Key Enablers of Industry 4.0 Development at Firm Level: Findings from an Emerging Economy

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ABSTRACT - Organizations in both developed and developing economies are paying great attention to the Industry 4.0 revolution and associated uses of technologies due to its potential benefits to the manufacturing industry. However, there are a limited number of empirical studies due to its early stage of adoption around the world, especially regarding the key technological factors that are necessary. This study addresses this research gap by identifying the factors that enable successful Industry 4.0 technologies adoption in an emerging economy country, grouping them, and ranking the groups based on priorities for adoption. The study adopts a mixed-method research methodology. Q-Sort technique and Analytic Hierarchy Process (AHP) respectively were used to group enabling factors and prioritize the groups for Industry 4.0 technologies adoption. Thereafter, semi-structured interviews of key stakeholders in the manufacturing sector in Thailand were carried out to validate and support findings from the quantitative analysis. Five industry experts from automotive and electronic parts/components manufacturers were interviewed. The results show that human capital is the most important readiness dimension for Industry 4.0 technologies implementation. Interoperability and data handling were found to be the next in importance. On the contrary, hardware and technology systems such as data security and technological infrastructure were identified as the least important of the technology readiness dimensions. These findings provide a different perspective to extant studies that posited that technology-based factors as the most important for Industry 4.0 success.

Managerial Relevance Statement

The rapid development of Industry 4.0 has significantly influenced manufacturing organizations' operations and decisions. As manufacturers increasingly seek to adopt Industry 4.0, it is important that they know where to direct their efforts and resources. This study emphasizes that human development issues are critical to the

success of Industry 4.0. The implication for managers is that human capital must be developed in tandem with technology. The study also highlights the importance of interoperability and therefore, managers must choose Industry 4.0 systems and technology with the ability to be interoperable with other systems and/or organizations in their ecosystems. Finally, the research encourages managers to consider production flexibility and process stability as the most important performance measures for Industry 4.0 implementation.

Keywords – Technology Readiness, Industry 4.0, Emerging Economy, Human Capital, Big Data, Implementation, Fourth Industrial Revolution, Thailand

I. INTRODUCTION

The fourth Industrial Revolution (Industry 4.0) is widely regarded as the latest industrial revolution that can transform manufacturing and enable the development of the smart factory of the future. Its ability to enhance productivity and enable the efficient use of organizational resources has led to increasing interest from both practitioners and academics [1-2]. Also, the potential for Industry 4.0 to transform the national productivity of nations and consequently, their fortunes, has led to interest from governments as well. The emerging nature of Industry 4.0 has been mirrored in the research and academic communities. Different studies have sought to understand and direct the knowledge base on Industry 4.0. For example, Hermann *et al.* [2] tried to explore a generally accepted definition for Industry 4.0 as well as establish the design principles that could underpin Industry 4.0. The research by Ramanathan [1] was focused on understanding the key components and characteristics that relate to readiness for Industry 4.0 adoption while Schumacher *et al.* [3] emphasized the importance of assessing the maturity of manufacturing enterprises towards Industry 4.0 by providing a holistic approach with eight broad dimensions and 65 maturity measurement items. On the other hand, many studies have focused on various aspects of Industry 4.0 technology components, including the role of cyber-physical systems in creating a smart factory [4] and enabling smart supply chains using Industry 4.0 technologies [5].

While there is, undoubtedly, increasing interest from both academia and industry concerning understanding and implementing Industry 4.0, it is still an emerging concept which many industry sectors are yet to fully explore and/or commit to. There is still much to learn and much to be discovered about the basic concepts, potential opportunities/benefits for companies, expected impact on manufacturing performance due to increased operational efficiencies, and development of new business models [6]. It is, therefore, important that academic research moves quickly to identify the knowledge gaps relating to Industry 4.0 and address them. This is particularly crucial in emerging economy countries that have become increasingly important as manufacturers on the world stage.

Although many studies have examined key concepts and challenges that organizations face in the Industry 4.0 transformation process, and in the assessment of readiness for implementation (e.g. [7-8]), research on understanding the enabling factors for implementing Industry 4.0 has not been adequately addressed. In particular, there is no understanding of which enabling factors are most important at this stage of the evolution of Industry 4.0. This research seeks to address this gap by identifying and evaluating the relative importance of Industry 4.0 enabling factors by classifying them into technology readiness dimensions and evaluating these dimensions. Therefore, the key research question that underpins this study is as follows: What are the key technology readiness dimensions that drive Industry 4.0 implementation in a manufacturing environment, and what is the relative importance of these technology readiness dimensions with regards to successful implementation?

The rest of the paper is organized as follows. the next section presents a review of the extant literature on Industry 4.0 and is followed by a description of the research methodology. Results and findings from the research are discussed next. Finally, discussion of findings and conclusions, including practical implications and future directions, are presented.

II. LITERATURE REVIEW

The term Industry 4.0 is used to denote a new wave of technological advancement that was described by Schwab [9] as the "fourth industrial revolution." The first industrial revolution in the 18th century was characterized by a paradigm shift from a mainly agricultural economy to an industrial economy powered by mechanical energy while the second industrial revolution involved the replacement of water and steam power with electrical energy [10-11]. The third industrial revolution ushered in the age of the internet and computing power [11]. Each of these revolutions has been the source of vastly increased industrial productivity and national wealth. Therefore, it is understandable that the potential for a new industrial revolution has been the source of much interest in the industry, government, and academia. According to Chai *et al.* [10], many countries are seeking to advance through the adoption of technologies related to the Internet and Industry 4.0. Industry 4.0, in particular, is generating much attention due to the exciting potential attributed to it to contribute substantially to productivity enhancement while enabling the prudent use of scarce resources [1-2]. From the knowledge management perspective in Industry 4.0, Manesh *et al.* [12], identified future research avenues capable of producing meaningful advances in managerial knowledge of Industry 4.0.

Consequently, academic researchers have started to place much emphasis on investigating different perspectives of Industry 4.0 including investigating a generally accepted definition and the design principles that will enable the implementation of the technological applications of Industry 4.0 [2]. Other researchers have sought to investigate the key elements and characteristics for Industry 4.0 readiness within the context of developing countries [1], [13] and investigating the ability of cyber-physical systems to enabling the creation of a smart factory of the future [4]. The emerging nature of Industry 4.0 also implies that many industrial sectors and countries are yet committed to adopting Industry 4.0 technologies at present. Without a doubt, there is much to be investigated and learned with regards to the basic concepts, potential opportunities, expected benefits and impacts on organizational performance, and the evolution of new business models within the context of Industry 4.0 [2], [6].

A. *Definition of Industry 4.0*

Industry 4.0 is still in its infancy and even though its deployment has now been suggested to be commercially viable, its full potential may not be realized for decades to come [14]. As with many innovations at an infancy level, there is no agreed definition of what Industry 4.0 is. Sirkin *et al.* [15] defined it as the deployment of "cyber-physical systems (CPS) and dynamic data processes that use massive amounts of data to drive smart machines" This definition makes a significant emphasis on the centrality of data and its use. In contrast, Brettel *et al.* [16] placed a greater emphasis on physical attributes when they wrote, "Industry 4.0 focuses on the establishment of intelligent products and production processes." Wolter *et al.* [17] suggested a wider perspective when they defined Industry 4.0 as follows, "Industry 4.0 is the technical integration of CPS in production and logistics as well as the application of the Internet and its services for industrial processes." This definition suggests that Industry 4.0 goes beyond the boundaries of manufacturing and impacts on the wider supply chain. Irrespective of which definition or perspective is adopted, it is clear that industry is potentially on the verge of adopting technology that will impact productivity, sustainability and the global economy for decades.

B. Industry 4.0 Technologies

Unsurprisingly, the emerging nature of Industry 4.0 and the lack of a commonly agreed definition or perspective implies that the component technologies and implementation models do not have general agreement either. A study by Deloitte [18] identified key technologies including the Internet of things (IOT), big data and analytics, simulation, advanced robotics, artificial intelligence (AI), additive manufacturing (3-D printing), cloud-based software platforms, and augmented reality. Tortorella *et al.* [13] identified additional technologies including digital automation (with and without sensors), remote monitoring and control, and integrated engineering systems. In addition to some of the technologies listed, others that have been suggested include cloud computing and cybersecurity [19]. In summary, Götz and Jankowska [20] asserted that as there is no clear definition of industry 4.0 "but rather a wide array of interdisciplinary technologies – with different levels of maturity and market availability – which facilitate digitization, automation and process integration along the value chains". The position, therefore, appears to be that there are some perspectives on what may be industrially possible within the realm of Industry 4.0 but the technologies to enable this and their integration into a cohesive whole is still largely unclear.

