		
	3. Interdepartmental cooperation	3/7	✓	
	4. Implementation of smart manufacturing talents	4/7	✓	
	5. Financial support to implement smart manufacturing	3/7	✓	
	6. Following government policies and regulations	2/7		
Manufacturing technology	1. Three-Dimensional Printing (additive manufacturing)	2/7		[55,82]
	2. Big data analysis technology	5/7	✓	
	3. Cloud computing	3/7		
	4. Implementation of the Industrial Internet of Things	4/7	✓	
	5. Industrial robot technology	2/7		
	6. Digitization of expertise	5/7	✓	
Supplier participation	1. Suppliers' determination to support implementation of smart manufacturing	4/7	✓	[91]
	2. Capability to design collaboratively with suppliers	3/7		
	3. Suppliers' flexibility in response to demand	5/7	✓	
	4. Information integration with suppliers	5/7	✓	
	5. Strategic integration with suppliers	2/7		
	6. Development of digital platforms with suppliers	2/7		
Customer participation	1. Customers' determination to support implementation of smart manufacturing	5/7	✓	[92]
	2. Provision of end-consumer needs and product trends by customers	6/7	✓	
	3. Capability to design collaboratively with customers	2/7		
	4. Information integration with customers	2/7		
	5. Strategic integration with customers	2/7		
	6. Development of digital platforms with customers	4/7	✓	

Manufacturing firms implement smart manufacturing to produce goods that meet end-consumers' needs and expectations. Even if manufacturers pay close attention to changes in market conditions, they may not be completely in synchronization with brand owners. If companies and customers collaborate to co-create value, they can gain more information about changes and product trends in the market [92]. As firms are under constant pressure to improve efficiency to reduce costs and resilience to minimize market risks [93], smart manufacturing has become an effective solution to meet customer needs in the challenging market environment [44,94]. Customers' support of smart manufacturing and working with other supply chain partners will simultaneously help improve market resilience and efficiency [95–97]. Close and constant collaboration with important customers provides essential relevant knowledge about the market through digital platforms [98,99]. Our analysis found the "customer participation" category includes the provision of end-consumer needs and product trends by customers, the development of digital platforms with customers, and customers' support of smart manufacturing.

3.4. Developing AHP Framework

To verify the appropriateness of relevant items for the AHP framework, we conducted the third wave of expert interviews. The interviews were aimed to determine the adequacy of the identified critical factor categories. The industry experts we interviewed suggested better descriptions of two categories, namely that "Internal management of enterprises" be changed to "Determination of enterprises to implement smart manufacturing" and "Manufacturing technology" to "Smart manufacturing technology". Thus, the key factors for implementing smart manufacturing were divided into four categories: determination of enterprises to implement smart manufacturing (A), smart manufacturing technology (B), supplier participation (C), and customer participation (D). Table 3 shows the definitions of these factors in the AHP framework.

Table 3. Common key factors for introducing smart manufacturing.

Key Factor	Description	References
A. Determination of enterprises to implement smart manufacturing		
A1. Financial support to implement smart manufacturing	Financial support is invested for the enterprise to implement smart manufacturing.	[21]
A2. Determination of senior executives to implement smart manufacturing	Business leaders are willing to plan carefully and risk investing in smart manufacturing projects.	[77]
A3. Interdepartmental cooperation	When smart manufacturing is introduced, a high degree of interdepartmental cooperation can be achieved within the enterprise.	[78,88]
A4. Implementation of smart manufacturing talents	The enterprise obtains professionals to implement smart manufacturing via internal training or external recruitment.	[19,50]
B. Smart manufacturing technology		
B1. Big data analysis technology	During the manufacturing process, equipment or systems generate large amounts of data. The enterprise uses the cloud system to store, access, and analyze these data and determine the processes that can be further optimized.	[82,84,85]
B2. Implementation of the Industrial Internet of Things	The enterprise integrates the internet of things technology into industrial production to realize a digital connection between equipment and to provide more effective value creation, greater flexibility, and better product and service solutions.	[82,92]
B3. Digitization of expertise	The enterprise transforms past practical experience or manufacturing processes into the digital format for use in manufacturing machines or smart systems.	[78]
C. Supplier participation		
C1. Suppliers' flexibility in response to demand	Suppliers respond flexibly to customized needs of manufacturers in response to market trends.	[91,93]
C2. Suppliers' determination to support implementation of smart manufacturing	Suppliers cooperate with manufacturers in activities related to the implementation of smart manufacturing.	[92]
C3. Information integration with suppliers	Manufacturers and suppliers integrate relevant information systems when smart manufacturing systems are being developed.	[29]
D. Customer participation		
D1. Provision of end-consumer needs and product trends by customers	Customers can grasp market trends and end-consumer needs and share them with manufacturers.	[92,94,95]
D2. Development of digital platforms with customers	Manufacturers and customers use information and communication technology to establish digital platforms.	[78,99]
D3. Customers' determination to support implementation of smart manufacturing	Customers and manufacturers share a highly trusted and long-term cooperative relationship, which stimulates the ambition to jointly implement smart manufacturing.	[95]

