Universidade do Minho
Escola de Economia e Gestão

Hussein Magdy Elhusseiny.

Industry 4.0 Adoption in Manufacturing SMEs: An Empirical Study on Cairo SMEs.

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Industry 4.0 Adoption in Manufacturing SMEs: An Empirical Study on Cairo SMEs.

Doctoral Thesis in Business Administration.

Work developed under the supervision of

Professor José António Crispim.

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To my Parents, I'm really hoping you're proud of me!...

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Published a research paper titled *"SMEs, Barriers and Opportunities on adopting Industry 4.0: A Review.",* Procedia Computer Science, Volume 196, 2022, Pages 864-871, ISSN 1877-0509, https://doi.org/10.1016/j.procs.2021.12.086. (https://www.sciencedirect.com/science/article/pii/S1877050921023097).

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Published a research paper titled *"A Review of Industry 4.0 Maturity Models: Theoretical Comparison in The Smart Manufacturing Sector."* 5th International Conference on Industry 4.0 and Smart Manufacturing - ISM 2023.

Reviewed a conference paper titled *" A Comparative Analysis of Digital Maturity Models to Determine Future Steps in the Way of Digital Transformation"* for the 5th International Conference on Industry 4.0 and Smart Manufacturing - ISM 2023.

Reviewed a Journal paper titled *"Assessing the Readiness for Industry 4.0 of Metalworking Companies: evidence in the South of Brazil"* for the Int. J. of Technological Learning, Innovation and Development.

Magdy Elhusseiny, H., & Crispm, J. (2025). *"Assessing Industry 4.0 adoption in Cairo SMEs: a study on manufacturing sector".* International Journal of Computer Integrated Manufacturing, 1–22. https://doi.org/10.1080/0951192X.2025.2545481

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INDUSTRY 4.0 ADOPTION IN MANUFACTURING SMES: AN EMPIRICAL STUDY ON CAIRO SMES.

ABSTRACT

The adoption of Industry 4.0 (I4.0) technologies presents substantial opportunities for manufacturing small and medium-sized enterprises (SMEs) to enhance productivity, foster innovation, and compete globally. However, the transition to I4.0 presents numerous challenges, particularly in developing regions such as Cairo, Egypt. This doctoral thesis investigates the adoption of I4.0 in manufacturing SMEs in Cairo, with the objective of developing a customized maturity model (MM) that accommodates their unique financial, technological, and organizational constraints.

This study conducts an extensive review of existing literature and critically evaluates 16 I4.0 maturity models (MMs) to identify key dimensions and maturity stages tailored to the needs of SMEs. Subsequently, a two-round Delphi survey involving 19 industry experts from diverse sectors, including automotive, textiles, metals, electrical equipment, and food & beverages, was conducted. The first round assesses the current ICT levels, key IT systems, and requisite skills for implementing I4.0 among Cairo SMEs, while the second round identifies the preferred dimensions and maturity items to construct a tailored MM.

The findings indicate a moderate level of ICT adoption, with extensive utilization of ERP systems but limited integration of more advanced technologies such as IoT, Big Data, and CPS. Through expert validation, the research underscores eleven essential dimensions critical to digital transformation, including organizational strategy, smart factory operations, employee development, leadership, and information systems. The developed model delineates five progressive maturity stages: Initial, Foundation, Progress, Managed, and Maturity; providing SMEs with a systematic guide to achieving digital transformation aligned with their operational realities.

Keywords: Industry 4.0, SMEs, Manufacturing, Maturity Model, Cairo, ICT Adoption, Delphi Method.

RESUMO

An adopção das tecnologias da Indústria 4.0 (I4.0) representa oportunidades significativas para as pequenas e médias empresas (PME) do sector industrial aumentarem a sua produtividade, inovarem e competirem a nível global. No entanto, a transição para a I4.0 coloca diversos desafios, especialmente em regiões em desenvolvimento como o Cairo, Egipto. Esta tese de doutoramento investiga an adopção da I4.0 nas PME industriais do Cairo, com o objectivo de desenvolver um modelo de maturidade (MM) adaptado às suas limitações financeiras, tecnológicas e organizacionais específicas.

Este estudo realiza uma revisão exaustiva da literatura existente e avalia criticamente 16 modelos de maturidade da I4.0 (MM) com vista a identificar dimensões-chave e estágios de maturidade ajustados às necessidades das PME. Posteriormente, foi conduzido um inquérito Delphi em duas rondas, envolvendo 19 peritos da indústria de vários sectores, incluindo automóvel, têxtil, metalomecânico, equipamentos eléctricos e alimentar e bebidas. A primeira ronda avalia os níveis actuais de TIC, os principais sistemas de TI e as competências necessárias para a implementação da I4.0 entre as PME do Cairo, enquanto a segunda ronda identifica as dimensões e os itens de maturidade preferidos para construir um modelo personalizado.

Os resultados revelam um nível moderado de adopção de TIC, com uso generalizado de sistemas ERP, mas com integração limitada de tecnologias mais avançadas, como a IoT, Big Data e sistemas ciber-físicos (CPS). Através da validação dos peritos, a investigação identifica onze dimensões essenciais para a transformação digital, como por exemplo: estratégia organizacional, operações de fábrica inteligente, desenvolvimento dos colaboradores, liderança e sistemas de informação. O modelo desenvolvido define cinco estágios progressivos de maturidade: Inicial, Fundação, Progresso, Gerido e Maduro; oferecendo às PME um guia faseado para alcançar a transformação digital, alinhado com as suas realidades operacionais.

Palavras-Chave: Indústria 4.0, PME, Manufatura, Modelo de Maturidade, Cairo, Adoção de TIC, Método Delphi.

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List of Abbreviations and Acronyms

Artificial Intelligence
AI
Augmented Reality
AR
Big Data Analysis
BDA
Benefit-of-the Doubt
Computer Aided-Design
CAD,
Customer Relationship Management
CRM
Cyber Physical System
CPS
Capability Maturity Model
CMM
Capability Maturity Model Integration
CMMI
Electronic data interchange
EDI
Enterprise Resource Planning
ERP
Industry 4.0
I4.0
Industry 5.0
I5.0
Information and Communication Technology
ICT
Information Systems
IS
Information Technology
IT
Internet of Things
IoT
Machine to Machine communication
M2M communication
Manufacturing Execution Systems
MES
Master of Business Administration
MBA
Maturity Model
MM
Product Data Management
PDM
Product Lifecycle Management
PLM
Public Private Partnerships
(PPPs)
Research questions
RQs
Small and Medium Enterprises
SMEs
Tourism Digital Maturity Model
TDMM
Technology Acceptance Adoption
TAM
Technology Organization Environment
TOE
Warehouse Management Systems
WMS

1. CHAPTER ONE: INTRODUCTION

1.1 Background

The Fourth Industrial Revolution known as Industry 4.0 (I4.0) epitomizes profound technological integration like cyber physical systems (CPS), Internet of Things (IoT), artificial intelligence (AI), big data analytics (BDA), and advanced robotics within contemporary Industrial and service domains (El Kadiri et al., 2016; Frank et al., 2019; Kolla et al., 2019; Lampropoulos et al., 2019; Lu & Weng, 2018; Manavalan & Jayakrishna, 2019; Oztemel & Gursev, 2020; Pacchini et al., 2019; R. D. Raut et al., 2019; Zhong et al., 2017).

These technologies synergistically foster unprecedented levels of automation, customization, and operational efficiency, redefining competitive advantage through the digitalization of production and services (Beier et al., 2020; Frank et al., 2019).

Global momentum behind I4.0 is evident: developed economies and enterprises are investing significantly to exploit these advancements, aiming to enhance resilience, sustainability, productivity, and cost-effectiveness in increasingly volatile markets (Stock & Seliger, 2016). Moreover, I4.0 integration aligns with sustainable and circular economy objectives; enabling resources optimization, energy efficiency, and waste minimization (Moeuf et al., 2020).

However, the path of I4.0 adoption sharply diverges between developed and developing countries. As emerging economies often contend with information and communication technologies (ICT) Infrastructure deficits, digital skills shortage, financial constraints (Touijer & Elabjani, 2025), fragmented digital ecosystems, and organizational complexities (Sony & Naik, 2020). Consequently, their digital transformation trajectories are uneven and less mature compared to developed countries (Tortorella et al., 2021).

As mentioned by (Mittal, Romero, et al., 2018) small and medium-sized enterprises (SMEs) in the manufacturing sector have consistently been regarded as the economic backbone for both developed and developing nations (Husin & Ibrahim, 2014; Mittal, Romero, et al., 2018; Tuyon et al., 2011). However, their perspective has not always been considered when adopting I4.0 technologies. Similarly, emerging smart manufacturing projects, such as the U.S. smart manufacturing initiatives, Germany's Indudtrie 4.0, and South Korea's Smart Factory strategy, exhibit some common patterns (Akdil et al., 2018; Mittal, Romero, et

al., 2018). These initiatives aim to stimulate economic development by implementing the key technologies of I4.0, including CPS, AI, IoT, BDA (Frank et al., 2019; Mittal, Romero, et al., 2018). However, they lack guidance specifically tailored to SMEs (Mittal, Khan, et al., 2018; Touijer & Elabjani, 2025).

The absence of SME-focused considerations poses a risk of hindering their digital transformation, which could ultimately hinder broader technological innovation and the establishment of an integrated smart manufacturing (Elhusseiny & Crispim, 2023; Mittal, Romero, et al., 2018; Touijer & Elabjani, 2025).

Thus, I4.0 presents significant opportunities for SMEs by promoting innovation and global competitiveness through the adoption of cutting-edge ICT (Müller & Voigt, 2018). Authors like Pacchini et al., (2019) mentioned I4.0 enabling technologies like IoT, CPS, cloud computing, big data, autonomous robots, additive manufacturing, and augmented reality.

Besides, previous studies summarized I4.0 enabler technologies as follows:

- Internet of things (IoT): The connection between sensors, machines, and devices enables objects to collect and exchange data. (Oztemel & Gursev, 2020b; Pacchini et al., 2019). In addition, IoT is used to collect data and monitor actions within the production environment, with the goal of solving business problems and enhancing customer services. (Lu & Weng, 2018).
- Big data analysis (BDA): It's an environment where a large amount of data (through IoT) is stored. (Pacchini et al., 2019), BDA is also used to create value from information. It optimizes the data generation process, suggests data integration from multiple sources, integrates various types of findings into business processes, and visualizes data to enhance decision-making. (El Kadiri et al., 2016; R. D. Raut et al., 2019).
- Cyber Physical System (CPS): An interconnected system managed by an information system facilitates the interaction between physical and digital objects. (Zhong et al., 2017). This interconnected system enables the production and management of the complexity of customized products by integrating the digital world (e.g., software, cloud computing, data analysis) with the physical world (Kolla et al., 2019) with information technology (Manavalan & Jayakrishna, 2019).
- Cloud computing: It plays a significant role in enhancing and transforming the current industry by connecting many computer servers and information. (Lampropoulos et al., 2019) to store data that facilitate real-time communication and information exchange across multiple manufacturing sites using cloud technology. (Manavalan & Jayakrishna, 2019; Moeuf et al., 2018).