To provide more clarity about Industry 4.0 and its technologies, several studies have sought to investigate the development of environments for its deployment. For example, Baur and Wee [21] identified 26 industry levers and 8 value drivers for Industry 4.0 implementation. The industry levers include smart energy consumption, routing flexibility, predictive maintenance, digital quality management, data-driven design to management, in situ 3D printing, and advanced process control. The value drivers are labor, inventories, quality, time-to-market, services/aftersales, resource/processes, asset/utilization, and supply/demand match. Other studies have sought to understand the right industry policy environment for Industry 4.0. In this regard, Kagermann *et al.* [6] recommended that action needs to be taken on eight key areas – standardization and reference architecture, managing complex systems, broadband infrastructure for industry, safety and security, work organization and design, training and continuing professional development, regulatory framework, and resource efficiency. In a separate study, Hermann *et al.* [2] identified six design principles for industry 4.0 which are: (i) interoperability, (ii) visualization, (iii) decentralization, (iv) real-time capability, (v) service orientation, and (vi) modularity while Götz and Jankowska [20] suggested that collaborative productivity in an Industry 4.0 environment requires four enablers – IT globalization, single source of truth, automation and co-operation. Separately, key components of Industry 4.0 systems and their integration into different organizational objects/processes were identified to be: (i) Internet of Things (IoT) integration with manufacturing processes [8], (ii) Cyber-physical system (CPS) through the integration of computation and physical processes [22], and (iii) Smart factories through vertical integration of IoT and CPS in their operations [2].

This multiplicity of studies and their very different and divergent perspectives are a clear indication that knowledge is still emerging in this area and it may take a bit longer for all the different perspectives and objectives to be converged effectively.

C. The Promise and Potential of Industry 4.0

The excitement and interest regarding Industry 4.0 and its declaration as the next industrial revolution are very much based on a vision of the potential that it holds. According to Preuveneers *et al.* [23], Industry 4.0

proposes a future form of production where machines are networked and communicate with business processes to enable efficient and sustainable manufacturing. A key component of this proposed future appears to be the role of CPS. CPS boundaries extend beyond a single enterprise and encompass the entire value chain. They consist of an internet-enabled network of sensors, machines, workpieces, and information technology (IT) systems [1]. These different components can interact with each other by exploiting Internet-based protocols and they have the capacity to analyze data for self-configuration, adapt to changes, and predict problems and failures [19]. CPS can also enable expedited responses to demand and supply changes, quality inconsistencies, and equipment breakdown thereby making production systems smarter and more efficient. Such efficient operations will enable customized production, lean manufacturing, and total productive maintenance (TPM). Ramanathan [1] went further to suggest that horizontal integration of global value chains can also be achieved whereby a multiplicity of supply chain functions such as inbound logistics, warehousing, production, warehousing, outbound logistics, marketing, sales, and after-sales service are networked to provide integrated transparency, high level of flexibility, traceability, and global optimization. In addition to the supply chain potential, CPS can also drive effective cross-disciplinary and cross-functional collaboration for through-engineering across the value chain. Through-engineering has been defined as a seamless approach for the design, development, and manufacture of new products and services across product and customer lifecycle [18].

In addition to the above, other potential benefits that have been attributed to Industry 4.0 include improved productivity, efficient resource utilization, increased savings, higher value delivery to customers, development of new business models, improvement of operational and strategic decision making [6], [16], [24-29]. These potential benefits are significant and paradigm shifting and organizations that can harness some or all of these potential benefits will become the successes of the future.

D. Challenges and Barriers to Industry 4.0

Although the potential benefits of Industry 4.0 are significant and many and the deployment of the associated technologies are still at infancy, there is already an indication that the deployment of Industry 4.0

and its technologies will be faced with challenges and barriers. According to Sung [30], these challenges will occur at both enterprise and political levels. Kagermann *et al.* [6] identified three main challenges to the vision of Industry 4.0 to be lack of standardization, work organization, and availability of products to enable the new systems. The study by Strange and Zucchella [14] identified cybersecurity risk, cross-national data transfer, legal and jurisdiction, and changing power relationships as issues that need to be resolved. They also cautioned that only organizations that can afford to invest in the technologies and highly skilled people will benefit the most. The need for highly skilled people is further emphasized by the evidence of required competencies by project team members of Industry 4.0 implementation projects [31]. Davis [32] also identified the lack of financial resources, reluctance to change, skills levels of employees, and organizational maturity level as four factors that can negatively affect digital manufacturing. Also, Wolter *et al.* [17] identified challenges related to reliability and stability of machine-to-machine communication and maintenance of the integrity of production processes as well as social challenges such as the loss of jobs and redundancy of corporate IT departments. While confirming most of the challenges found earlier, Karadayi-Usta [33] identified relationships between those challenges and investigated how each factor triggers other factors as the basis for root-cause analysis of barriers. In a similar context, Konanahalli *et al.* [34] identified the skills gap and inadequate preparedness as significant barriers to the implementation of big data. Finally, Frank *et al.* [35] suggested that the current advances in Industry 4.0 predominantly focus on front-end technologies while the back-end technologies are still challenging to organizations.

From the literature, it is clear that Industry 4.0 has great potential and it is also clear that knowledge relating to Industry 4.0 technologies and their deployment is still emerging. Strange and Zucchella 14] raise several questions relating to location, internalization and ownership of systems, sites, control and ownership while Ramanathan [1] suggested evaluation criteria for assessing the readiness for transformation to Industry 4.0 in developing countries especially ASEAN. In July 2017, World Summit for the Information Society Forum was hosted by the International Telecommunication Union (ITU) and the UN Industrial Development Organization (UNIDO) to assist developing countries to prepare for Industry 4.0. The discussion highlighted the importance of having a coherent strategy for industry 4.0, and well-established ecosystems to support the adoption, implementation, and development of industry 4.0 technologies. Another important enabler was collaboration among interested parties – public and private partnership within a country and internationally. A group of industry experts suggested the important role of international organizations (i.e. UNIDO, JICA, GTZ) to share knowledge and technologies, to connect stakeholders in different industries and cultures, and to provide human resource development (reskilling and retraining programs) or to set-up new talent and education programs [36:21]. The discussion also included issues on cybersecurity laws, IPR protection, standards and technological infrastructure, physical, institutional and technological needs respectively.

E. Technology Readiness and Industry 4.0 Implementation

Technology readiness is a precondition for the successful implementation of Industry 4.0. Technology readiness refers to "how to prepare a new technology such that it is made ready for its deployment in a very specific (organizational) setting" [37:1230]. In this study, technology readiness refers to technological resources available for organizations to mobilize for high performance ICT infrastructure and interoperability, implementation of big data, data sharing and cybersecurity as well as IT human capital development. Low technology readiness restrains an organizations' ability to become Industry 4.0-capable.

Compared to developed countries, many emerging countries are lagging in technological infrastructure [38]. However, Industry 4.0 implementation requires large investments in IT infrastructure which encompasses a comprehensive broadband Internet infrastructure [6] and a set of firm-wide services involving computing services that connect workers, suppliers and customers into a coherent digital world [39]. Broadband Internet infrastructure therefore needs to be expanded on a massive scale, both within developing countries and between developing countries and their partner countries/business partners. For example, China's ICT development strategy, "Broadband China" is a "top-down" approach with local government providing guidelines [40]. Given that Industry 4.0 is driven by mobility and real-time data interchange [41], a well-integrated IT infrastructure is critical to support the growing interconnectivity of machines, products and people for online business and communications.