The structure of this study is shown in Figure 2, and the AHP questionnaire was developed based on the structure. The first level of this study is to determine the key factors for implementing smart manufacturing. After the literature review and expert interviews, four second-level critical-factor categories are obtained. After an initial investigation and screening with scholars, thirteen third-level-specific critical factors are obtained. The fourth level of this study identifies the significant critical factors for implementing smart manufacturing, which can serve as insights for companies that aspire to implement smart manufacturing in the future.

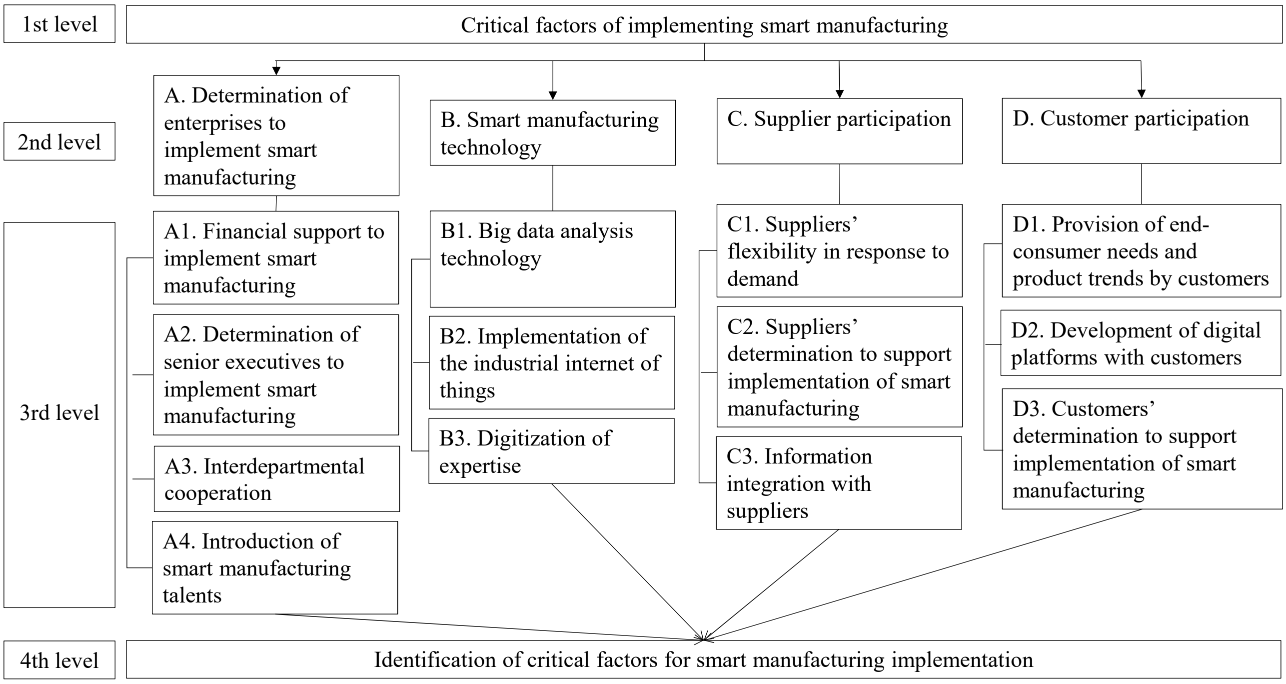

Figure 2. AHP framework for identifying critical factors of smart manufacturing implementation.