- Autonomous robot: Robots that can interact intelligently and flexibly with each other and humans in their working environments are being developed. (Pacchini et al., 2019).
- Additive manufacturing (AM): This technology, also known as "3D-printing," enables the small-scale production of customized and complex parts. (Pacchini et al., 2019).
- Augmented reality (AR): The real operations and simulation industries emerged together to provide some benefits, especially in product design. AR is considered one of the cutting-edge technologies of I4.0, particularly in creating a smart manufacturing environment. (Oztemel & Gursev, 2020). Furthermore, this technology enables human interaction with virtual objects that co-exist with a physical environment virtually (Pacchini et al., 2019).
- Artificial intelligence (AI): This technology enables manufacturing systems to intelligently perceive the environment in which they are deployed and make real-time decisions about when to perform a specific operation. (Pacchini et al., 2019).

Based on the previously mentioned I4.0 technologies, benefits, and opportunities, I4.0 is crucial for economic development, industrial growth, and ensuring sustainable supply chains (SC). Besides, as authors have mentioned, I4.0 introduces revolutionary methods to production by merging information technology (IT) with manufacturing processes.

> *"Industry 4.0 combines embedded production system technologies with intelligent production processes to pave the way for a new technological age that will fundamentally transform industry value chains, production value chains, and business models"* (Zhong et al., 2017, p.615).
>
> *"The networking of people and things and the convergence of the real and virtual worlds enabled by Information and Communication Technology (ICT)"* (Kolla et al., 2019, p.754).
>
> *"The convergence of industrial production and information and communication technologies, called Industrie 4.0"* (Hermann et al., 2016, p.3928).
>
> *"Smart Manufacturing, the fourth revolution in the manufacturing industry considered a new paradigm, is the collection of cutting-edge technologies that support effective and accurate engineering decision-making in real-time through various ICT technologies converging with existing manufacturing technologies"* (Kang et al., 2016, p.111).

> *"In essence, Industrie 4.0 will involve the technical integration of CPS into manufacturing and logistics and the use of the Internet of Things and Services in industrial processes, affecting value creation, business models, downstream services, and work organization"* (Müller, Kiel, et al., 2018, p.1128).
>
> *"Industry 4.0 comprises a variety of technologies enabling the development of a digital and automated manufacturing environment and the digitization of the value chain"* (Oesterreich & Teuteberg, 2016, p.122).
>
> *"Industry 4.0 involves the development and integration of innovative information and communication technologies into the industry"* (Barreto et al., 2017, p.1246).

Manufacturing SMEs in Egypt play a crucial role in the national economy and have recently benefited significantly from the country's robust digital transformation (Buza & Taha, 2025; ITIDA, 2025). The ICT sector, which forms the backbone of the digital ecosystem, experienced remarkable growth, with a 14.4% increase in fiscal year 2023/2024, anchoring its position as the fastest-growing sector in Egypt (Buza & Taha, 2025; ITIDA, 2025).

Furthermore, Egypt's ICT market is projected to achieve substantial growth, with an estimated increase from USD 23.6 billion in 2023 to USD 53.1 billion in 2030 (Mordor Intelligence, 2025). This growth is attributed to various factors, including investments such as the Digital Egypt initiatives, the establishment of large-scale data centers, and Egypt's strategic position as a hub for multiple submarine cables (Mordor Intelligence, 2025).

Within this expanding market, SMEs are exhibiting one of the most remarkable growth trajectories, with a projected compound annual growth rate (CAGR) of approximately 16%. This indicates a growing adoption of ICT services among SMEs (Mordor Intelligence, 2025).

Furthermore, the 2025 OECD review of SME and entrepreneurship policy in Egypt demonstrates the importance of providing customized support through government and stakeholders, to improve access to digital infrastructure, enhance employees' digital skills and data literacy, manage cybersecurity risks, foster more open and functional markets for digital goods and services (OECD, 2025). These measures will significantly enhance digital transformation among SMEs. (OECD, 2025).

Despite the previously said challenges, manufacturing SMEs face a range of technological barriers that hinder their digital transformation and competitiveness (Aboelmaged, 2018; Elziaty et al., 2024). Recent data demonstrates that digitalization among Egyptian SMEs still in its infancy, with limited adoption of

advanced systems such as enterprise resource planning (ERP), manufacturing execution systems (MES), and customer relationship management (CRM) (OECD, 2025).

In addition, there's a significant gap in the integration between information technology and operational technology (*Egypt Overview: Development News, Research, Data | World Bank*, n.d.). Innovation progress within manufacturing SMEs is low; as according to the World Bank Enterprise Survey, only 1.5% of small enterprises introduced a new product or service in 2020, and just 1.3% reported using technology licensed from foreign countries (*Egypt Overview: Development News, Research, Data | World Bank*, n.d.).

These rates are considerably lower than those of large firms (*Egypt Overview: Development News, Research, Data | World Bank*, n.d.). Furthermore, SMEs report persistent shortages of advanced digital skills and data literacy, which significantly hinder their ability to implement and maintain digitalization effectively (OECD, 2025).

This is due to the limitations of governmental support which further exacerbates these challenges, as many initiatives lack coordination and specific targeting for the manufacturing sector (OECD, 2025).

Also, recent empirical studies, such as (Elziaty et al., 2024) demonstrate that technological and infrastructure constraints remain substantial barriers to e-commerce and digital business model adoption, despite their strong link to improving SME performance (Elziaty et al., 2024). Collectively, these findings indicate that without addressing technology adoption gaps, workforce readiness, and policy coordination, manufacturing SMEs may struggle to achieve meaningful progress toward I4.0 maturity.

1.2 Research Justifications

Industry 4.0 has created a significant strategic Imperative for the global manufacturing sector (Touijer & Elabjani, 2025), rendering traditional approached insufficient to meet contemporary market demands (Mittal et al., 2018). While large enterprises have increasingly leveraged I4.0 to enhance competitiveness, SMEs face substantial hurdles in navigating this complex and resource intensive transition (Horváth & Szabó, 2019; Luthra & Mangla, 2018; Mittal, Khan, et al., 2018; Touijer & Elabjani, 2025).

This challenge is particularly acute in Egypt, where SMEs form the backbone of the industrial economy, yet their adoption of I4.0 remains fragmented and nascent (Abd El Aziz & Kandil, 2018; Aboelmaged, 2018; 'OECD Economic Surveys: Egypt 2024', 2024). The failure of these manufacturing SMEs to modernize poses a direct threat to the nation's economic resilience and growth (Moussa & Tarek, 2023).

Moreover, previous studies like Javaid & Haleem, (2019); S. S. Kamble, Gunasekaran, & Sharma, (2018); Luthra & Mangla, (2018) suggested that although I4.0 adoption can enhance operational performance, and product innovation, however, the barriers like lack of IT Infrastructure, poor management support, digital operations, qualified workforce, financial constraints, cybersecurity, integrated database, governmental support, research, and development (R&D) (Luthra and Mangla, 2018; Mittal et al., 2018; Horváth and Szabó, 2019) remain persistent, specifically for SMEs (Luthra & Mangla, 2018; Mittal, Khan, et al., 2018).

Furthermore, existing I4.0 maturity models (MMs) are often too generic or designed for the realities of large, well-resourced enterprises in developed countries, making them unsuitable for SMEs in a developing context like Egypt (Akdil et al., 2018; Magdy Elhusseiny & Crispim, 2023; Mittal, Khan, et al., 2018; Schumacher et al., 2016).

Despite global understanding of digital transformation, Egyptian manufacturing SMEs lack a validated MM that captures their technological, organizational, and cultural readiness (Aboelmaged, 2018; SME and Entrepreneurship Policy in Egypt: SME Digitalisation in Egypt | OECD, n.d.).

Existing models are not suited to their context, offering limited diagnostic tools and strategic utility (Elhusseiny & Crispim, 2023; Magdy Elhusseiny & Crispim, 2023; Mittal, Khan, et al., 2018). Without a contextually grounded model, SME managers and policymakers are unequipped to assess maturity, benchmark progress, or plan digital Interventions effectively (Elhusseiny & Crispim, 2023; Magdy Elhusseiny & Crispim, 2023; Mittal, Khan, et al., 2018).

Therefore, this research study is justified by the critical need to bridge this gap, by developing and empirically validating a MM customized for Cairo manufacturing SMEs.

1.2.1 The Role of Maturity Models in Industry 4.0 Transformation

To navigate the complex journey of I4.0 adoption, manufacturing enterprises require structure guidance. Maturity Models (MMs) have emerged as critical instruments for this purpose, serving as both a diagnostic tool and a strategic roadmap (Akdil et al., 2018; Mittal, Khan, et al., 2018; Schumacher et al., 2016).

The primary function of I4.0 MM is to provide a structured framework for an enterprise to assess its current capabilities against a defined evolutionary path, thereby identifying critical gaps between its current state and its digital transformation goals (Mittal, Khan, et al., 2018). Moreover, MMs serve as critical tools

to help manufacturing enterprises, including SMEs, effectively navigate the complex journey of I4.0 adoption. Here are the key reasons for using I4.0 MMs:

1. Industry 4.0 manufacturing maturity models are crucial for several reasons. They provide a structured approach to evaluate and guide the adoption of Industry 4.0 technologies within manufacturing enterprises. (Akdil et al., 2018; Mittal, Khan, et al., 2018; Schumacher et al., 2016). By evaluating the maturity levels, companies can identify their current position in the I4.0 journey and understand the gaps that need to be addressed to advance towards full digital transformation. This process is essential for companies to remain competitive in a rapidly changing industrial landscape (Akdil et al., 2018; Mittal, Khan, et al., 2018; Schumacher et al., 2016).
2. Maturity models assist in setting clear goals and developing roadmaps for technology implementation, which is crucial for strategic planning. (Akdil et al., 2018; Mittal, Khan, et al., 2018; Schumacher et al., 2016). They provide a means to monitor progress over time, enabling companies to track their improvements and make necessary adjustments to their strategies. (Akdil et al., 2018; Mittal, Khan, et al., 2018; Schumacher et al., 2016).
3. Furthermore, maturity models enhance decision-making by offering insights into areas necessitating investment or improvement, thereby optimizing resource allocation. (Santos & Martinho, 2020).

In essence, I4.0 MMs act as a diagnostic tool, guiding companies through the complex process of digital transformation by highlighting areas of strength and those needing development. This ensures a more efficient and effective adoption of I4.0 principles, ultimately leading to improved productivity, innovation, and competitiveness in the global market (Santos & Martinho, 2020).