Industry 4.0 is regarded as “smart factories”, powered by cyber-physical systems [42]. The smart machines, storage systems, and production facilities integrated with the cyber-physical system enable the process of sharing data and information, initiating actions, and controlling each other [43]. With increasing cyber-physical systems in the manufacturing industry, organizations can achieve interoperability in which systems, people, and information can intercommunicate [44-45], create intra-organization cross-linking and cross-organization integration into interconnected industrial value creation networks [46-47] in real-time [2]. This industrial value creation generates technological leaps in machine-to-machine and human-to-machine communication and collaborations [48]. Literature suggests that developing countries are facing particular challenges for digitalization for Industry 4.0. For example, the digitalization of cyber-physical systems is slow-going in India [49]. India’s first “smart factory” was set-up in Bengaluru and other major Indian states are taking gradual steps towards Industry 4.0 [50]. In a study of the Indian manufacturing sector, Luthra and Mangla [51] posited that Industry 4.0 is in its nascent stage and identified four dimensions of key challenges to Industry 4.0 for a sustainable supply chain. These dimensions are organizational challenges, legal and ethical issues, strategic challenges, and technological challenges [51]. Technological challenges include lack of global standards and data sharing protocols, lack of infrastructure and Internet-based networks, lack of integration of technology platforms, and poor existing data quality [51]. These challenges are also identified in other studies (e.g., [49], [52]). With the large volume of data being shared with business partners in the industrial value creation networks, organizations need to ensure data ownership and security to protect their data from unauthorized access [32], [53]. Examples of private data include human resource personal data, financial statements, reports of research, and business trades [54] as well as process know-how [55]. Therefore, the integrity of the data exchange between enterprise software applications of business partners must be protected by service agreements [56] and cybersecurity measures [57-58]. For example, China introduced the “Basic Security Requirements for Government Department Cloud Computing Service Providers” as the security standard for providing cloud computing services to public agencies. Essentially, many of the information systems, data management, and authorization were not designed with open and collaborative networks, thereby making them more vulnerable to cyber-attacks [23]. Hence, organizations need to develop security strategies and systems geared to cybersecurity which increase protection from attack across the business value chain [18].

Digital skills and cross-functional expertise are vital for the success of Industry 4.0 implementation [49]. Therefore, up-skilling the workforce is critical to fill the demand-skill gap [49]. In China, human capital is one of three critical factors identified to realize the national agenda “Made-in-China 2025”, a Chinese version of Industry 4.0 [59]. Also, adopting Industry 4.0 principles requires a cultural change among employees in developing countries to undertake new workplace challenges including entrepreneurial spirit and failure tolerance. Resistance to change by staff poses a challenge to the implementation of Industry 4.0 [60].

Finally, using the design principles for Industry 4.0 adoption developed by Hermann *et al.* [2] and Liao *et al* [47], the six implementation dimensions for Industry 4.0 technology readiness were established as follows for this study: (i) Improve and develop the internet system; (ii) Human knowledge of technology and how to use it; (iii) Improve the ability of machines and devices to connect to the internet; (iv) Ability to manage big data; (v) Data sharing between or within organizations; and (vi) Develop data security systems.

This study contributes to current knowledge on Industry 4.0 by investigating, identifying and evaluating the enabling factors for Industry 4.0. The study is carried out within the context of a developing country where this strategy is at the early stage of implementation. The importance of carrying out Industry 4.0 studies in developing countries was highlighted by Li [59] who stressed that Industry 4.0 was conceived in developed countries which are traditionally more advanced with respect to automation and information technology while emerging countries face a disadvantage due to the lower levels of maturity of prior industrial stages. Therefore, a study which sheds light on enabling factors relating to Industry 4.0 in emerging countries is timely and important.

III. RESEARCH METHODOLOGY

The research methodology consisted of four stages: (1) literature review of more than 80 articles including 40 papers analyzed for enabling factors (Table I) and 44 articles analyzed for the broader Industry 4.0 topic, (2) *Q*-Sort-based identification and categorization of enabling factors for Industry 4.0 implementation into six groups of technology readiness dimensions (3) empirical evaluation of the six groups (relative importance and ranking of groups for Industry 4.0 implementation) using Analytic Hierarchy Process (AHP) based on input from industry and academic experts (Table V), and (4) verification and explanation of empirical findings using semi-structured interviews with executives of manufacturing organizations whose profiles are shown in Table IX. The data collection procedures complied with the ethical guidelines of the lead university.

A. Stages 1 and 2 – Identification and Categorization of Enabling Factors

The first stage was identifying and categorizing prominent enabling factors for Industry 4.0 implementation. This involved: (i) determination of factors reflecting the technology readiness perspective through a systematic literature review and (ii) validation of these factors using the *Q*-Sort technique [61]. Adopting the systematic review approach suggested by Tranfield *et al.* [62], a review panel of eight experts from industry (3 practitioners), academia (3 researchers), and government agencies (2 Thai government policy officers) was formed. Input from the expert review panel through group discussions [63] and an iterative process of identifying key themes combined with findings from the literature review guided the review process.

The emerging nature of Industry 4.0 and the relative lack of published research in relation to more established concepts implied that a wide-ranging literature review was carried out. Broader keywords including enabling factors, connectivity, smart manufacturing, digital transformation, and disruptive technologies were used in the identification of relevant literature, emphasizing the need for an unbiased search [62]. From the literature search, a range of potential enabling factors (see TABLE I) for Industry 4.0 implementation was identified with the common requirement that each enabling factor referred to the ability of an organization to implement Industry 4.0. The literature searches also identified key performance measures mentioned in studies that have examined Industry 4.0 implementation. Four measures were found to be the most common as shown in Table I – Cost reduction; Flexibility in production/service; Process stability; and Reduction of energy/pollution.

The expert review panel was asked to assign each enabling factor to the most relevant dimension of technology readiness using the Q-sort questionnaire. The experts were selected based on (i) their main roles and responsibilities involve Industry 4.0 knowledge or implementation, (ii) holding a management or academic research position, and (iii) industry experience of over 15 years. Details of the expert review panel are shown in Table II.

The opinions of the experts were used to sort each factor into dimensions of technology readiness based on the agreement between the experts. The questionnaire consisting of six dimensions and a "not applicable" (N/A) dimension and forty enabling factors are determined. In each sorting round, the experts are given a detailed definition/description of each dimension and enabling factor. The experts are then asked to match each enabling factor with one of the dimensions. Experts are also permitted to select "not applicable" if they felt that an enabling factor does not match one of the dimensions. The procedure to carry out the Q-Sort method could be summarized as below [61, 73]:

i. Calculate the coefficients of the agreement for multiple raters and multiple categories, the coefficients of agreement on a particular dimension, the percentage agreement among the experts for each item, and the item placement matrix,

ii. Evaluate the coefficients of agreement, if the coefficients of the agreement are lower than 0.65, the experts will need to be re-sorted until the value goes over 0.65.

iii. Examine the off-diagonal entries in the placement matrix.

TABLE I
PERFORMANCE MEASURES AND POTENTIAL ENABLING FACTORS IN IMPLEMENTING INDUSTRY 4.0

	Ghobakhloo [64]	Reischauer [65]	Fatorachian and Kazemi [66]	de Sousa Jabbour *et al.* [60]	Frank *et al.* [35]	Dalenogare *et al.* [67]	Majeed and Rupasinghe [68]	Moeuf *et al.* [69]	Xu *et al.* [70]	Kiel *et al.* [53]	Liao *et al.* [47]	Ivanov *et al.* [71]	World Economic Forum [36]	UNIDO [72]	Sung [30]	Kiel *et al.* [26]	Deloitte [18]	Brettel et al. [16]	Kagermann *et al.* [6]	Porter and Heppelmann [24]
Performance measures in implementing Industry 4.0																				
Cost reduction	✓			✓		✓		✓				✓			✓			✓		
Flexibility in production/service		✓									✓	✓	✓	✓		✓	✓			
Process stability				✓	✓		✓		✓		✓				✓				✓	✓
Reduction of energy/pollution	✓	✓	✓					✓					✓			✓		✓		✓
Enabling Factors in Implementing Industry 4.0																				
Standardization and reference architecture	✓				✓			✓		✓	✓			✓			✓			
Compatibility between different versions of software/hardware to connect with Internet						✓	✓		✓		✓				✓		✓			✓
Managing complex systems		✓		✓		✓	✓		✓	✓					✓			✓		
Use of open standards of Industry 4.0 technologies that facilitate coordination of operations across organizational boundaries	✓			✓				✓		✓		✓		✓	✓	✓			✓	✓
Training and continuing professional development					✓	✓	✓		✓		✓			✓		✓				✓
Ability to scale cloud infrastructures			✓					✓		✓			✓							✓
Develop and improve online communication							✓											✓	✓	
Broadband infrastructure for industry		✓			✓						✓						✓			
Automation and co-operation	✓		✓	✓		✓				✓				✓			✓			
Storing complex data and big data	✓		✓			✓			✓			✓						✓		
Single source of truth		✓			✓			✓			✓	✓			✓					✓
Motivate staff in organizations to gain new knowledge	✓								✓								✓		✓	
Effective cross-disciplinary and cross-functional collaboration						✓				✓				✓	✓	✓		✓		✓
Develop low energy wireless sensors/devices to support machine-to-machine solutions				✓	✓			✓				✓	✓							
Develop data exchange systems across devices/platforms	✓						✓				✓		✓		✓					✓
Reskill and retrain staff to use disruptive technology and knowledge			✓	✓		✓		✓								✓			✓	