4. Results

4.1. Descriptive Statistics of the Sample

In this study, the sample firms were selected through a snowballing approach. A total of 23 questionnaires were distributed, and 21 were returned. Among the returned questionnaires, three were deleted as they were incomplete, resulting in a sample of 18 firms. The number of large enterprises and SMEs was the same, nine each. Among the large enterprises, five were listed companies, and one was an emerging firm. Table 4 presents the sample profile.

Table 4. Demographics of respondents.

Type	**Item**	**Number of Respondents (%)**		
		All Enterprises (*n* = 18)	**Large Enterprises (*n* = 9)**	**Small and Medium-Sized Enterprises (*n* = 9)**
Industry	Textile	1 (6%)		1 (11%)
	Food	1 (6%)	1 (11%)	
	Paper tube	2 (11%)	1 (11%)	1 (11%)
	Electronics	9 (50%)	5 (56%)	4 (44%)
	Optronics	2 (11%)	2 (22%)	
	Metal manufacturing	2 (11%)		2 (22%)
	Plastic resin	1 (6%)		1 (11%)
Role in the supply chain	Assembly plant	1 (6%)	1 (11%)	
	Manufacturer	14 (78%)	8 (89%)	6 (67%)
	Product design	1 (6%)		1 (11%)
	Upstream raw material supplier	2 (11%)		2 (22%)
Number of employees (2020)	Fewer than 50	6 (33%)		6 (67%
	51–200	3 (17%)	2 (22%)	3 (33%)
	201–500	2 (11%)		
	More than 1001	7 (39%)	7 (78%)	
Annual turnover (2020)	Less than TWD 0.1 billion	6 (33%)		6 (67%
	TWD 0.1–1 billion	3 (17%)		3 (33%)
	TWD 1–5 billion	2 (11%)	2 (22%)	
	More than TWD 5 billion	7 (39%)	7 (78%)	

This study conducted a consistency test by assessing the CR value for the consistency ratio of each questionnaire item. If the CR value is less than or equal to 0.1, then no contradiction exists, and the comparison results between the questionnaire items are considered credible [100]. The average CR values for the second-level factors are as follows. For Factor A, the average CR value for all companies is 0.0524, for large enterprises, it is 0.0556, and for SMEs, it is 0.0434. For Factor B, the average CR value for all companies is 0.0153, for large enterprises, it is 0.0148, and for SMEs, it is 0.0140. For Factor C, the average CR value for all companies is 0.0393, for large enterprises, it is 0.0543, and for SMEs, it is 0.0200. For Factor D, the average CR value for all companies is 0.0227, for large enterprises, it is 0.0282, and for SMEs, it is 0.0147. All CR values of the 18 questionnaires met the standard and were deemed suitable for further analysis.

4.2. AHP Analysis Results

4.2.1. Ranking of Critical Factors for Implementing Smart Manufacturing by Large Manufacturers

Table 5 shows the analysis results of the weights of factors at each level from the expert sample of large enterprises. In terms of the four categories of the second level, the determination of enterprises to implement smart manufacturing (category A) had the highest importance, followed by smart manufacturing technology (category B), customer participation (category D), and supplier participation (category C). The category ranking of the second level is consistent among the entire expert group. The top six rankings of specific critical factors were: determination of senior executives to implement smart manufacturing (A2), implementation of smart manufacturing talents (A4), interdepartmental cooperation (A3), financial support to implement smart manufacturing (A1), implementation of IIoT (B2), and digitization of expertise (B3).

Table 5. Rankings of the importance of key factors for introducing smart manufacturing (large manufacturer group).