To address this, this research study initiated a systematic process to synthesize these existing models; as will be detailed in Chapter 2, a critical review was conducted to Identify the common dimensions and exemplary maturity items across the published I4.0 literature.

Subsequently, in chapter 3, a theoretical comparison of the 16 identified MMs was performed to distill a set of essential dimensions that are most relevant for SMEs. This analysis revealed core thematic areas critical for SME transformation, including organizational strategy, smart factory, smart operation, smart product, employees, leadership, customers, culture, governance, technology, data-driven governance, IT infrastructure, and information systems. These synthesized dimensions from the foundational structure for the tailored MM developed in this research.

1.3 Research Aim, Objectives, and Questions

1.3.1 Research Aim

The purpose of this research study is to develop and validate an Industry 4.0 maturity model (MM) specifically designed for Cairo manufacturing small and medium-sized enterprises (SMEs). Unlike existing MMs, which are typically tailored for large or multinational organizations in developed countries, this model is specifically intended for SMEs operating within the context of developing countries.

1.3.2 Research Questions

To achieve this aim, the research addresses the following central questions:

1. What are the barriers and opportunities of adopting I4.0 in manufacturing SMEs?
2. What are the essential dimensions of I4.0 maturity that are consistently identified across existing theoretical models?
3. Which of these theoretical dimensions are most relevant and critical for manufacturing SMEs operating within the specific context of Cairo, Egypt?
4. How can these validated dimensions be structured into a progressive, multi-level MM that provides a realistic and actionable pathway for SME digital transformation?
5. What are the critical dimensions and capabilities that determine digital maturity in the tourism sector?

1.3.3 Research Objectives

The following objectives outline the specific tasks that will be undertaken to answer the research questions and fulfil the research purpose:

A. Systematically review and synthesize existing I4.0 studies in developed and developing countries.
B. Systematically review and synthesize existing I4.0 MMs; In order to Identify a comprehensive set of common theoretical dimensions and maturity stages/levels.
C. Empirically validate and prioritize these theoretical dimensions; through a multi-round Delphi study with Industrial experts from Cairo manufacturing sector, ensuring contextual relevance.

D. Develop a customized I4.0 MM; composed of the experts validated (weighted) dimensions and structured into five-progressive maturity levels (Initial, Foundation, Progressing, Managed, and Maturity).
E. Operationalize a quantitative scoring protocol for the tailored model, enabling an objective assessment of the current digital maturity level of Cairo's manufacturing SMEs.
F. Identify the critical maturity dimensions that could guide tourism SMEs towards digitalization in developing countries.

Table 1: Demonstrates the distribution of research questions, objectives, and methods.

	Chapter 2			**Chapter 3**	**Chapter 4**
Research papers	1	2	3	4	5
Title	SMEs, Barriers and Opportunities on Adopting Industry 4.0: A Review.	A Review of Industry 4.0 Maturity Models: Adoption of SMEs in The Manufacturing and Logistics Sectors.	A Review of Industry 4.0 Maturity Models: Theoretical Comparison in The Smart Manufacturing Sector.	Assessing Industry 4.0 Adoption in Cairo SMEs: A Study on The Manufacturing Sector.	Towards a Digitalized Tourism Maturity Model: A Conceptual Framework.
Research questions	1 & 2			3 & 4	5
Research objectives	A & B			C, D, & E	F
Method	Systematic Literature Review.	Critical Review.	Theoretical Comparison.	Delphi-method.	Theoretical Framework.
Data Collection	Academic Databases (e.g., Scopus & Web of Science).			Two rounds Delphi-surveys (experts' opinion)	Academic Databases (e.g., Scopus & Web of Science).

Source: Self-collaboration.

1.4 Study Delimitation

The scope of this research study is intentionally delimited to manufacturing SMEs with Greater Cairo region to provide a deep, contextually rich analysis of I4.0 adoption in a representative developing economy. While manufacturing SMEs form the backbone of Egypt's industrial sector, they remain significantly under-represented In I4.0 maturity research ("OECD Economic Surveys: Egypt 2024," 2024).

The selection of Cairo as the geographical focus Is strategic. As Egypt's primary Industrial and economic hub, it accounts for a substantial share of the country's manufacturing activities (Aboelmaged, 2018; 'OECD Economic Surveys: Egypt 2024', 2024). This makes Cairo an ideal for Investigating the specific barriers that persist even when foundational conditions are partially met, allowing the proposed MM to address operational and strategic realities rather than just Infrastructural deficits.

The sector focus on manufacturing SMEs Is justified by their pivotal role In Egypt's Industrial economy and their unique vulnerability to resources limitations, skill shortages, and digital fragmented technological Infrastructure, which can hinder their high potential for digital transformation (Bilal et al., 2024). Consequently, the MM developed in this study is purposefully designed to address the specific operationalization realities and adoption constraints characteristic of SME In this precise context.

1.5 Research Methodology

This research study employed a multi-stage, exploratory sequential mixed-methods research design to develop and validated a customized I4.0 MM for manufacturing SMEs. The research study was executed in three primary phases, moving sequentially from broad theoretical exploration to specific, context-driven model development, as follows:

Phase 1: Literature Review and Theoretical Framework Development:

The foundational stage of this research study Involved a comprehensive literature review to synthesize the core conceptual components of existing MMs. This phase was not a simple review, but an analytical process designed to deconstruct the current body of knowledge. Following the established protocols for evidence-based research (Tranfield et al., 2003), systematic research was conducted in academic databases like Scopus, ScienceDirect, WoS; to identify the relevant MMs.

This process resulted in the identification of 16 main I4.0 MMs published between 2016 and 2020. A multi-stage analytical process was then conducted to synthesize their core components. This Involved:

1. **Systematic extraction:** all reported dimensions, exemplary maturity Items, and maturity levels were systematically extracted from each model into a structured database.
2. **Thematic synthesis:** an iterative process of comparison and grouping was used to identify overlapping constructs and develop a unified set of 11 common dimensions that consistently appeared across the literature (e.g., Organizational strategy, Smart factory, Technology, ... etc.,). This synthesis distilled the fragmented literature into a cohesive set of higher-order themes, forming the initial theoretical framework for the study.

Phase 2: Exploratory Delphi Study (Round -1: Current ICT Level):

To ground the theoretical framework in the operational realities of Cairo manufacturing SMEs, a two-round Delphi method was employed. The Delphi method is a well-suited tool for building consensus among a panel of experts on complex issues (Culot et al., 2020; Okoli & Pawlowski, 2004; Skulmoski et al., 2007) and has been widely used in technology adoption research (Touijer & Elabjani, 2025).

A panel of 19 Industrial experts was recruited using a purposive sampling strategy, with stringent criteria for Inclusion (e.g., top-management level, minimum 9 years of experience, ... etc.,). The first Delphi round (R1) was an exploratory assessment of the digital level and readiness among Cairo's SMEs. A five-section questionnaire was developed, mapping practical, operational questions to the 11 literature-derived dimensions. This round served two purposes:

- To gather empirical information on the current ICT adoption level, IT systems in use, key barriers, training, skills needed, and stakeholders Involvement.
- To contextually test the relevance of the theoretical dimensions, identify significant gaps between the comprehensive frameworks found in the literature and the practical realities of the surveyed firms.

Phase 3: Perspective Delphi Study (Round-2: Consensus and Validation):

The findings from round-1 confirmed a significant gap and necessitated a second, perspective Delphi round. The purpose of this round was to leverage the iterative nature of the Delphi method to build expert consensus on a final, tailored set of dimensions for the new model. Experts were asked to rate the essentiality of each of the 11 common dimensions and their 55- exemplary maturity items on a five-point Likert scale.

This consensus building process deliberately filtered the initial framework, reducing it from 11 literature-derived dimensions to 10 expert-validated dimensions with 32 exemplary maturity items. This was a critical contextual refinement, where the expert panel eliminated components deemed too complex,

resource intensive, or irrelevant for the SME context. The output of this phase was a set of cores, empirically validated constructs that formed the final view of the tailored model.

1.6 Thesis Structure

This dissertation is divided into six chapters as follows:

Chapter One: Introduction.

This chapter serves as an introduction to the research topic, presenting the research questions, outlining the research aims and overarching objectives. It also provides an overview of the research methodology, highlights the research's originality, and concludes by outlining the thesis structure.

Chapter Two: Literature Review.

This chapter presents a comprehensive literature review in three analytical sections. The first section employs a systematic literature review (SLR) approach guided by PRISMA guidelines. It analyzes 54 peer-reviewed articles published between 2017 and 2021 that explore the challenges and opportunities of I4.0 adoption by manufacturing SMEs in both developed and developing countries. This contextual exploration sheds light on the actual issues and underscores the need for a customized model tailored to Cairo's SMEs.

Section two delves into a critical review of 16 I4.0 maturity models, assessing their applicability to manufacturing SMEs. These models were selected from a distinct yet partially overlapping collection of studies from Section One, providing insights into their diverse scopes, structural elements, and underlying assumptions. This comparative analysis offers a comprehensive understanding of the maturity models.

Section three presents a theoretical comparison of the same 16 maturity models, identifying common and divergent dimensions. This comparison reveals inconsistencies and redundancies in published models, contributing to the identification of key dimensions essential for Cairo-specific customization.

Chapter Three: Assessing Industry 4.0 Adoption in Cairo SMEs: A Study on The Manufacturing Sector.

This chapter presents the development of I4.0 MM through expert engagement, ensuring that the selected maturity dimensions are both academically grounded and contextually relevant. This is due to the lack of generic MM for SMEs in developing countries to adopt I4.0. It begins by Identifying key I4.0 technologies and reviewing existing MMs to understand how digital readiness is assessed in manufacturing contexts. Based on this, A two-round Delphi survey involving 19 industrial experts was conducted. The first

round assessed existing ICT levels, IT systems, stakeholder involvement, and training needs, while the second round identified the most relevant dimensions for a tailored model. Findings show moderate ICT integration, widespread ERP use, and partial digital transformation among Cairo SMEs. However, the adoption of advanced I4.0 technologies remains limited. the proposed model is intended for SMEs mangers, and policymakers as a practical framework to plan, monitor and support I4.0 adoption in developing economies.

Chapter Four: Towards a Digitalized Tourism Model: A Conceptual Framework.

This chapter extends the theoretical contribution of this research study by proposing a conceptual framework for tourism SMEs as a significant services sector in Egypt. While previous chapters (2 & 3) have theoretically and empirically examined the impact of I4.0 in manufacturing SMEs, this chapter further extends the perspective on digitalization in tourism as a counterpart to the service sector. It assumes that both sectors face distinct yet interrelated challenges in adapting to digital transformation.

Based on the review of existing tourism digitalization frameworks and literature, persistent barriers such as infrastructure constraints, fragmented governance approaches, and skills gaps are identified alongside opportunities that can be achieved through the exploitation of ICT, data analytics, and smart services ecosystems.