TABLE I
PERFORMANCE MEASURES AND POTENTIAL ENABLING FACTORS IN IMPLEMENTING INDUSTRY 4.0 (Continued…)

	Ghobakhloo [64]	**Reischauer [65]**	**Fatorachian and Kazemi [66]**	**de Sousa Jabbour *et al.* [60]**	**Frank *et al.* [35]**	**Dalenogare *et al.* [67]**	**Majeed and Rupasinghe [68]**	**Moeuf *et al.* [69]**	**Xu *et al.* [70]**	**Kiel *et al.* [53]**	**Liao *et al.* [47]**	**Ivanov *et al.* [71]**	**World Economic Forum [36]**	**UNIDO [72]**	**Sung [30]**	**Kiel *et al.* [26]**	**Deloitte [18]**	**Brettel et al. [16]**	**Kagermann *et al.* [6]**	**Porter and Heppelmann [24]**
Enabling Factors in Implementing Industry 4.0																				
Cross-national data transfer legal and jurisdiction	✓				✓		✓					✓		✓				✓	✓	✓
Ability to reach consensus				✓					✓	✓			✓			✓				
Cross-organizational cooperation	✓	✓				✓						✓		✓						
Skills levels of employees and organizational maturity					✓		✓							✓			✓	✓		✓
Use multi-disciplinary team to implement industry 4.0 technologies			✓					✓					✓		✓				✓	
Reliability and stability of machine-to-machine communication				✓		✓				✓		✓								
Data sharing in supply chain/networks				✓			✓				✓	✓						✓		✓
Stability of internet			✓			✓			✓					✓			✓	✓	✓	
Develop comprehensive security systems which cover human, data and environment	✓	✓			✓			✓		✓	✓				✓				✓	
Well-established ecosystems to support the adoption of Industry 4.0						✓		✓			✓				✓	✓		✓		
Collaboration among interested parties – public and private partnership within a country and internationally	✓		✓	✓					✓	✓		✓	✓				✓			✓
New talent and education programs		✓	✓				✓							✓		✓		✓		
Cyber security	✓				✓			✓			✓		✓		✓		✓			✓
Intellectual Properties Right (IPR) protection	✓			✓		✓				✓		✓				✓			✓	
Ability to integrate data, functionality and processes		✓			✓								✓				✓			
IT connectivity				✓												✓				
Compatibility between different versions of software							✓		✓		✓					✓				✓
Vertical and horizontal system integration	✓					✓				✓				✓				✓		
Inter-firm networks and strategic co-operations							✓					✓			✓					✓
Democratic style of leadership	✓							✓	✓							✓				
Open communication			✓		✓									✓						
Standards and technological infrastructure		✓		✓							✓		✓						✓	
Cultural change including risk taker, entrepreneurial spirit, and failure tolerance	✓					✓	✓			✓		✓			✓					
Improve knowledge, skills and abilities of data scientists		✓		✓									✓				✓			

TABLE II
DETAILS OF EXPERTS PARTICIPATING IN Q-SORT METHOD

No	Group	Profession	Experience
1	Practitioner	VP – Manufacturing	Project Leader - Industry 4.0 Implementation, Electronics Parts/Components Mfg Company
2	Practitioner	Director – Global Supply Chain Division	Project Leader - IoT/Smart Manufacturing, Automotive Parts/Components Mfg Company
3	Practitioner	Director – Operations	Project Leader - Big Data Analytics/Cloud Computing Implementation, Retails
4	Academic	Professor	Research in the area of Sensor Technology, Robotics, Cloud Computing
5	Academic	Associate Professor	Research in the area of Robotics/Automation
6	Academic	Associate Professor	Research in the area of Smart Operations/Manufacturing/Supply Chain
7	Policy Maker	Senior Researcher	Capacity Building and Industry 4.0 Promotion Policy Development
8	Policy Maker	Senior Researcher	Set-up the Supporting Policy for SMEs to implement Industry 4.0 technologies

TABLE III
ASSIGNMENT OF ENABLING FACTORS INTO DIFFERENT TECHNOLOGY READINESS DIMENSIONS

Technology Readiness	Enabling Factors for Implementation of Industry 4.0
Dimension 1 (D1)	Stability of internet
	Promotion of business online
	Develop and improve online communication
Dimension 2 (D2)	Reskill and retrain staff to use disruptive technology and knowledge
	Improve knowledge, skills, and abilities of data scientists
	Cultural change including risk-taker, entrepreneurial spirit & failure tolerance
	Use multi-disciplinary team to implement industry 4.0 project including robotics, IoT, and big data analytic solutions
	Motivate staff in organizations to gain new knowledge
Dimension 3 (D3)	Compatibility between different versions of software/hardware to connect with the Internet
	Develop low energy wireless sensors/devices to support machine-to-machine solutions
	Develop data exchange systems across devices/platforms
	Use of open standards of 4IR technologies that facilitate coordination of operations across organizational boundaries
Dimension 4 (D4)	Ability to scale cloud infrastructures
	Storing complex data and big data
	Ability to reach consensus
Dimension 5 (D5)	Cross-organizational cooperation
	Data sharing in the value chain
	Promote Industry 4.0 in manufacturing and trade associations
Dimension 6 (D6)	Develop comprehensive security systems which cover human, data, and environment

TABLE IV
KAPPA COEFFICIENTS (K_j) FOR TECHNOLOGY READINESS DIMENSIONS

Category	K_j	$Var(K_j)$	$\frac{Kj}{SE(Kj)}$
Total	0.79	0.0023774	16.1039880
D1	0.73	0.0109875	6.9543683
D2	0.83	0.0165068	6.4749927
D3	0.67	0.0146693	5.5634289
D4	0.85	0.0111901	8.0132490
D5	0.86	0.0116156	7.9589030
D6	0.79	0.0094388	8.0971671

After 2-3 rounds of iterations (agreement between experts), nineteen enabling factors were kept (TABLE III) based on the calculation of the *Kappa Coefficient* (K_j), which is the coefficients of agreement on a particular dimension. TABLE IV presents the K values for the identified dimensions. The table shows that the Cohen's Kappa coefficient for all six dimensions was over 0.65 therefore suggesting construct validity.

B. Stage 3 – AHP Analysis of the Enabling Factors: Technology Readiness Perspective

In the third stage, AHP was used to determine the relative weight of importance among six technology readiness dimensions to achieve Industry 4.0 organizational performance [74-75]. AHP was most suited to the study because this method is a complete methodology to structure complex issues by hierarchically decomposing factors and employing scoring questions to attain judgements for both tangible and intangible qualitative criteria [76-78]. Ten experts selected from the manufacturing industry and research universities were invited to share their insight and experience in implementing and/or researching Industry 4.0. Demographic details of the experts in stage 3 are shown in Table V. Based on a range of organizational performance measures from literature (TABLE I) and confirmation of experts' opinion on organizational performance relevant for Industry 4.0, four performance measures were selected as key objective measures for evaluating the relative importance of six technology readiness dimensions. FIGURE I shows the hierarchical structure of Industry 4.0 implementation from technology readiness and performance measures.

As shown in FIGURE I, several enabling factors for Industry 4.0 implementation are used to evaluate technology readiness, from the perspective of key performance measures. Enabling factors at level 3 of AHP hierarchy were sorted and combined into relevant technology readiness dimensions, based on experts' opinions. Technology readiness dimensions and performance were evaluated using relative importance of each, based on inputs from industry experts, through AHP approach.