1st Level	2nd Level			3rd Level				
Decision-Making Goal	Critical Factor Category	Weight	Ranking	Specific Critical Factor	Weight	Ranking	Overall Weight	Overall Ranking
Key factors for manufacturers to implement smart manufacturing	A. Determination of enterprises to implement smart manufacturing	57.9%	1	A1. Financial support	17.00%	4	9.84%	4
				A2. Determination of senior executives	38.15%	1	22.08%	1
				A3. Interdepartmental cooperation	21.14%	3	12.23%	3
				A4. Smart manufacturing talents	23.70%	2	13.72%	2
	B. Smart manufacturing technology	23.8%	2	B1. Big data analysis technology	24.89%	3	5.93%	7
				B2. Industrial IoT	39.18%	1	9.34%	5
				B3. Digitization of expertise	35.93%	2	8.56%	6
	C. Supplier participation	8.95%	4	C1. Suppliers' flexibility in response to demand	35.54%	2	3.18%	11
				C2. Suppliers' determination	26.96%	3	2.41%	12
				C3. Information integration with suppliers	37.50%	1	3.35%	10
	D. Customer participation	9.35%	3	D1. Provision of end-consumer needs and product trends	37.09%	2	3.47%	9
				D2. Development of digital platforms	38.43%	1	3.59%	8
				D3. Customers' determination	24.49%	3	2.29%	13

4.2.2. Ranking of Critical Factors for Implementing Smart Manufacturing by SME Manufacturers

Table 6 shows the analysis results of the weights of the factors at each level from the expert sample of SMEs. The category ranking of the second level was consistent with that of the large enterprise group. The top five rankings of critical factors were: recruiting smart manufacturing talents (A4), financial support to implement smart manufacturing (A1), interdepartmental cooperation (A3), determination of senior executives to implement smart manufacturing (A2), provision of end-consumer needs and product trends by customers (D1), and digitization of expertise (B3).

Table 6. Rankings of the importance of key factors for introducing smart manufacturing (small and medium-sized manufacturer group).

1st Level	2nd Level			3rd Level				
Decision-Making Goal	Critical Factor Category	Weight	Ranking	Specific Critical Factor	Weight	Ranking	Overall Weight	Overall Ranking
Key factors for manufacturers to implement smart manufacturing	A. Determination of enterprises to implement smart manufacturing	50.3%	1	A1. Financial support	26.87%	2	13.52%	2
				A2. Determination of senior executives	19.00%	4	9.56%	4
				A3. Interdepartmental cooperation	26.41%	3	13.29%	3
				A4. Smart manufacturing talents	27.72%	1	13.95%	1
	B. Smart manufacturing technology	21.8%	2	B1. Big data analysis technology	31.38%	2	6.84%	7
				B2. Industrial IoT	30.54%	3	6.66%	8
				B3. Digitization of expertise	38.08%	1	8.30%	6
	C. Supplier participation	11.00%	4	C1. Suppliers' flexibility in response to demand	36.12%	1	3.89%	10
				C2. Suppliers' determination	31.08%	3	3.42%	12
				C3. Information integration with suppliers	32.80%	2	3.61%	11
	D. Customer participation	16.87%	3	D1. Provision of end-consumer needs and product trends	55.95%	1	9.44%	5
				D2. Development of digital platforms	17.98%	3	3.03%	13
				D3. Customers' determination	26.07%	2	4.40%	9

5. Discussion and Conclusions

5.1. Discussion

The primary contribution of this paper is the application of the TOE framework to rank critical factors for manufacturers implementing smart manufacturing, examined from a supply chain management perspective. Additionally, based on these findings, a strategic plan is proposed to guide manufacturers in adopting smart manufacturing as a competitive strategy.

In addition to discussing the technical factors that are imperative for smart manufacturing, this study provides insights into soft factors such as the supply chain partner relationship and internal management of the enterprise. Concerning the critical factor categories, the determination of enterprises to implement smart manufacturing and smart manufacturing technology was found to be the most important. The internal advantage of the enterprise was shown to be more important than cooperative relationships with supply chain partners for implementing smart manufacturing. The determination of senior executives, recruitment of necessary talents, interdepartmental cooperation, and investment of financial resources were all important critical factors, even more important than manufacturing technology. The results provide important insights to management that implementing smart manufacturing requires the organization to secure the required resources (both human and financial) and the commitment of senior managers. In addition, customer participation outweighs supplier participation in importance, demonstrating that smart manufacturing is a customer-centric venture. Exchanging end-consumer information with customers is more critical than establishing digital platforms.