The conceptual model of tourism maturity for SMEs describes dimensions related to diversity considerations, including organizational strategy, customer experience, technology readiness, and cultural adaptability.

Through the two industries of manufacturing and tourism, the thesis provides a broader view of Egypt's digital economy and demonstrates how different sector-specific management models can be aligned to enhance national competitiveness.

Chapter Five: Conclusions and Future Research Directions.

A conclusive analysis of the research findings is presented, accompanied by suggestions for future research direction.

2. Chapter Two: Literature Review

2.1 Section One: SMEs, Barriers and Opportunities on Adopting Industry 4.0: A Review.

Abstract

Industry 4.0 allows SMEs to enhance their manufacturing industries and compete globally, through the deployment of cutting-edge technologies. The purpose of this review is to identify the barriers and opportunities of adopting industry 4.0 in the manufacturing sector in developed vs developing countries. In total, 54 studies met the screening criteria. The synthesized factors were classified into dimensions to help the understanding of what type of difficulties SMEs face in the transition to the 4.0 generation. This study found that developing countries face more barriers but also perceive more opportunities in relation to industry 4.0. Organizational Barriers and Technical Barriers are the main types of barriers studied in both types of countries. In terms of benefits, studies emphasize gains in terms of operations management in first and then questions related to market, sustainability, and supply chain.

Keywords: Industry 4.0, SMEs, Manufacturing, Barriers, Opportunities.

2.2 Introduction

Industry 4.0 (I4.0) presents significant opportunities for SMEs, enabling them to innovate and enter global markets. Many researchers (e.g.,(Mittal, Khan, et al., 2018)) mentioned that SMEs are the major driving force of manufacturing industries. The adoption of I4.0 brings new opportunities for SMEs, helping them to Innovate and compete in global markets (Mittal, Khan, et al., 2018). Like any other manufacturing project, I4.0 Implementation comprises a set of activities/phases, but it entails a high level of complexity (Hirman et al., 2019) as digitalization needs several different project management competences (see, (Ribeiro et al., 2021)).

To have knowledge about the possible barriers and opportunities of I4.0 adoption is Important to define the profile of the project manager that will coordinate Implementation and to the risk analysis of the Implementation project.

Research published between 2017 and 2021 was reviewed to synthesize the barriers and opportunities and discuss the differences between developed and developing countries. Until now, most studies: a) have focused on I4.0 adoption in multinational and large enterprises, b) have listed a number of Issues without relating them to developed or developing countries (Buer et al., 2020); and only a limited number of c) have Investigated SMEs I4.0 adoption In the manufacturing sector, d) have demonstrated the potential benefits of I4.0 to SMEs, e) have focused on the particular barriers faced by SMEs In developing countries (P. Kumar et al., 2021), and f) have classified the main barriers Into dimensions (e.g. Organizational, technical, legal) (AL-Shboul, 2019; Ghadge et al., 2020a; Yüksel, 2020).

The scope of the review is defined by the following research questions:

- RQ1: What are the main barriers that hinder SMEs (in developed and developing countries) from adopting I4.0 in the manufacturing sector?
- RQ2: What are the opportunities of adopting I4.0 in SMEs manufacturing sector (in developed and developing countries)?

This review will provide a synthesis of the extent, nature, and quality of evidence in relation to SMEs I4.0 adoption in the manufacturing sector, highlighting what is lacking in the literature.

2.3 Research Approach

The methodological approach follows the best recommendations of (Matarazzo et al., 2021a), that divide the reviews in key main steps: scope, planning through PRISMA: searching, screening, eligibility, and study quality (Siddaway et al., 2019) (see Figure 1). This review update previous literature reviews of previous literature reviews of Mittal, Khan, Romero, & Wuest, (2018) (about Smart Manufacturing maturity/assessment models); of (Ortt et al., 2020) (about success of implementation of Industry 4.0); and of (Jimeno-Morenilla et al., 2021) about technology enablers for the implementation of I4.0 to traditional manufacturing sectors) on a more specific topic: confrontation between manufacturing SMEs challenges face on developed vs developing countries.

This literature review involves a systematic search process to locate all relevant works that address one or more of the research questions outlined in the previous section. The criteria for Inclusion and exclusion used in the review are explicitly stated in table 2. The criteria guiding the selection of the keywords was extracted from recent articles related to I4.0, SMEs, and the manufacturing sector context (Benitez et al., 2020; S. Kamble et al., 2020; Maldonado-Guzmán et al., 2017; Moeuf et al., 2020; Ramírez-Durán et al., 2021).

Table 2: Inclusion and exclusion criteria used with explanation.

Inclusion/Exclusion	Criteria	Criteria Explanation
Exclusion	Search engines Not-related (NR)	Search engines results that do not have results matching with the study scope like ProQuest.
	Loosely related (LR)	NR1- not related title, not academic paper e.g. book part or conferences reviews. NR2- I4.0/SMEs are not related to the manufacturing sector e.g. offshoring, reshoring, medicine, accounting, education, finance, large enterprises, multinational enterprises, and safety management. LR1- I4.0 is generally discussed.
	Partially related (PR)	LR2- I4.0 is only used as an example and/ or a future recommendation. LR3- I4.0/and or one of its' key technologies (e.g. IoT) is only used as a keyword.
Inclusion	Closely related (CR)	LR4- I4.0 is only used as a reference. LR4- Barriers/challenges/benefits/opportunities of SMEs to adopt I4.0 is not mentioned. LR5- SMEs is only used as a reference. PR1- I4.0 benefits/barriers to the manufacturing sector. PR2- A study about the benefits/barriers of adopting IoT/BDA/AR/cloud-computing in SMEs manufacturing sector without mentioning I4.0 PR3- I4.0 adoption in developing or Id countries is discussed or surveyed or reviewed. CR-The research paper is mainly dedicated to I4.0 adoption in SMEs

Source: Author's Own Contribution.

The search terms used in the search were as follows (Figure 1):

"SME"[Title/Abstract] AND " Industry 4.0"[Title/Abstract] AND "Manufacturing"[Title/Abstract] AND ("Opportunities"[Title/Abstract] OR "Benefits"[Title/Abstract]) AND ("Challenges" [Title/Abstract] OR "Barriers" [Title/Abstract]) AND ("Developed"[Title/Abstract] OR "Developing Countries"[Title/Abstract]).

The bases for searching the identified keywords were ScienceDirect, Emerald Insights, ProQuest and Scopus databases and Web of Science (WoS). The search returned 803 documents mainly from Science Direct and Emerald Insights databases. However, no relevant documents were found on ProQuest database. Thus, 54 articles were eligible for full reading and inclusion in the review.

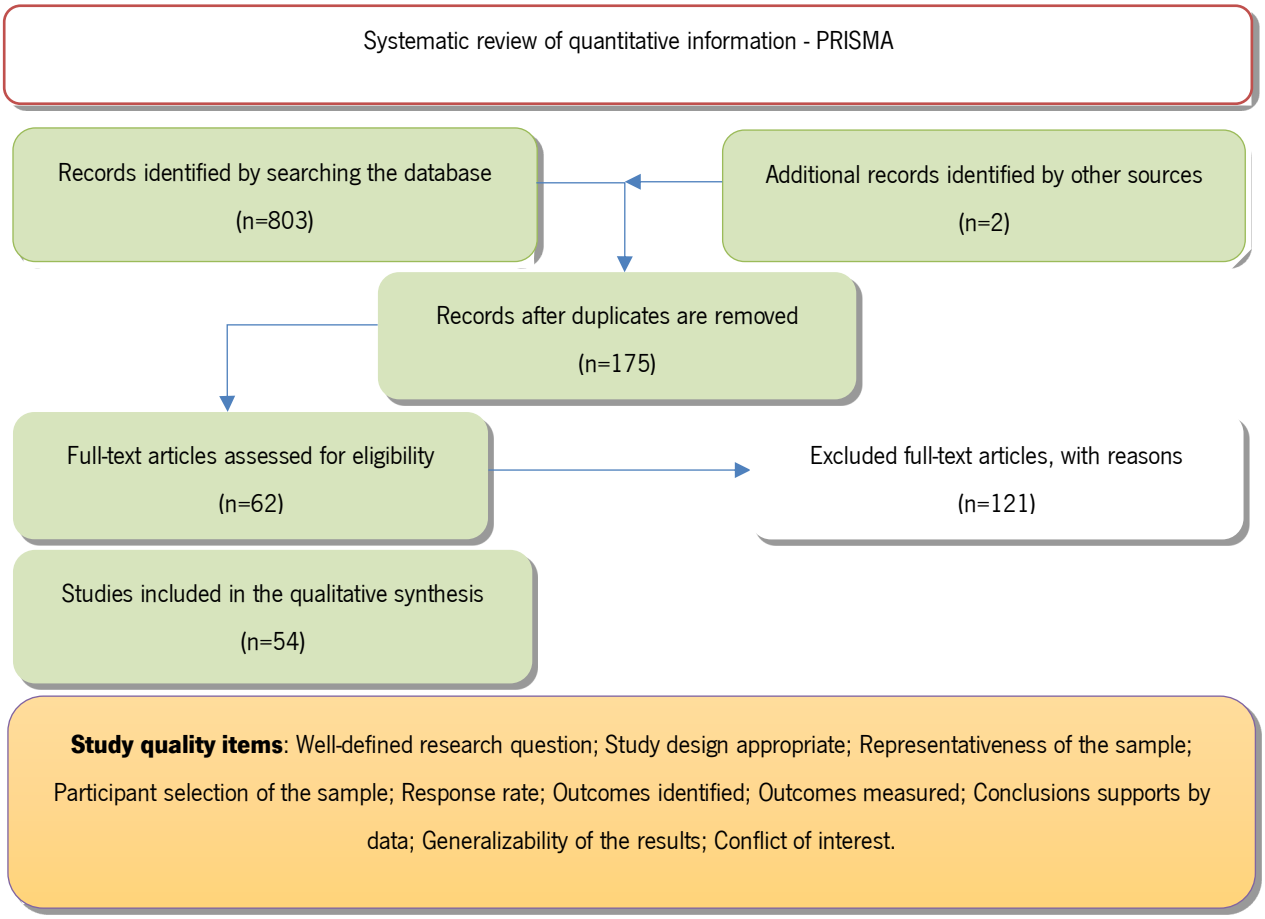


Figure 1: PRISMA flow chart.

2.4 Findings and Discussion

Table 3 show the SMEs barriers and opportunities (RQ1) found across developed and developing countries classified into four main dimensions: Technical (AL-Shboul, 2019), Organizational, Technological and Legal barriers (Ghadge et al., 2020).

Technical Barriers (TB) include: a) information communication technology (ICT) infrastructure, one of the most significant barriers in developing countries like India, China, Egypt, Indonesia, South Korea, Italy, Turkey, and Greece (Al-Sayed & Yang, 2018; AL-Shboul, 2019; Buer et al., 2020; Kandil & Abd El Aziz, 2018; P. Kumar et al., 2021; Pirola et al., 2019; Sahi et al., 2020; Sánchez-Rodríguez et al., 2019; Shin, 2017; Viswanathan & Telukdarie, 2021).