TABLE V
DEMOGRAPHIC DETAILS OF THE EXPERTS PARTICIPATING IN AHP ANALYSIS

No	Group	Profession	Experience
1	Academic	Associate Professor	Principal investigator (PI) research project - Robotics & Automation, and 3D printing technology, more than 15 years
2	Academic	Assistant Professor	Lab Head – IoT, Cloud Computing, and smart factory more than 10 years
3	Academic	Associate Professor	Principal investigator (PI) research project - Big Data Analytic/Cloud Computing, over 10 years
4	Industry	Factory Manager (Automotive Parts)	Project Leader - IoT implementation in supply chain (warehouse and distribution systems)
5	Industry	Director – Manufacturing (Electronics Parts)	Project Leader - Big Data Analytics and Cloud-based platform development
6	Industry	VP – Operations Electrical Appliance	Project Leader - Robotics and Automation Systems implementation
7	Industry	VP – Manufacturing (Electronics Parts)	Project Leader - IoT and Sensors (for maintenance systems) implementation
8	Industry	Director – Supply Chain (Retail)	Project Leader - IoT/Big Data Analytics in managing supply chain (Pilot project)
9	Industry	Director – Production (Automotive Parts)	Project Leader – Robotics/Automation implementation
10	Industry	VP – Global Sourcing (Electronics Parts)	Project Leader – 3D technology/Rapid Prototype/Robotics implementation

TABLE VI shows the result of the AHP analysis, indicating the relative importance of each objective measure (Level 2) and technology readiness dimension (Level 3). It is important to note that number of experts used in this study when applying the AHP method are acceptable comparing to similar studies [75], [79].

Then, a sensitivity analysis was carried out by exchanging the weights of two criteria among themselves, while the weights of other criteria remain unchanged [80-83] to analyze how changing the criteria weights influence the ranking results. In this study, since there were four performance measures, six combinations were analyzed, in which each combination was stated as a Scenario (S). Different names were given for each calculation. For example, the ‘C1-2’ meant that the weights of the 1st and 2nd performance measure were switched (while the weights of the 3rd, 4th, and 5th criteria remained the same), and this scenario was named ‘S1’. The weights of alternatives were re-calculated, and then, the alternatives were re-ranked for each scenario. The results indicate that the robustness of the overall ranking is acceptable (TABLE VII and FIGURE II). In particular, Human capital, Interoperability, and Data security indicated no movement whatsoever. On the other hand, ICT infrastructure and Data Sharing showed the most movement indicating greater sensitivity to weightings given to performance measures.

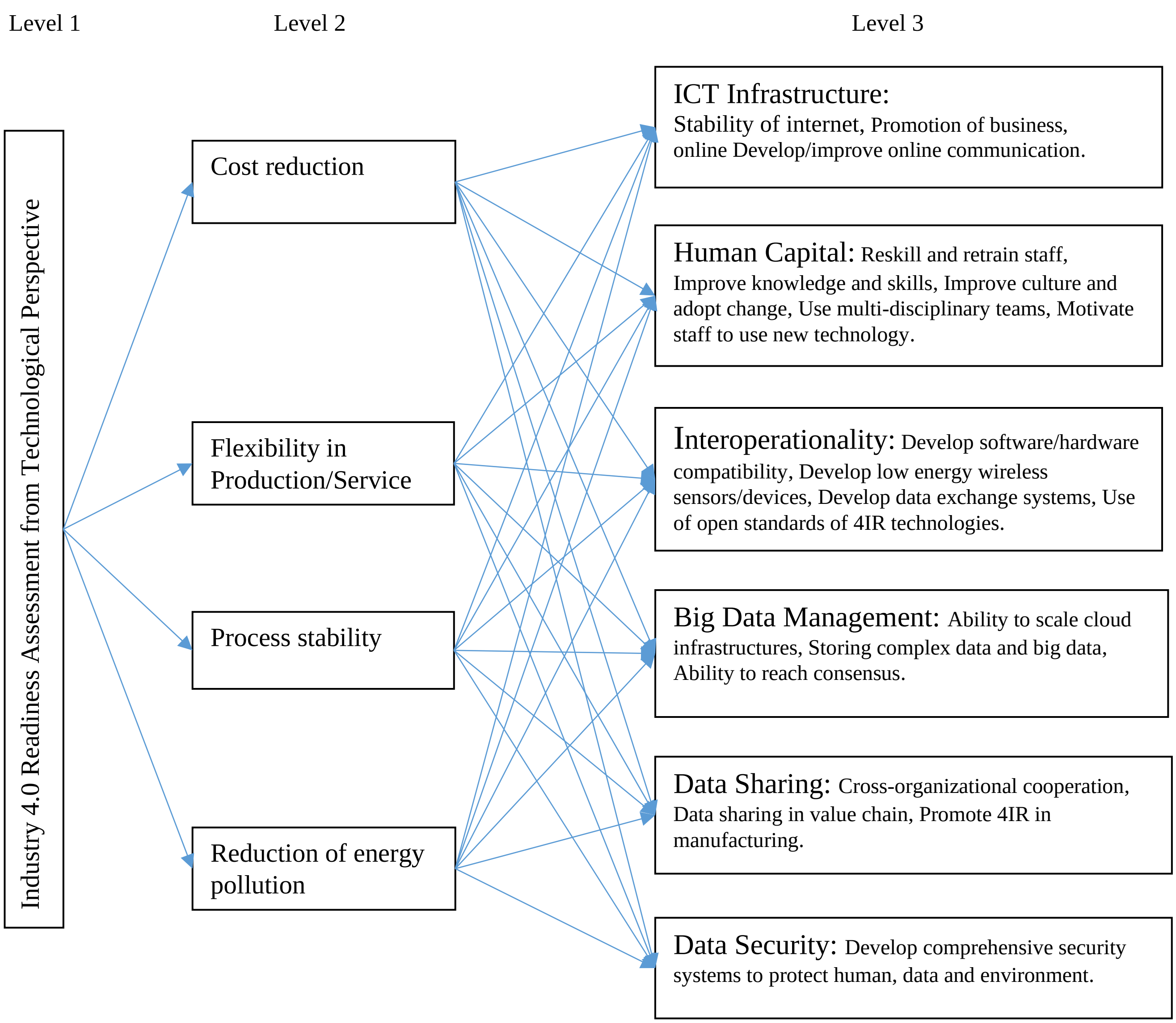

FIGURE I. Hierarchical Structure of Industry 4.0, Technology Readiness Dimensions, and Performance Measures

TABLE VI
RELATIVE IMPORTANCE OF PERFORMANCE MEASURES AND TECHNOLOGY READINESS DIMENSIONS

Technology Readiness Dimension	Performance Measures (Relative Weighted Score)			
	Cost Reduction (0.193)	Flexibility in Production/Service (0.377)	Stability of Process (0.340)	Reduction of Energy/Pollution (0.089)
D1: ICT infrastructure (e.g. Internet system)	6 (0.116)	4 (0.141)	3 (0.158)	6 (0.107)
D2: Human Capital (Ability of human capital with knowledge in technology and its adoption)	1 (0.294)	1 (0.256)	1 (0.261)	1 (0.243)
D3: Interoperationality (Ability of machine and device for connectivity through the internet)	2 (0.208)	3 (0.173)	2 (0.178)	3 (0.190)
D4: Big Data Management (Ability to manage big data)	5 (0.118)	2 (0.187)	4 (0.145)	4 (0.128)
D5: Data Sharing (Data sharing within and/or across organizations)	3 (0.143)	5 (0.136)	6 (0.120)	2 (0.207)
D6: Data Security (Ability to develop/improve data/cyber security systems)	4 (0.120)	6 (0.106)	5 (0.139)	5 (0.126)

TABLE VII
SENSITIVITY ANALYSIS RESULTS BY EXCHANGING THE WEIGHTS OF TWO PERFORMANCE MEASURES

Technology Readiness Dimensions	**Overall Weights (*Ranking*)**						
	S0 No-Change Scenario	S1 C1-2	S2 C1-3	S3 C1-4	S4 C2-3	S5 C2-4	S6 C3-4
D1: ICT Infrastructure	0.140 (4)	0.135 (5)	0.134 (5)	0.139 (5)	0.140 (4)	0.130 (5)	0.127 (5)
D2: Human Capital	0.266 (1)	0.273 (1)	0.271 (1)	0.261 (1)	0.266 (1)	0.262 (1)	0.261 (1)
D3: Interoperationality	0.183 (2)	0.189 (2)	0.187 (2)	0.182 (2)	0.183 (2)	0.189 (2)	0.187 (2)
D4: Big Data Management	0.152 (3)	0.140 (3)	0.148 (3)	0.153 (3)	0.151 (3)	0.135 (4)	0.147 (4)
D5: Data Sharing	0.139 (5)	0.129 (4)	0.142 (4)	0.145 (4)	0.138 (5)	0.158 (3)	0.160 (3)
D6: Data Security	0.121 (6)	0.123 (6)	0.118 (6)	0.121 (6)	0.122 (6)	0.126 (6)	0.117 (6)