5.1.1. Importance of Specific Factors for Implementing Smart Manufacturing

The research results reveal that the determination of senior executives is the most important factor for implementing smart manufacturing for large enterprises. Because large enterprises typically have more financial resources and human talent than SMEs, the determination and commitment of key decision makers are key factors. Interestingly, the determination and commitment to implement smart manufacturing are relatively less important for SMEs. As SMEs have limited resources, and even if senior executives have a strong desire to implement smart manufacturing, they might hesitate to move forward because of their limited resources. Buer et al. (2021) [101] also believe that large companies are speedier in implementing smart manufacturing because of their financial and talent advantages. The results of this study are consistent with the views of Buer et al. (2021) [101].

The recruitment of smart manufacturing talent is considered to be the most critical factor by SMEs. This result is also supported by a comment by one of the interviewees from SMEs, as follows:

> "We have always been worried about lack of human talents. Now very few young people have the desire to learn these skills and crafts, which will cause a serious talent gap. We can only hire foreign workers to make up for the lack of such talents".

SMEs, especially in traditional industries, often face the problem of insufficient professional workers, making it difficult to implement smart manufacturing. For large enterprises, securing smart manufacturing talent is one of the most critical factors in a highly competitive market. Compared with the usual recruitment of talent in various departments, recruiting professionals who can introduce smart manufacturing is not easy, consistent with previous research [102]. Many companies provide focused training programs to current employees and organize a special taskforce by selecting outstanding employees who can lead the implementation plan for smart manufacturing.

Financial support to implement smart manufacturing ranks as the second critical factor for SMEs but the last for large enterprises. It indicates that large enterprises have fewer concerns about resource deficiency than SMEs. As smart manufacturing is a major project that requires a considerable amount of organizational investments, SMEs often consider the project with much caution and hesitation.

Interdepartmental cooperation ranks as the third factor in implementing smart manufacturing. In SMEs, interdepartmental communication is easy and informal as they have few employees. However, in SMEs of traditional industries, many process technologies and knowledge are concentrated with a few masters, which makes informal communication important. An interviewee from an SME asserted the following:

> "Masters often have their own characteristics as a master of trade, and it is difficult for them to accept new things".

This statement highlights the importance of informal interdepartmental communication in SMEs. For large enterprises, although manufacturing process technologies are rarely concentrated with a few people, integrating the opinions of various departments and specialists is often challenging.

5.1.2. Importance of Smart Manufacturing Technology

SMEs believe that the digitization of expertise is the most essential factor for the implementation of smart manufacturing. This factor is deemed especially important for companies whose manufacturing process technologies are concentrated in a few process masters. Digitization requires close cooperation between system and programming professionals/process masters, and constant modifications of the digitized content need to be conducted to ensure the result is better than the original process quality. For large enterprises, although the degree of automation is higher than that of SMEs, their capabilities still need to stand the test of how to integrate more advanced manufacturing technologies with knowledge digitization.

Big data analytics technology is not the most vital factor for large enterprises and SMEs, but it can bring great added value. After sorting and analyzing past manufacturing experiences, enterprises are better prepared to continuously optimize the process and reduce the probability of disruptions or errors. In addition, big data analysis of product information enables enterprises to grasp end-customers' needs and product trends with increased agility.

The implementation of IIoT ranks first for large enterprises, surpassing big data analytics and digitization of expertise. Connecting and sharing information about the existing production operations and processes using IIoT to improve production efficiency is widely practiced by large enterprises. This technology can improve the efficiency of communication and debugging between production machines. For SMEs, the implementation of IIoT ranks third. At present, machines at most SME manufacturing plants are operated independently and are old, and the transportation or communication between workstations is still performed by manual operating systems. To implement smart manufacturing, upgrading workstations and machines should precede the application of IIoT.