This barrier is addressed as a major obstacle for enterprises to apply advanced technologies, e.g., cloud computing, IoT, etc., (AL-Shboul, 2019);

b) lack of skilled employees and skilled managers, (Bag et al., 2020a; Buer et al., 2020; Ghobakhloo & Ching, 2019; P. Kumar et al., 2021; Onu & Mbohwa, 2021; Sahi et al., 2020; Torn & Vaneker, 2019; Viswanathan & Telukdarie, 2021; Yüksel, 2020), which is also considered as a barrier in a developed country like Germany (Ghobakhloo and Ching, 2019)

Organizational Barriers (OB) include lack of financial resources, lack of management support, fear/resistance to change, and lack of R&D (Bag et al., 2020a; Ghobakhloo & Ching, 2019; Onu & Mbohwa, 2021; Pontevedra et al., 2021; Yu & Schweisfurth, 2020; Yüksel, 2020). Moreover, the fear of demobilization, demand uncertainty, and failure of I4.0 technologies (R. Kumar, Singh, Dwivedi, et al., 2020).

Technological Barriers (TECB) come from the fact that I4.0 comprises many advanced technologies to support SMEs to innovate manufacturing, logistics processes, and activities. However, SMEs are slower in deploying such technologies (North et al., 2019): a) due to the lack of knowledge to use advanced services technologies (e.g., ERP, CAD (Onu and Mbohwa, 2021).

Artificial Intelligence (Blixt & Simon, 2021), or I4.0 applications like BDA (Cunha et al., 2020)), and b) due to the complexity of maintenance or usage of the said applications (Sánchez-Rodríguez et al., 2019) (such as computing complex data (R. Kumar, Singh, & Dwivedi, 2020)) or unstructured data (Maroufkhani et al., 2020)).

Legal Barriers (LB) are related to the lack of collaboration and integration between managers and departments, privacy concerns (Raut et al., 2018; Ghadge et al., 2020; Viswanathan and Telukdarie, 2021), e.g. Cloud-computing is limited is SMEs due to some privacy concerns (Asiaei & Nor 2019).

The developed countries like Germany, USA, Japan, France, were the first of deploying I4.0 (Calış Duman & Akdemir, 2021). The opportunities of adopting I4.0 were synthetizing according two strategic dimensions (Buer et al., 2020; Calış Duman & Akdemir, 2021; Chen, 2020; Cunha et al., 2020; Mangla et al., 2020; Ortt et al., 2020; Pirola et al., 2019; Rafael et al., 2020): horizontal and vertical Integration.

Horizontal Integration (HI): I4.0 technologies e.g., Internet of things (IoT), cloud-computing, big data analytics (BDA), cyber physical system (CPS) allow the integration and management between different customers, suppliers, and manufacturing plant (partners of the supply-chain SC).

This is beneficial for SMEs allowing them to efficiently forecast demand, manage inventory, and effectively perform logistics activities. For example, BDA adoption in SMEs can increase the competition in

domestic and foreign markets, enable to make better decisions by managers, increases operational performance, and allows better business performance for SMEs in competing large enterprises (Maroufkhani et al., 2020). Cloud-computing allows SMEs to store, access, use, calculate data in real-time over the internet in a secure manner (R. Raut et al., 2018). Moreover, cloud-computing could enhance productivity, reduce costs, and is a promising opportunity for SMEs to be more competitive in the market (Asiaei & Nor 2019; Mangla et al., 2020).

Vertical Integration (VI): includes the integration between different departments inside enterprises e.g., production, procurement, etc., to ensure better production, customized products, planning, quality, reducing wastes and costs.

Table 3: A summary of SLR Studies.

#	Study	Dimension	Barriers	Benefits	Developed vs developing
1	(P. Kumar et al., 2021)	OB, TB, TECHB	Lack of ICT infrastructure, skilled employees, data integration.	N/M	India
2	(Calış Duman & Akdemir, 2021)	HI & VI	N/M	HI &VI	Germany, USA, France, Japan
3	(Yüksel, 2020)	OB, TB	Financial constraints, lack of skilled employees, ICT infrastructure.	Digital collaboration, flexibility, and cost reduction.	Turkey
4	(Rafael et al., 2020)	HI & VI	N/M	HI &VI	Spain
5	(Dassisti et al., 2019)	TB, OB	Lack of knowledge, technical expertise, financial constraints.	N/M	Developing
6	(Sahi et al., 2020)	OB, TB	Financial constraints, skilled employees	N/M	India
7	(R. Kumar, Singh, Dwivedi, et al., 2020)	OB, TB	Lack of knowledge, financial constraints, governmental support, R&D, ICT-infrastructure, skilled employees, reluctance in embracing new technologies	Digital collaboration, smart manufacturing, economic sustainability.	India
8	(Ghobakhloo & Ching, 2019)	OB, TB	Financial constraints, skilled employees, knowledge.	N/M	Iran
9	(Yu & Schweisfurth, 2020)	OB, TB	Lack of knowledge, skilled employees.	Cost reduction, real-time information.	Germany
10	(Onu & Mbohwa, 2021)	OB, TB	financial constraints, governmental support	Increase revenue, saving resources.	Developing
11	(Bazaz et al., 2021)	TB, OB	Lack of knowledge, technical expertise, skilled employees.	Saving resources, mass-customization.	Finland
12	(Torn & Vaneker, 2019)	TB, OB	Financial constraints, skilled employees.	Cost reduction, flexibility, mass-customization.	Netherlands

13	(Blixt & Simon, 2021)	TB, OB	Lack of knowledge, financial constraints.	N/M	Denmark
14	(Ghobakhloo & Fathi, 2020)	OB, TB	Lack of knowledge.	N/M	Germany
15	(Buer et al., 2020)	OB, TB	Financial constraints, lack of data integration	HI &VI	Norway
16	(Sánchez-Rodríguez et al., 2019)	TB, OB	Lack of ICT infrastructure, financial constraints, technical expertise.	Time & cost reduction, demand forecasting, smart manufacturing, risk management.	France
17	(Chen, 2020)	HI & VI	N/M	HI &VI	Taiwan
18	(Mangla et al., 2020)	HI & VI	N/M	HI &VI.	India
19	(R. Raut et al., 2018)	TB, OB, LB	Lack of top-management support, data integration, privacy concerns.	Cloud computing, cost reduction, increasing investments.	India
20	(Ortt et al., 2020)	HI & VI	N/M	HI & VI	Netherland
21	(S. Kumar et al., 2020)	OB, TB	Lack of skilled employees, knowledge	HI & VI	China, India, Japan
22	(Cunha et al., 2020)	TB, OB	Financial constraints, skilled employees	Digital collaboration, saving recourse.	Brazil
23	(Kaushik & Singh, 2019)	OB, TB	Financial constraints.	Global competition, smart manufacturing, flexibility	India
24	(Ul Haq & Franceschini, 2019)	OB, TB, TECB	Lack of training, knowledge, financial constraints, reluctance in embracing new technologies.	Flexibility, smart manufacturing.	Italy
25	(Kandil & Abd El Aziz, 2018)	OB, TECB, OB	Lack of ICT infrastructure, financial constraints, skilled employees, training.	N/M	Egypt
26	(Al-Sayed & Yang, 2018)	HI& VI	N/M	Digital collaboration, smart manufacturing, sustainability	China
27	(Maroufkhani et al., 2020)	OB, TB	Lack of knowledge, ICT infrastructure, financial constraints.	Smart manufacturing, real-time solutions.	Iran

28	(Rahman et al., 2017)	OB, TC,	Financial constraints, lack of technical expertise, knowledge.	N/M	UK
29	(Asiaei & Nor, 2019)	TECB	Reluctance in embracing new technologies, privacy concerns.	Cost reduction, smart manufacturing, flexibility, economic development.	Malaysia
30	(Indrawati et al., 2020)	OB, TB	Lack of skilled employees, financial constraints.	N/M	Rieu, Indonesia
31	(Ghadge et al., 2020)	TECB, OB, TB, LB	Lack of ICT infrastructure, financial constraints, management support, technical expertise, privacy concerns.	N/M	N/M
32	(Shin, 2017)	OB	Lack of knowledge, technical expertise.	Global competition.	South-Korea
33	(Pirola et al., 2019a)	TECB	Lack of data integration.	HI&VI, cost reduction.	Italy
34	(AL-Shboul, 2019)	OB	Lack of governmental support.	N/M	Developing
35	(Dutta et al., 2020)	OB	Lack of skilled employees.	Mass-customization.	India
36	(D. Kumar et al., 2017)	HI & VI	N/M	Flexibility, cost reduction, smart manufacturing, security, privacy, reliability.	India
37	(Pinto et al., 2019)	HI & VI	N/M	Smart manufacturing	Portugal
38	(Nimawat & Gidwani, 2020)	OB, TB	Lack of technical expertise and governmental support.	Digital collaboration, real-time data, smart manufacturing.	India
39	(Horváth & Szabó, 2019)	TB, TECB	Lack of ICT infrastructure, reluctance in embracing new technologies.	Smart manufacturing, real-time data.	Euro. Union
40	(Majumdar et al., 2021)	OB, TB	Lack of skilled employees, governmental support, R&D	N/M	India
41	(Turkyilmaz et al., 2021)	OB, TB	Lack of knowledge, financial constraints, governmental support, ICT infrastructure.	N/M	Kazakhstan

42	(Matarazzo et al., 2021)	OB, TB	Financial constraints, skilled employees, knowledge.	N/M	Developed & developing
43	(Jimeno-Morenilla et al., 2021)	HI & VI	N/M	Global competition, mass-customization.	Developed & developing
44	(Moeuf et al., 2020)	TB, OB	Lack of technical expertise and knowledge.	N/M	France
45	(S. Kamble et al., 2020)	TB, OB	Lack of governmental support, ICT infrastructure.	N/M	India
46	(Maldonado-Guzmán et al., 2017)	TB, OB	Financial constraints & unskilled employees.	N/M	Latin America
47	(Ramírez-Durán et al., 2021)	TB, OB	Financial constraints, ICT infrastructure, privacy concerns.	N/M	Spain
48	(Benitez et al., 2020)	TB, OB	Lack of governmental support, ICT infrastructure, skilled employees.	N/M	Brazil
49	(Viswanathan & Telukdarie, 2021)	TB, OB	Lack of skilled employees, financial constraints	N/M	South Africa
50	(Bag et al., 2020)			Smart manufacturing, flexibility, saving resources.	Developed
51	(North et al., 2019)	TB, OB	Lack of knowledge and management support.	Faster growth.	N/M
52	(Aboelmaged, 2018)	TB, OB	Lack of IT infrastructure, financial constraints, skilled employees.	N/M	Egypt
53	(Schumacher, Erol and Sihn, 2016)	TB, OB	Lack of knowledge.	HI & VI	Developing
54	(Mittal et al., 2018)	TB, OB	Financial constraints, ICT infrastructure.	Mass-Customization.	Developing