Remark: C1: Cost Reduction, C2: Flexibility in Production/Service, C3: Stability of Process, C4: Reduction of Energy/Pollution

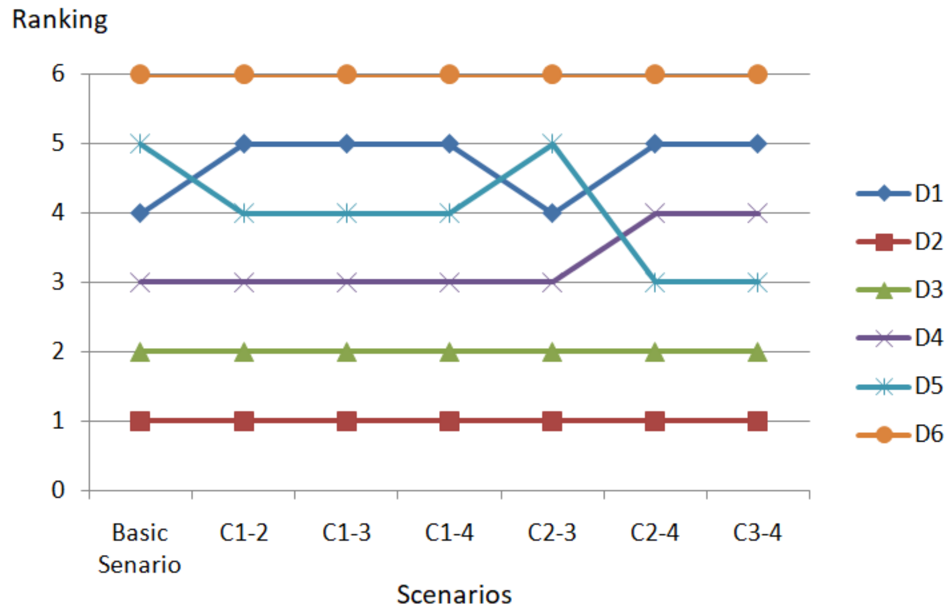

FIGURE II SENSITIVITY ANALYSIS OF RANKING RESULTS WHEN THE WEIGHTS OF TWO CRITERIA (PERFORMANCE MEASURES) WERE EXCHANGED

When a sensitivity analysis was applied by considering the different groups of experts (top management, middle management, and academic) and using the same procedure, the results (TABLE VIII and FIGURE III) also show acceptable robustness of overall ranking, especially for D2 and D3. Human Capital and Interoperability showed no changes but ICT infrastructure showed the greatest sensitivity indicating that different groups rated its influence a bit more variably

TABLE VIII
SENSITIVITY ANALYSIS RESULTS BY CHANGING THE WEIGHTS OF IMPORTANCE OF THREE EXPERT GROUPS

Technology Readiness Dimensions	**Overall Weights (*Ranking*)**						
	S0 (Basic Scenario) 1:1:1	S1 2:1:1	S2 1:2:1	S3 1:1:2	S4 2:2:1	S5 2:1:2	S6 1:2:2
D1: ICT Infrastructure	0.140 (4)	0.144 (3)	0.142 (5)	0.128 (6)	0.146 (4)	0.135 (4)	0.133 (5)
D2: Human Capital	0.266 (1)	0.280 (1)	0.260 (1)	0.271 (1)	0.270 (1)	0.279 (1)	0.263 (1)
D3: Interoperationality	0.183 (2)	0.188 (2)	0.182 (2)	0.181 (2)	0.186 (2)	0.185 (2)	0.180 (2)
D4: Big Data Management	0.152 (3)	0.144 (4)	0.154 (3)	0.152 (3)	0.148 (3)	0.147 (3)	0.155 (3)
D5: Data Sharing	0.139 (5)	0.134 (5)	0.42 (4)	0.132 (5)	0.139 (5)	0.132 (5)	0.138 (4)
D6: Develop Security	0.121 (6)	0.109 (6)	0.120 (6)	0.135 (4)	0.111 (6)	0.122 (6)	0.131 (6)

Remark: A basic scenario (top managers: middle managers: academicians weight ratio) = 1:1:1

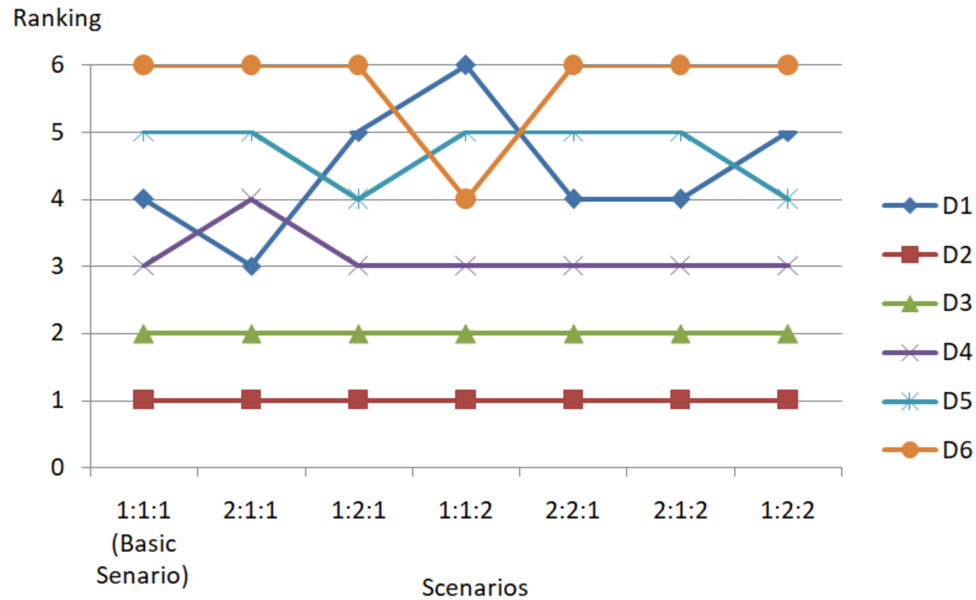

FIGURE III SENSITIVITY ANALYSIS OF RANKING RESULTS WHEN THE WEIGHTS OF THREE GROUPS OF EXPERTS WERE CHANGED

C. *Stages 4 – Semi-structured Interviews of Industry Managers*

Stage 4 involved semi-structured interviews carried out with five senior executives in organizations that are implementing Industry 4.0. The interviews aimed to provide a 'rich' data context and help to explain some of the findings from the AHP analysis. Each interview took 60 minutes and was audio-recorded. All interviewees were given the opportunity to seek clarification and ask questions about the study objectives and the interview process before the start of the interviews. The five interviewees were (i) a Director of the regional manufacturing division of a US IT equipment manufacturer with 26 years of industry experience and 4 years of Industry 4.0 implementation (W), (ii) a Director of the manufacturing division of a Japanese IT equipment manufacturer with 25 years of industry experience and 2 years of Industry 4.0 implementation (N), (iii) Vice President (VP) of the Global Manufacturing Division of a US electronics manufacturer with 22 years of industry experience and 5 years of Industry 4.0 implementation (E), (iv) VP of Global Manufacturing for a Japanese automobile manufacturer with 28 years of industry experience and 6 years of Industry 4.0 implementation (I), and (v) Director of the Regional Manufacturing Division of a Thai electronics component manufacturer with 37 years industry experience including 2 years of Industry 4.0 implementation (K). Details of each company and industry 4.0 implementation are outlined in TABLE IX.