5.1.3. Importance of Supplier Participation

For large enterprises, most senior managers believe that information integration with suppliers matters the most. At present, most enterprises create communication platforms with external partners. Information integration with suppliers includes order details, such as prices, specifications, delivery dates, terms of trade, notification channels for abnormal conditions, and others. Transparent data on the information system improve the efficiency and accuracy of the communication and information transmission between manufacturing companies and suppliers and support companies in introducing smart manufacturing. The second in the ranking is suppliers' flexibility in response to variable demand. During the development of smart manufacturing, it is inevitable to encounter situations of small batch production or product modifications. When the demand for raw materials changes, suppliers' support and cooperation are critical. In contrast, small manufacturers believe that suppliers' flexibility in response to customer needs is more important than information integration. SMEs have fewer resources to build large-scale information systems and rely on long-term cooperative relationships with suppliers. Unlike large enterprises, which prioritize digital information-sharing platforms, SMEs value strong, adaptable relationships with suppliers to overcome resource constraints and facilitate smart manufacturing. By fostering close partnerships, SMEs can access critical supplier expertise and flexibility, which enables them to respond more dynamically to market demands. Such relationships are essential for SMEs to bridge resource gaps and enhance their resilience in adopting smart manufacturing practices.

5.1.4. Importance of Specific Factors in Customer Participation

For large manufacturers, establishing digital platforms with customers based on advanced ICT is most significant. A digital platform can digitize the supply chain processes. Establishing such a cross-organization platform allows the integration of practice systems and the exchange of information between supply chain partners, and it helps manufacturers quickly respond to end-consumers' needs. However, for small manufacturers, establishing digital platforms with customers is less important. Establishing digital platforms requires enormous capital and human investments, and large manufacturers have an easier time establishing digital platforms between large customer groups.

For SMEs, smart manufacturing can also help secure information about end-consumers' needs and product trends. However, SMEs have scarce resources to keep in close contact with the terminal market. If customers are willing to share information with manufacturers, SME manufacturers can capture customer needs faster and reduce communication costs, thus supporting If the two parties collaborate for shared goals with mutual trust, the synergy effect will be enhanced with a win–win partnership.

5.2. Strategic Planning

The biggest challenges in implementing smart manufacturing from a supply chain perspective include securing executive commitment, acquiring skilled talent, fostering interdepartmental collaboration, and ensuring adequate financial support. Large enterprises often prioritize the Industrial Internet of Things (IIoT) and the digitization of expertise, while smaller firms focus more on understanding consumer needs and product trends.

This study addresses these challenges by ranking these critical factors and proposing a strategic plan for manufacturers. The key recommendations include strengthening executive determination, accelerating talent recruitment, enhancing interdepartmental cooperation, and leveraging IIoT and big data analytics. These strategies help overcome resource limitations and technical barriers, ensuring that smart manufacturing aligns with both organizational capabilities and market demands.

First, strengthening the determination of senior executives is vital to implementing smart manufacturing. One of the keys for enterprises to develop smart manufacturing is that the top management team or business owners of SMEs must take ownership of the introduction plan. Managers' support and commitment are needed to obtain the required funds and assign or recruit human talents for the project. In the initial implementation stage, in addition to setting up a special project team to lead the project forward, enterprises are also advised to inform all employees and other stakeholders about the project. During the implementation phases, various departments may experience friction from knowledge asymmetry or an increased workload caused by the project. Holding regular information-sharing seminars on the project's progress and related topics is recommended to enable a sense of shared ownership and accomplishments about the project. Such regular communication about the project's progress will reduce conflicts caused by parochialism during the coordination among various departments.

Second, accelerating the digitization of expertise is essential to facilitate the storage of manufacturing-related knowledge. The digitization of expertise is the foundation of smart manufacturing, which embeds past production experience and knowledge into production machines to solve future production problems. The digitization of expertise can also promote knowledge sharing and achieve digital transformation for creating new business models and new customer value in the future. In addition, it can be the basis for introducing IIoT, and digitized knowledge promotes the connection between factory workstations. In SMEs, the degree of digitization of expertise is typically low, which in turn affects the implementation of smart manufacturing. A large amount of capital investment is required to digitize the tacit knowledge of masters or engineers. Because masters or engineers may be reluctant to fully participate in the digitization project, transparency, and close communication with them is necessary to promote smart manufacturing.