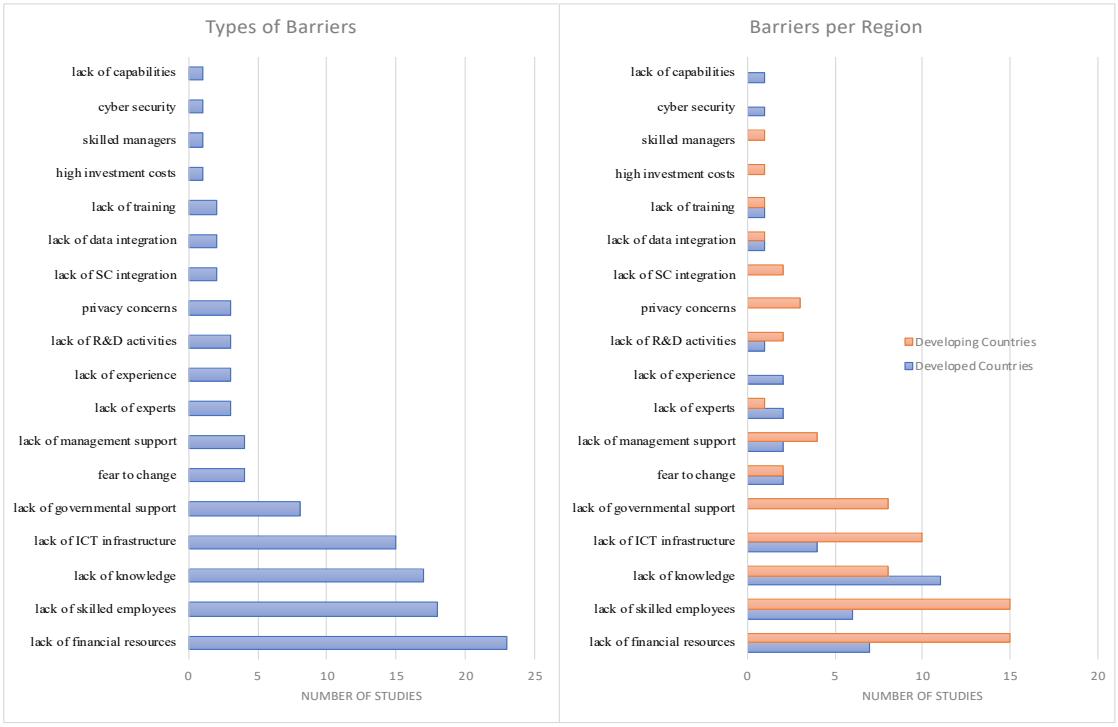


Figure 2: Types of Barriers per Regions.

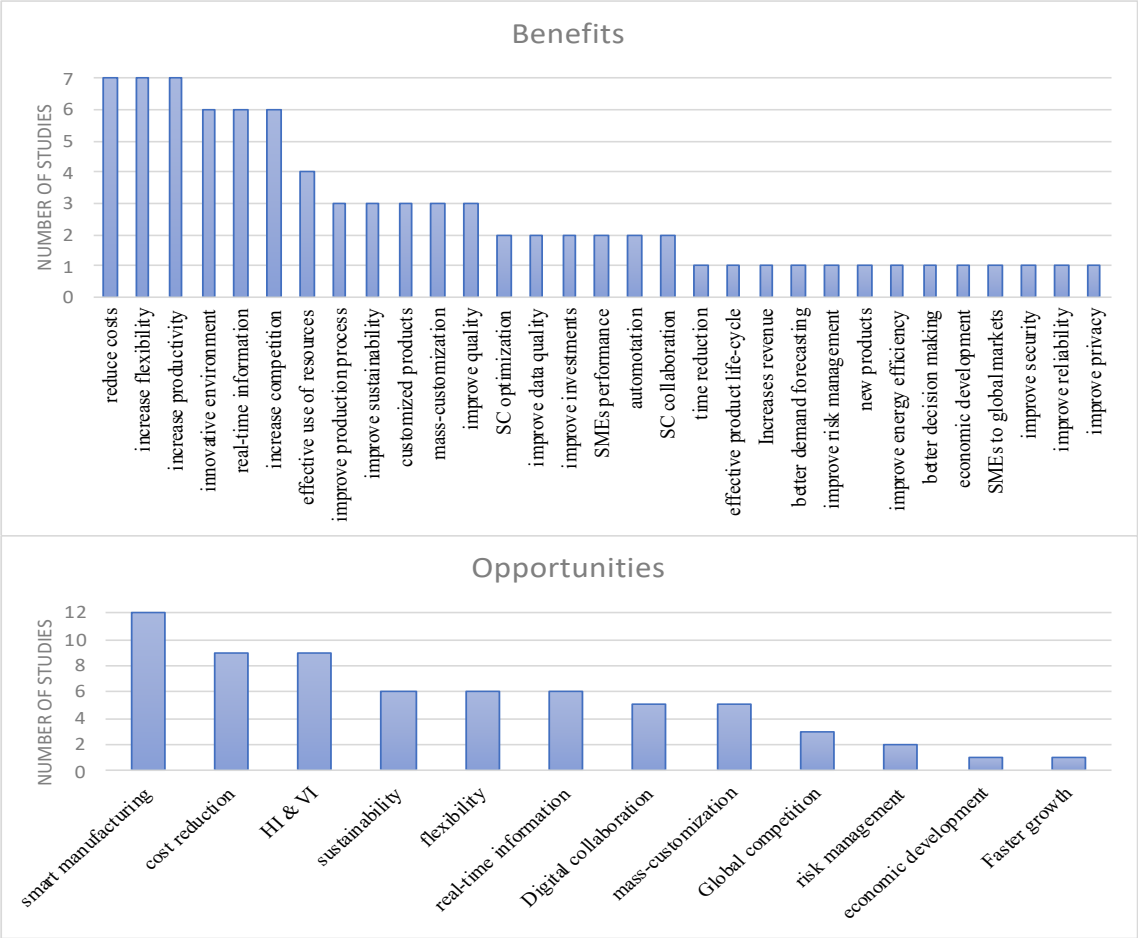


Figure 3: Industry 4.0 Benefits and Opportunities.

The barriers that appear often in the studies are (Figure 2): lack of financial resources, lack of skilled employees, lack of knowledge (technological), lack of ICT infrastructure, lack of governmental support. With the exception to lack of knowledge, all of them are more related to developing countries. Emphasize that lack of governmental support is only mentioned in studies of developing countries.

Other barriers that only are mentioned for these countries are privacy concerns, lack of SC integration, skilled managers, and the high investment costs. In terms of the classification proposed, Organizational Barriers (78%) and Technical Barriers (71%) are the main type of barriers studied, very few studies (only six, 11%) study Technological Barriers for I4.0 adoption and only one had consider the Legal Barriers.

In prementioned more opportunities (Figure 3), with exception to: Digital collaboration (100%), sustainability, flexibility, real-time information, and mass-customization (all with 66, 7%) that were more mentioned in studies about developing countries, are equally referenced in studies of both types of countries.

That somehow reflects the evolution stage of the companies about technology adoption, and about market pressure, and supply chain pressure of the regions where companies work.

In terms of benefits, studies emphasize gains in terms of operations management in first and then other questions related to market, sustainability, and supply chain. Main opportunities are smart manufacturing implementation, cost reduction and integration (vertical as horizontal). Again, we see that I4.0 is mainly studied from an internal (company) perspective.

2.5 Conclusion, Limitations, and future research

This Review explores two RQ: identify the main barriers and opportunities of I4.0 adoption in the manufacturing sector by SMEs. This study found that developing countries face more barriers but also perceive more opportunities in relation to industry 4.0.

Organizational Barriers (78%) and Technical Barriers (71%) are the main type of barriers studied in both types of countries. Legal Barriers was almost forgotten, so if we think that digital collaboration and information transfer are an increasing reality, this must be a topic for future research.

I4.0 is mainly studied from an internal (company) perspective with smart manufacturing leading the research topic in both types of country. Therefore, there is space for topics like sustainability and supply chain collaboration within the manufacturing industry.

2.6 Section Two: A Review of Industry 4.0 Maturity Models: Adoption of SMEs in The Manufacturing and Logistics Sectors.

Abstract

The purpose of this paper is to critically review the current available (large/SMEs) Maturity Models (MM) for Industry 4.0 (I4.0) adoption in manufacturing and logistics sectors, as well as recognize the specific requirements of SMEs for MM adoption. In total, 16 MM were studied with various scopes, where 5 studies applied on SMEs. To this end, this paper identified manufacturing SMEs specific requirements, conducted a review of current MM, and identified the main MM scopes for SMEs and large enterprises as well. This study found that Smart Manufacturing, Smart Supply Chain (SC), Product Development, Digitized Data collection & Analytics, Technological Infrastructure, Smart Logistics, Performance Evaluation, and Employee participation are the main scopes used for SMEs.

Keywords: Industry 4.0, Maturity Model, SMEs, Manufacturing, Logistics.

2.7 Introduction

A MM is a tool used to measure a set of aspects and capacities in an organization, aiming to identify the current state of an organization and room for improvement (Angreani et al., 2020). In addition, MM provides the necessary criteria and characteristics needed to be fulfilled to achieve a required maturity level in a specific area e.g., manufacturing (Carvajal Carmen L.and Moreno, 2017). MM provides guidance on the usability process and practices implemented in an organization, allowing identification of areas needed to be improved upon (Carvajal Carmen L.and Moreno, 2017).

In Industry 4.0 (I4.0) context, terms like readiness, roadmap, framework, assessment models, and maturity index have been used to refer how enterprises (SMEs/Large) could measure their current state and implement I4.0 (Angreani et al., 2020) Thus, the scope of review is determined by the following research questions:

- (RQ1): what are SMEs requirements to adopt I4.0?
- (RQ2): what are I4.0 MMs that could allow SMEs to implement I4.0 within the manufacturing sector?

Research published between 2015 and 2022 was reviewed to synthesize the main MM applied dimensions and answer the research questions.

Currently, a) most studies have focused on large/multinational enterprises in the manufacturing sector, b) smart logistics and/or SC integration has almost been forgotten, c) SMEs specific requirements have been addressed in only one study, d) some models (e.g., MM2: PwC) missed SMEs financial constraints especially in developing countries, e) this study updates the current MM of (Mittal et al., 2018; Angreani, Vijaya and Wicaksono, 2020) relevant to SMEs scopes.

This review is based on the recent published studies from the following databases: ScienceDirect, Springer, and Scopus. The search terms were based on recent articles related to MM, SMEs and I4.0 in the manufacturing sector [Title/Abstract]: "MM" AND "SMEs" AND "Industry4.0" AND "Manufacturing" AND "Logistics" OR "Supply chain".