TABLE IX
PROFILES OF COMPANIES

No	Companies that are based in Thailand	*Project*
1	***Company W*** - This is one of the world's largest data storage manufacturers. They produce data storage technology with high capacity, flexibility, and speed. Their products are at the heart of many of the world's largest data centers, and embedded in advanced smartphones, tablets, and PCs. Company *W* employs more than 70,000 people in locations worldwide, designing, developing, manufacturing and marketing their solutions for the data-driven world. With headquarters in the US, this company was established in 1970. Subsidiary in Thailand consists of two operations: Hard Disk Drive Operations and Magnetic Head Operations. Thailand is company's largest manufacturing base, where the company employs more than 1,500 engineers and scientists, and over 28,000 workers in aggregate.	IoT, Could-based Manufactu-ring Systems, Industrial Robotics, and Big Data Analytic since 2015.
2	***Company N*** – This company manufactures spindle motors for HDDs and components for spindle motors. Hard disc drives are used for a wide range of information products including PCs. The heart of these HDDs is the spindle motor. In 1979, this company put the world's first HDD spindle motor to practical use - to directly drive the disc spindle, thus replacing the conventional belt-driven method. Since then, the company has continued to introduce leading-edge technology in this field to a point where, today, this company is the leading manufacturer of spindle motors with a 70% share of the world market.	IoT, Industrial Robotics, and Cloud-based Manufacturing since 2017.
3	***Company E*** – This company is a global leader in home appliances, based on deep consumer insight and developed in close collaboration with professional users. The company offers thoughtfully designed, innovative and sustainable solutions for households and businesses, with products such as refrigerators, dishwashers, washing machines, cookers, vacuum cleaners, air conditioners, and small domestic appliances. In 2014, this company had sales of USD 12 billion and about 60,000 employees. The headquarters are located in Sweden, and one manufacturing plant is based in Thailand.	IoT, Could-based Manufactu-ring Systems, Industrial Robotics, and Big Data Analytic since 2014.
4	***Company I*** – This company started the production and sale of automotive in Thailand in the 1950s, ahead of other competitors based on trust in the potential of Thai country and people. Ever since, vehicles and diesel engines produced by this company are excellent in durability and reliability. The superior design has attracted users' attention and gained the overwhelming support of Thai consumers for years. As this company realized the trust in Thailand's potential and Thai people's capability, the company moved the production base of 1 Ton pick-up truck to Thailand in 2002. Furthermore, the company moved its R&D base of pick-up truck to Thailand in 2010.	IoT, Industrial Robotics, and Big Data Analytic Solutions since 2013.
5	***Company K*** - This company is a manufacturer and distributor of a motor compressor, reciprocating type for refrigeration products i.e. refrigerators, freezers, commercial refrigerators, and air conditioners. The company produces motor compressor by their own technology under international management systems. The company aims to be the leading ASEAN motor compressor manufacturer with high quality products, on-time delivery and competitive price. The company has continued to increase production capacity and develop new models to serve the market expansion and its requirement in ASEAN, China, Middle East, Australia, U.S., and Africa. The Company also produces a Condensing Unit which is the component of refrigeration products, electrical motor parts, and other motor compressor parts. The Company and other investors invested and established 6 new companies to produce major parts and raw materials of the compressor to replace the import and local purchasing to reduce the production costs and to improve product quality, and aim to be the leader in the motor compressor business in ASEAN.	IoT and Industrial Robotics since 2018.

IV. Results and Findings

The results from the study are presented in two sections. First, the results from the AHP analysis are presented. This includes the ranking and the relative importance of the identified six technology readiness dimensions associated with enabling factors as well as the overall ranking of technology readiness dimensions for Industry 4.0 readiness, based on the relative importance of each performance measure. In the second section, key insights from the semi-structured interviews are also presented.

A. Findings from AHP Analysis

Table VI presents the findings from the AHP analysis. It shows that Flexibility in Production/Service was identified as the most important dimension of performance with a weighting of 0.377 followed by Stability of Process (0.340). The third ranked performance measure was Cost Reduction (0.193) while the least ranked was Reduction of Energy/Production (0.089). The ranking of the technology readiness dimensions for each of the performance measures is presented as follows.

With respect to *Cost Reduction*, Human capital (0.294) was the most important technology readiness dimension followed by Interoperationality (0.208) and Data sharing (0.143). The fourth most important technological dimension was the Cyber/Data security system (0.120) followed by Big data management (0.118) while ICT Infrastructure (0.116) was the least ranked.

For *Flexibility in Production/Service*, Human capital (0.256) was also the highest ranked followed by Big data management (0.187) and Interoperationality (0.173). The fourth most important technology readiness dimension was ICT infrastructure (0.141) followed by Data sharing (0.136) while Cyber/Data security system (0.106) was the least ranked.

With respect to *Stability of Process*, Human capital (0.261) was the most important technology readiness dimension followed by Interoperationality (0.178) and ICT Infrastructure (0.158). The fourth most important technology readiness dimension was Big data management (0.145) followed by Cyber/Data security system (0.139) while Data sharing (0.120) was the least ranked.

Finally, for *Reduction of Energy/Pollution*, Human capital (0.243) was again ranked highest followed by Data sharing (0.207) and Interoperationality (0.190). The fourth most important technology readiness dimension was Big data management (0.128) and Cyber/Data security system (0.126) while ICT infrastructure (0.107) was the least ranked.

When looking holistically across all four performance measures and their relationships with the technology readiness dimensions, Table VI presents some interesting insight. Without doubt, Human capital was the most important technology readiness dimension while Interoperationality was generally the next most important. The two data handling dimensions (Big data management and Data handling) were overall next in importance. In contrast, the two technology systems dimensions (Cyber/Data security system and ICT infrastructure) were not generally considered as important as the others

B. *Findings from Semi-Structured Interviews*

The semi-structured interviews enabled clarification of the views of industry practitioners regarding Industry 4.0 technology readiness dimensions. Particular emphasis was placed on understanding why highly ranked technology readiness dimensions were so highly regarded. From the AHP analysis, the most highly ranked dimension was Human capital. Comments from the respondents indicate that human capital must be considered early in the Industry 4.0 journey since the employees will be required to operate in the new environment and the possession of the right skills and attitude are critical to success. According to Interviewee K,

> *"Before implementing the industry 4.0 strategy, our top management considered the competencies of employees/operators as the ability of a person to operate in a reflective and autonomous manner. It also includes the ability to learn, to develop an ownership attitude and ethic."*

While Interviewee I noted,

> *"In implementing Industry 4.0 strategy, employees/operators are responsible for a broader process scope and need the ability to understand the relations among processes, information flows, disturbances, and potential solutions to such interfaces."*

The interviews indicated that one of the reasons why human capital was so highly ranked was the relative scarcity of Industry 4.0 related skills among the workforce. As an emerging technology, not many employees or organizations have had the opportunity to acquire the requisite skills. According to Interviewee W,

> *"There's a need for talent with advanced technological skills to work with new technologies in settings ranging from smart factories to networked supply. However, since these skill sets are relatively new, they're in low supply especially in emerging economies country."*

The interviewees all stressed the importance of interoperationality. However, their emphases differed from one another. While some interviewees stressed inter-organization compatibility, others were more focused on intra-organization connectivity. The following statements were made in this respect:

> *"Compatibility or interoperationality among standard's devices and platforms is crucial for our Industry 4.0 implementation project. We must ensure that all business partners (suppliers, customers, and third-party service provider) can exchange and share information using a common language across a common interface".* Interviewee I

> *"Interoperability between the manufacturing software, shop–floor operations, and the processes performed by different equipment is one of the most important issues for the project team to consider to design an efficient and effective 4IR project. This includes the synchronization among automation devices-cloud services/platforms and users."* Interviewee E

However, the interviewees were clear that there needs to be more progress for reaching a common standard for Industry 4.0 Technology. For example, Interviewee N stated,

> *"We believe that one of the most effective approaches in implementing industry 4.0 strategy is the application of open standards or platforms such as IEEE, ISO/IEC, and NIST."*

Without a doubt, Industry 4.0 technologies are based significantly on the ability to manage and use data. Hence, data handling is a core component of the deployment of these technologies. According to Interviewee W,

> *"Before making a big investment in implementing Industry 4.0 in our company, the project team realized that any digital transformation (i.e. Internet of Things, artificial intelligence, or robotics)*

required stable and capable data services platforms via cloud infrastructures".