Third, updating factory equipment and strengthening the establishment of IIoT and big data collection are crucial. Wei et al. (2017) [103] proposed that the connected platform provided by the IIoT enables mature industries to transition themselves to the digital age. They further explained that machines, devices, and products in this era needed to be interconnected to enhance the organizational dynamic capabilities. The resource sharing and network connection facilitated by machines, equipment, and systems can integrate virtual and physical elements, transforming data into intelligent information to make better decisions. Large companies are also actively promoting the IIoT in factories. Machines and equipment of SMEs are usually relatively old or obsolete and cannot be connected to the Internet. Therefore, updating factory equipment will accelerate the process of introducing smart manufacturing.

Fourth, manufacturers can use IoT technology to accelerate the exploration of consumer needs. Most manufacturers valued the paradigm of "scale". Thus, the core concept of competitiveness is to achieve economies of scale for efficiency and waste reduction. However, in recent years, the development of smart manufacturing technology has enabled manufacturers to gradually realize the paradigm of "scope," and companies can expand product categories to meet changes in downstream customer needs. The use of IoT technology helps effectively collect the needs and preferences of end-consumers. IIoT, big data analysis, and expertise digitization enable manufacturers to be agile in supplying products that meet consumer needs. Regardless of the size of enterprises, they should actively establish digital platforms with customers to promote the sensitivity of the entire supply chain partners to the demand of end-customers.

Fifth, SME manufacturers should actively seek government support, in terms of funding, training, and expertise for introducing smart manufacturing. The government can subsidize key resources to accelerate the upgrading of machines and equipment, as well as for the digitization of expertise. SME manufacturers can also collaborate with their supply chain partners in developing digital platforms for close communication and information sharing in introducing smart manufacturing. Given their limited resources, SMEs often face significant challenges in independently acquiring the capital, advanced technology, and skilled personnel necessary for smart manufacturing implementation. Therefore, government support and strong partnerships are essential for SMEs to bridge these resource gaps and enhance their competitive capabilities in a rapidly evolving industry.

5.3. Limitations and Future Research

While this study is based on rigorous and robust methodologies that encompassed the literature and industry experts' knowledge, it has some limitations. We discuss these in terms of data collection, coverage of critical factors, and the AHP method. Let us address the limitations related to data collection. First, the scope of this study was general manufacturers. Although analyzing the key factors for implementing smart manufacturing in various sectors of manufacturing has merit, different sectors may have their unique market environments. Future research could distinguish different manufacturing sectors to investigate different unique critical factors for each sector. Second, this study collected field data in Taiwan. The manufacturing industry of each country has its unique strengths and weaknesses, as well as different government policies and regulations. However, we recognize that different regions have distinct manufacturing environments, government policies, and resource allocations, which could influence the critical factors for smart manufacturing. Future research could extend these findings through comparative studies in different regions to highlight how various economic, regulatory, and cultural contexts shape smart manufacturing adoption. Such cross-regional analysis would deepen the understanding of these critical factors and refine strategic recommendations for broader applicability. In addition, the use of snowball sampling, while effective in accessing knowledgeable respondents, may introduce bias by limiting sample diversity. Future research could address this limitation by employing random sampling across a broader range of manufacturing firms to enhance representativeness.

While this study utilizes the TOE framework and a supply chain perspective to examine critical factors in smart manufacturing implementation, several areas warrant further exploration. For instance, while financial support is identified as a key factor, specific strategies for securing funds and understanding the potential return on investment are not deeply examined. Additionally, other human factors—such as employee resistance, training needs, and the role of organizational culture—require greater attention, as do ethical considerations like workforce displacement, data privacy, and environmental impact. Future research could address these financial, human, and ethical aspects for a more comprehensive understanding. Moreover, external environmental factors, such as government policies, market dynamics, and technological trends, were not extensively covered. These elements, which vary significantly across regions, could be included in future studies to provide a broader and more nuanced understanding of smart manufacturing adoption across diverse contexts.

Although AHP is one of the important multi-criteria decision-making methods and is suitable for the research problem, the methodology has certain limitations, particularly in its reliance on subjective judgments in pairwise comparisons. Future studies could complement AHP with additional quantitative methods to minimize potential biases. Second, although all the AHP categories in this study were extracted from the literature and supplemented by in-depth interviews with industry experts and academic researchers' reviews, no data were collected from the academics through AHP questionnaires. In the future, including the opinions of the academic community could increase the richness of the importance rankings of critical factors for introducing smart manufacturing.

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