2.8 Related Work

2.8.1 SMEs Requirements

Mittal S (Mittal et al., 2018) is the only study that has mentioned the specific requirements of SMEs to implement I4.0 in the manufacturing sector. According to Mittal S (Mittal et al., 2018) these requirements are *"Finance, Technical Resources Availability, Employee Participation, Product Specialization, Alliances, Organizational Culture, and Collaboration"* (Mittal et al., 2018).

The mentioned requirements can be used to record differences between large/multinational enterprises and SMEs. Thus, can be used in MM assessment (Mittal et al., 2018).

Overall, this study has conducted a comprehensive review that criticized some MM and identified SMEs main requirements to apply I4.0 in the manufacturing sector.

The study has highlighted 4 main points that may pave the way for SMEs to adopt I4.0, mainly:

a. a MM should have a clearly defined *"level 0"* which, focuses on the fundamental needs like IT, computerization of business functions, integration at production and shopfloors.

b. the transition from *"level 0"* to *"level 1"* will include some difficulties in the organizational structure, as it involves new technologies adoption, learning skills, etc.
c. it is important for SMEs to determine the current level and to move forward towards I4.0 adoption using a readiness/assessment tool.
d. the deployment of a tailored MM that reflects SMEs vision towards I4.0 adoption (Mittal et al., 2018). However, this study is mainly based on previous research without collecting primary data (Mittal et al., 2018).

2.8.2 (MM1): IMPULS-Industrie 4.0 Readiness

This readiness model classifies SMEs in 6 phases (outsider, beginner, intermediate, experienced, expert, and top performer), with 6 dimensions of I4.0 (organizational strategy, smart factory, smart operation, smart products, data collection, and employees) (Ramos, de Freitas Rocha Loures and Deschamps, 2020).

The said model considers horizontal and vertical integration as base technologies to support SMEs connectivity with suppliers and customers. However, the 6 dimensions consider digitization, smart products, etc. as the way towards I4.0, which might not be applicable on a wide range as most of SMEs were classified as outsiders (Mittal et al., 2018; Ramos, de Freitas Rocha Loures and Deschamps, 2020).

2.8.3 (MM2): Industry 4.0/Digital operations self-assessment (PwC)

According to the 2016 Global Industry 4.0 Survey, the PwC maturity model consists of 4 phases of maturity (Digital novice, Vertical integrator, Horizontal collaborator, and Digital champion), with 6 dimensions (Digital business and customer access, Digitization of products/services, Data analytics, IT infrastructure, IT architecture, Security, and Digital culture) (Geissbauer et al., 2016).

This model also presents the ability for enterprises to measure their current position (AS-IS) and provided instructions for the future adoption (TO-BE) (Ramos, de Freitas Rocha Loures and Deschamps, 2020).

However, this model assumes the presence of already digitized SC in enterprises. Thus, it might not be applicable for SMEs due to financial constraints, especially in developing countries (Mittal et al., 2018; Elhusseiny and Crispim, 2021).

2.8.4 (MM3): Industry 4.0 Maturity Model

Schumacher (2016) suggests a MM that can be used to assess SMEs' current position to adopt I4.0 in the future. The MM is based on a survey of 9 dimensions (Strategy, Leadership, Customers, Products, Operations, Culture, People, Government, and Technology) (Schumacher, Erol and Sihn, 2016)

However, this model is not applicable due to the lack of access to all the model related information e.g., survey (Mittal et al., 2018; Ramos, de Freitas Rocha Loures and Deschamps, 2020).

2.8.5 (MM4): SIMMI 4.0 (System Integration Maturity Model for I4.0)

SIMMI 4.0 MM describes the necessary components to fulfil the requirements of I4.0 environment through 5 stages and 4 dimensions. These stages are: Basic digitization level, Cross-department digitization, Horizontal/vertical integration (HI, VI), Full digitization and Optimized digitization (Leyh et al., n.d.).

Dimensions of this MM are: VI, HI, Digital product development, and Cross-sectional technology criteria. This MM has been applied based on enterprises in general without pointing to SMEs or even a specific sector. Moreover, the said model has not proven its applicability or practicability in any enterprise (Leyh et al., n.d.).

2.8.6 (MM5): Maturity Model in SMEs towards Industry 4.0

Ganzarain and Errasti, (2016) proposed a strategy for SMEs to be as a main enabler for I4.0. According to this study, SMEs lack the basic prerequisites and tools for I4.0 adoption like lack of knowledge. Thus, authors followed a 3-stages MM for SMEs, which particularly:

a. The development of I4.0 vision.
b. I4.0 technological vison informed by network, products, and process.
c. Polices, management and training for employees (Ganzarain and Errasti, 2016). Although, this study might allow SMEs to analyse their financial condition, however, assessment is absent in this model (Mittal et al., 2018). Thus, it might be suitable for SMEs general vision towards I4.0 adoption.

2.8.7 (MM6): Maturity Model for Digital Transformation

This MM focuses on the digital transformation of enterprises (in general) within the manufacturing sector as well as, the usage of I4.0 base technologies like IoT, cyber-physical systems (CPS), etc. in digitizing

the SC in the future (Klötzer & Pflaum, 2017) The proposed model consists of 5 levels of maturity (Digitization awareness, Smart products, smart services, service systems, and data-driven) (Klötzer & Pflaum, 2017)

Although, this model has added value to the literature as it had addressed the MM within a digitized SC. However, it has been only applied on the German manufacturing enterprises, not mention it's inapplicability on SMEs.

2.8.8 (MM7): Guideline Industrie 4.0

This MM focuses on certain guidelines that could allow German SMEs to implement I4.0, on 5 stages, namely: (Knowledge, analysis, creativity, evaluation, and application) (Mittal et al., 2018; Angreani, Vijaya and Wicaksono, 2020).

Moreover, the said model provides a step-by-step information for SMEs to realize their vision towards I4.0. However, the proposed method lacks a few information related to the types of digitization tools e.g., sensors, IoT, etc. Furthermore, industry sector is not mentioned (Mittal et al., 2018; Angreani, Vijaya and Wicaksono, 2020).

2.8.9 (MM8): Smart Assessment Model

This assessment model uses the analytic network process (ANP) method, focusing on evaluating the level of smart factory more precisely as well as to determine the weights of criteria, and main dimensions for decision makers (Schuh et al., n.d.).

Authors have summarized the main elements of smart manufacturing (e.g., production process, efficiency, zero-waste, ICT integration, etc.) and proposed a conceptual framework for SMEs assessment. The assessment model consists of 4 main criteria and 10 sub-criteria: (Leadership: Leadership & strategy as sub-criteria), (Process: Product Development, Product Planning, Process Control, Quality Control, Facility Management, and Logistics Management as sub-criteria), (System & Automation: Information System, and Facility Automation as sub-criteria), (Performance: Performance Assessment as sub-criteria) (Lee et al., 2017).

This model was practically applied on 20 SMEs (manufacturing sector) in the Republic of Korea and found that ANP method reflects more precise weighting calculations. Therefore, it can be generalized on more future studies (Lee et al., 2017).

2.8.10 (MM9): Actech Industrie 4.0 Maturity Index

This model provides manufacturing enterprises with a guideline that might be a tailored digital roadmap for I4.0 adoption. Actech Industrie 4.0 Maturity Index consists of 6 stages (Computerization, connectivity, visibility, transability, predictive capacity, and adaptability) (Schuh et al., n.d.) This index has applied several case-studies in German manufacturing sector, however, none of them was bases on SMEs.

2.8.11 (MM10): DREAMY (Digital Readiness Assessment Maturity model)

This MM focuses on the manufacturing enterprise's ability for I4.0 technological change, through the assessment of strength and weakness of its current state. Moreover, it highlights the main opportunities in each enterprise allowing them to overcome their weaknesses by using digital transformation (De Carolis et al., 2017) .

This model consists of 5 readiness levels (initial, managed, defined, integrated, and digital oriented) (De Carolis et al., 2017). Although, this MM was applied on three case-studies in manufacturing sector, however, none of them was based on SMEs.

2.8.12 (MM11): Methodology for modelling and assessing human activities within cyber-physical systems (CPS)

Fantini, Pinzone, & Taisch (Fantini et al., 2020) have proposed a methodology that guide the process of integrating employees and managers with CPS. According to authors, this approach might encourage engineers and managers to identify their strategy and technical interventions on the shop floor.

This model consists of 6 dimensions (abstraction, decision making, innovations, social interaction, human component, and CPS component) (Fantini et al., 2020).

The mentioned methodology consists of 4 phases: problem setting, scoping, analysis, and assessment. This method was applied using two case-studies, which provided a guideline for I4.0 step-by-step adoption (Fantini et al., 2020)

However, this study has focused only on the I4.0 vertical integration (inside companies). Besides, SMEs were not mentioned.

2.8.13 (MM12): 360 Digital Maturity Assessment (360 DMA)

This model focuses on the production digital transformation in terms of facilitation and identification of the assessed company context-specific improvement. This model was applied on three case-studies having the same level of maturity. However, different recommendations have been proposed to each company according to their strategic goals, core function, and key performance indicators (Colli et al., 2019)

This assessment approach consists of 5-dimension (technology, connectivity, competences, value creation, and governance) with 5-stages of readiness (creation of awareness, definition of scope, data collection, evaluation, and debriefing) (Colli et al., 2019).

However, this model lacks verification of its effectiveness, which must be conducted by actual observation. Moreover, this model was applied only on large enterprises (Colli et al., 2019).

2.8.14 (MM13): Framework of the adoption patterns of Industry 4.0

This study aims to clarify the implementation patterns of I4.0 in the manufacturing sector, through proposing a framework. The proposed framework consists of two layers: front, and base technologies. Front-layer considers 4-demnsions (smart manufacturing, products, SC, and working), while base technologies consist of 4-elements (Internet of Things (IoT), CPS, Big Data Analytics (BDA), and cloud-computing) (Frank, Dalenogare and Ayala, 2019).

The said method was applied on manufacturing companies via surveys and found that application of base-technologies might be challenging, since BDA is not implemented in most companies (Frank, Dalenogare and Ayala, 2019).

Although, this study can contribute for practical implementation, however, it lacks SMEs adoption.

2.8.15 (MM14): Development of an assessment model for industry 4.0: industry 4.0 maturity model

This MM applied SPICE (Software Process Improvement and Capability dEtemination) approach for framing a MM for I4.0 (Gökalp et al., 2017) The MM consists of 5-demensions (IT, data governance, information flow, process transformation, and organizational structure/strategy), with 5-readiness levels considering *"level-0 in-complete"*, performed, managed, established, predictable, and optimized (Gökalp et al., 2017) .

Moreover, the model highlighted the need to increase investment in employee's awareness, skills, and participation towards I4.0. However, this model does not consider SMEs due to lack of access to base-technologies e.g., IoT (Gökalp et al., 2017).