Interviewee I noted that there is a multitude of data documented in organizations and it is important to determine, exactly what data will be most useful. The interviewee further expressed the importance of inclusivity of internal data owners. Perhaps, more importantly, they expressed the need to consider setting up an organizational function to manage the data requirements of Industry 4.0. They stated as follows:

"To implement 4IR solutions/platforms, every business unit involved must be able to participate in making decisions on the variety of data transmitted and retrieved via different functions within the company and across the supply chain. Hence, Central Data and Analytics Unit has been established in our company to handle this task."

V. Discussion

This study set out to identify and rank the factors that enable technology readiness for the implementation of Industry 4.0 and how these factors would impact different dimensions of organizational performance. The findings of this study are important within the context of the need for manufacturing organizations to integrate technology into their operations to improve their capabilities and productivity. Industry 4.0 has been credited with the potential to improve productivity and organizational performance [31, 33]. Hence research on technology readiness dimensions that can improve the manufacturing capabilities and hence organizational performance within the context of Industry 4.0 can make significant contributions to academic knowledge as well as industry practice [31, 33]. The key insights and contributions from the study are discussed as follows.

A. The Primacy of Human Capital

Many extant studies (e.g. [8], [35]) have highlighted the challenges that evolution technological development poses to the implementation of Industry 4.0. However, this study is emphatic in its findings that technological issues are not the most important enablers of performance. Rather it is the softer issue of human capital and the development of requisite skills for Industry 4.0 that are most important. While Davis [32] suggested that the poor skills level of employees can negatively affect digital manufacturing, this study has gone further to highlight two important factors. First, human capital is more important than all other factors considered. Secondly, the primacy of human capital is uniform across all dimensions of performance measurement. The suggestion, therefore, is that irrespective of whatever performance an organization seeks from the implementation of Industry 4.0 technologies, the most important enabling factor that needs to be considered is human capital and the abilities of employees to manage the technological transition.

The interviews confirmed that the importance of human capital was due to the need to take ownership of the technological deployment process and the relative scarcity of requisite skills among employees. Therefore, the suggestion is that while there has been much emphasis on the development of technology, there has not necessarily been an equivalent emphasis on developing the employee skills needed to deploy these technologies. Based on these findings, the authors would propose that if Industry 4.0 is to be as widely adopted as currently forecasted, then there will need to be a significant development of employees' technological skills and understanding of Industry 4.0 to enable employees to take ownership.

B. The Necessity of Interoperationality

Based on the AHP analysis, interoperationality was ranked second highest overall and significantly higher than the two dimensions associated with data handling. The second highest ranking given to interoperationality, puts into context, the findings from previous studies. The base premise and aim of Industry 4.0 are to develop machines and equipment that can operate in an internet-enabled environment and connect with one another and the wider world [1], [23]. Hence, interoperability is central to Industry 4.0 success. The interviews confirmed the importance of interoperability and it was indicated by one of the interviewees that it is an issue to be considered at the design stage. However, it was also indicated in the interviews that there is still a lack of agreed open standards for interoperationality. The challenges of common standards and open infrastructure have also been identified in the literature (e.g. [14], [36]). Therefore, the centrality of interoperability to the implementation of Industry 4.0 and the current lack of commonly agreed standards are key issues why it is such an important consideration to organizations implementing Industry 4.0. However, it is likely that once common standards and protocols are agreed upon and accepted, then interoperability may become less of a concern for Industry 4.0 implementation.

C. Data Handling is Key

The Internet has played a key role in societal change by enabling efficient transfer of data. All sectors of society have benefitted greatly from internet enabled transfer of data and a major industry has developed with respect to the generation and handling of data. This study indicates that the ability to manage and share data are important readiness dimensions of Industry 4.0. Sirkin *et al.* [15] had indicated that massive amounts of data were required to drive the smart machines that will dominate Industry 4.0 hardware. The interviews confirmed that stable data systems are important and there is a suggestion that a separate data handling function within organizations would be needed for Industry 4.0 data management. Hence, the transformation of society through the generation and management of ever-increasing data will continue with Industry 4.0 implementation.

D. The Relative Importance of Hardware

The study shows that the technology systems dimensions - Cyber/Data security system and ICT infrastructure were the least important of the six readiness dimensions. Although it is clear that the Industry 4.0 requires transmission over the internet, the ability of the internet infrastructure to manage this is not a major concern. This may be because of the established pattern of innovation in internet capacity (e.g. 5G technology). Similarly, while Industry 4.0 involves transmission of data over the internet and internet security is an important challenge to deployment of Industry 4.0 [14, 64], it is not deemed to be as important as most of the other technology readiness dimensions. This may also be because the issue of cyber security is already prominent in current internet use as it entails many sensitive industry sectors including finance, banking, defense, industry, etc. Hence the authors conclude that implementation of Industry 4.0 generally aligns and/or fits in with current socio-technical considerations in ICT infrastructure and cyber security and as such, industry practitioners may not feel the need for particular efforts related to Industry 4.0.

E. Industry 4.0 and Environmental Sustainability

According to Baur and Wee [21], smart energy consumption should be an important lever for Industry

4.0 implementation. However, the findings from this study suggest otherwise. The AHP analysis clearly shows that of the four different performance measures, Reduction of Energy/Pollution was significantly lower than the other three dimensions. The implication is that despite the significant global emphasis on environmental sustainability and the need for organizations to consider the impact of their operations on the environment, the reduction of energy use and pollution is not seen as very important when considering desired outcomes of Industry 4.0 implementation. Therefore, at this time, process performance outcomes such as process stability and production flexibility are considered to be significantly more important than environmental outcomes based on the findings of this study. It is unclear what implications this may have for societal acceptance of Industry 4.0 technologies if deployment of such technologies turns out to have negative environmental outcome connotations.

VI. Conclusion

Using AHP analysis interviews, the study identified that human factors were regarded as the most important readiness factor for Industry 4.0 implementation. This finding is important because many previous studies (e.g. [8] [16] [35] [60]) have focused on technology-based factors as key for Industry 4.0 success. The study also found that interoperability and data handling were next in importance. On the contrary, hardware and technology systems factors such as data security and ICT infrastructure were seen as the least important of the technology readiness factors.

The interviews confirmed that Industry 4.0 technology is either being implemented or has been implemented by organizations in developing countries such as Thailand. In implementing these technologies, the organizations experienced and overcame some challenges and were able to provide a rich data context to the rankings identified in the AHP analysis. The interviews specified the importance of identifying and putting in place readiness factors before implementing Industry 4.0 technologies.

The study has important industry and theoretical implications. For industry managers, the study is emphatic in its findings that significant attention has to be placed on the development of human capital and the skills necessary for Industry 4.0 success. The study also highlighted the importance of interoperationality. The implication is that technology developers and industry adopters need to be deliberate in their actions to not only ensure that different Industry 4.0 technologies and components can interact but also that organizations in a supply chain ensure compatibility with their interacting organizations.

The study also has implications for academic and theoretical understanding of Industry 4.0 readiness. In particular, it is important to identify and understand the theoretical underpinnings of Industry 4.0 technology readiness. The finding that human factors are important to suggest that the resource-based view (RBV) theory may be a relevant underpinning theory by considering skills for Industry 4.0 as rare, valuable, and inimitable in fostering success. The importance of interoperationality characterized by compatibility and connectivity is supported by the theoretical framework for operationalization of Industry 4.0 in manufacturing [66]. In this context, interoprationality is an integral part of the operationalization framework and is supported by systems theory where the application of Industry 4.0 technological innovations can enable smart detection and connectivity on the production floor through the creation of CPSs, their communication mechanisms, and the resulting comprehensive integration [66]. Based on systems theory, technologies can allow systems to easily search for dynamic and intelligent IT-based systems and to autonomously connect/communicate with them [84]. The theoretical connection of interoperationality with system theory is further evidenced from the notion of the ability of advanced technologies to create great value for manufacturing companies through enabling smart operations and comprehensive integration of technological innovations and manufacturing systems [85-86].

Future studies will be important to further develop an understanding of Industry 4.0 implementation. Such studies could investigate the identified enabling factors in greater qualitative depth. Future research could also analyze the impact of differences between developed and developing economies within the context of Industry 4.0 implementation. Finally, future studies could investigate the organizational co-implementation of Industry 4.0 with other initiatives (e.g. sectoral and country level Industry 4.0 roadmap and promoting/supporting policy).

ACKNOWLEDGEMENTS

This research was supported by the Bualuang ASEAN Chair Professorship Scheme and Thammasat School of Engineering, Thammasat University, Thailand.

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