2.8.16 (MM15): Towards a framework for assessing the maturity of manufacturing companies in industry 4.0 adoption.

This model aims to evaluate the maturity stage of an enterprise that has already implemented I4.0. Although it consists of three aspects (strategy, maturity, and performance) and 30 maturity items, the study lacks a complete explanation of each maturity stage (Mittal et al., 2018).

Moreover, this model might not be suitable for SMEs, since it is based on a company model that already has taken steps towards I4.0 adoption (Mittal et al., 2018).

2.8.17 (MM16): Maturity and readiness model for Industry 4.0 strategy

This model proposed a MM that includes 4- maturity levels (level 0: I4.0 requirements not fulfilled, level 1: automation of data collection, level 2: data sharing and integration, and level 3 data sharing at high-level). Besides, 3-scopes (smart products, services, business process, and strategy) (Akdil et al., 2018) Although, this model has compared previous MM in terms of maturity, readiness, and industry sector (Akdil et al., 2018). However, the proposed model did not consider SMEs requirements(Mittal et al., 2018).

Table 4: A summary of the proposed Maturity Models.

MM	Purpose	Building Design	Base-Tech	Methods	Sector	SME
MM1 (Mittal et al., 2018; Ramos, de Freitas Rocha Loures and Deschamps, 2020)	Assess the stages of evolution to categorize companies	6 stages with 6 scopes and 18 evaluations criteria	HI&VI	Online Survey	Manufacturing and industrial Engineering	Yes
MM2 (Ramos, de Freitas Rocha Loures and Deschamps, 2020)	Help companies to assess their position for a digital success	4 stages and 7 scopes	HI&VI	Survey	Manufacturing	N/M
MM3 (Schumacher, Erol and Sihn, 2016)	Transforming the abstract concepts of smart manufacturing into items that can be measured in real production environments	5 stages with 9 scopes and 62 evaluation criteria	Digitization, ICT, (M2M)	interviews, Likert-scale survey)	Manufacturing	N/M
MM4 (Leyh et al., n.d.)	Classification of the IT system within the context of I4.0	5 scopes	HI&VI	Interviews and Survey	N/M	N/M
MM5(Ganzarain & Errasti, 2016)	Helps SMEs to detect future growth markets	3 stages	Technologies	Assessment analysis of SMEs profile.	Manufacturing	Yes
MM6(Klötzer & Pflaum, 2017)	Evaluation of SC and manuf.	5 maturity levels	Digitization	N/M	Manufacturing and SC	N/M
MM7 (Mittal et al., 2018; Angreani, Vijaya and Wicaksono, 2020)	Provide step-by-step for German SMEs to realize their vision towards I4.0	5 stages	Technologies	N/M	N/M	Yes

MM8 (Lee et al., 2017)	Propose a framework assessment for smart factories	4 criteria with 10 sub-criteria	ICT	ANP	Manufacturing, Logistics, Quality control, sales.	Yes
MM9 (Angreani et al., 2020; Schuh et al., n.d.)	Helps and asses' companies to transform towards I4.0	6 stages	HI&VI	Survey, case-studies	Manufacturing/Logistics	N/M
MM10 (De Carolis et al., 2017)	Allows the assessment of the current digital readiness and identifies a set of opportunities for manufacturing companies	5 scopes	VI	Survey, case-studies	Manufacturing	N/M
MM11 (Fantini et al., 2020)	Support employee to integrate within CPS to move towards the desired scenario	6 scopes	VI	Case-studies	Manufacturing	N/M
MM12 (Colli et al., 2019)	Facilitate the contextualization of the assessed company and identify of a specific improvement recommendation	5 scopes with 5 readiness levels.	HI&VI	Survey, case-studies	Manufacturing	No
MM13(Frank, Dalenogare and Ayala, 2019)	Assess the maturity in smart manufacturing	5 scopes with 3 to 4 readiness levels	HI&VI	Multivariate statistics (cluster K-means)	Manufacturing and SC	Yes
MM14 (Gökalp et al., 2017)	Create a common base for assessing I4.0	5 scopes with 5 readiness levels	HI&VI	N/M	Manufacturing	No
MM15 (Mittal et al., 2018)	Evaluate the maturity stage of enterprises already started the adoption of I4.0	3 scopes with 30 readiness levels	HI&VI	Interviews	Manufacturing	No

MM16 (Akdil et al., 2018)	Provides an index to calculate the readiness for organizations towards I4.0	4 levels of maturity with 3 scopes	HI&VI	Survey	Manufacturing/ SC	No

2.9 Findings and Discussions

Figure (4) illustrates the main analysis of the studied maturity models (MM). Concerning large enterprises in the manufacturing sector: Technological Infrastructure (81.3%), Organizational Strategy (56.3%), Data Processing & Analytics (50%), Smart Manufacturing, Digitized Business, Product Development, and Digitization of Products (all with 44%) are the main MM scopes studied in previous research.

This somehow reflects the emergence of digitization in the coming era, that's pave the way for I4.0 adoption in the manufacturing sector. Concerning SMEs, previous studies reflect the shortage of MM application in relation to SMEs as only 5 studies have focused on SMEs (see Table:1).

However, the analysis of these studies shows that the main MM scopes might be suitable for SMEs are: Smart Manufacturing, Smart SC, Product Development, Digitized Products, Technological Infrastructure, Smart Logistics, Performance Evaluation, Employee participation, and Data Collection & Processing. These findings reflect the awareness of SMEs towards I4.0 as well as smart logistics and SC (see fig. (2)). Although SMEs faces related challenges like lack of governmental support, skilled employees, technological infrastructure, and other barriers (Elhusseiny and Crispim, 2022).

However, the analysis of the mentioned MM reflects SMEs intention to change and competing large/multinational enterprises in the future. Especially, SMEs are the main driving force of manufacturing sector (Mittal et al., 2018; Elhusseiny and Crispim, 2022).

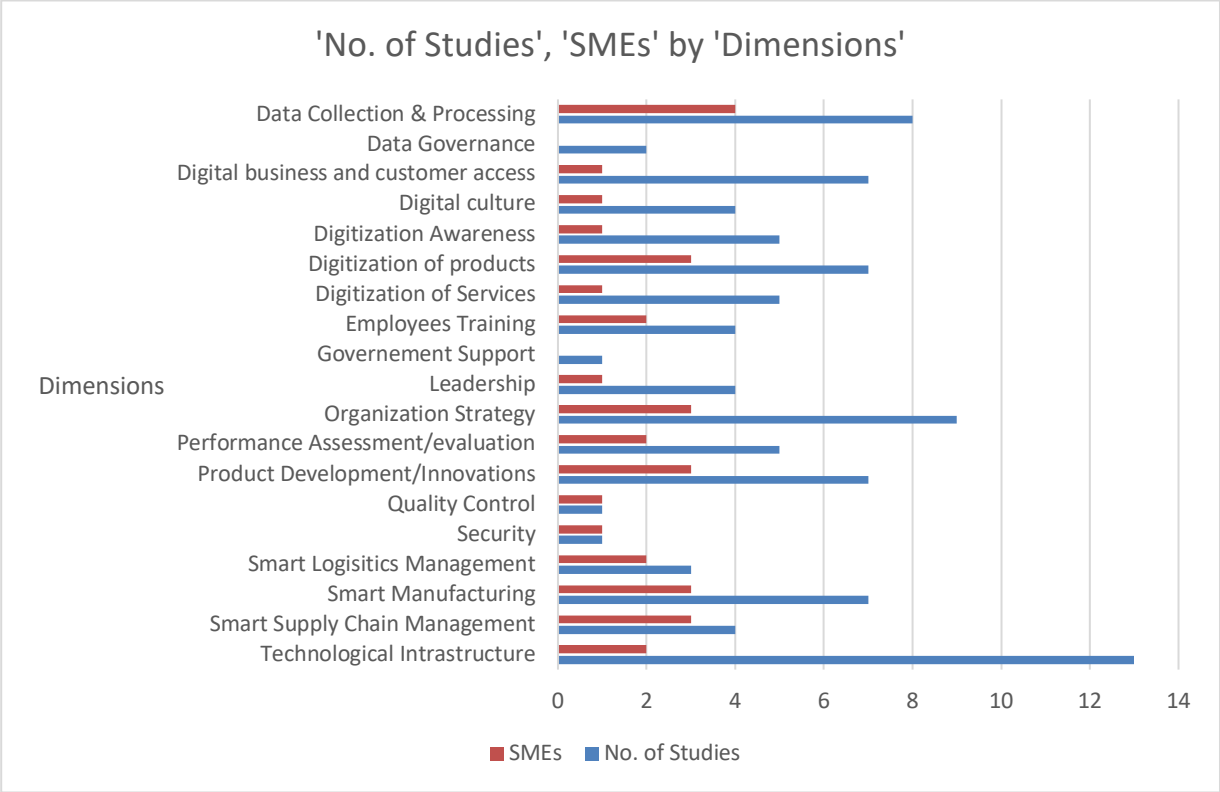


Figure 4: Maturity Models Main Scopes.

Source: Author's Own Contribution.

2.10 Conclusion and Future Research Directions

This review begins with identifying the main requirements of SMEs MM in the manufacturing sector, which are Finance, Technical Resources Availability, Employee Participation, Product Specialization, Alliances, Organizational Culture, and Collaboration.

Then, a critical review of the current on MM I4.0 within manufacturing and logistics/SC sectors is conducted through a guiding (RQs), to establish a solid finding towards the main MM scopes that could be used for SMEs as well as large enterprises.

Moreover, identifying the main levels that may pave the way for SMEs to adopt I4.0. Results of the review show that: Technological Infrastructure, Organizational Strategy, Data Processing & Analytics, and Digitization of products and services are the main scopes studied in large enterprises. In terms of SMEs, this review demonstrates the lack of MM studies (5 and only "2" studied logistics/SC).

Furthermore, Smart Manufacturing, Smart SC, Product Development, Digitized Data collection & Analytics, Technological Infrastructure, Smart Logistics, Performance Evaluation, and Employee participation are the main scopes for SMEs MM I4.0 manufacturing and logistics sectors. Therefore, there is a space for topics like digitized SC and logistics I4.0 MM in SMEs within the manufacturing industry, and SMEs specific requirements in the context of developing countries for I4.0 adoption.

2.11 Section Three: A Review of Industry 4.0 Maturity Models: Theoretical Comparison in The Smart Manufacturing Sector

Abstract

The purpose of this study is to conduct a theoretical review of the existing Industry 4.0 (I4.0) Maturity Models (MM) in the manufacturing sector, with a focus on both large and small and medium enterprises (SMEs), to gain an in-depth understanding of the present state-of-the-art A comprehensive analysis was conducted on a total of sixteen maturity models within the manufacturing sector, encompassing a range of scopes and stages. Notably, only six of these studies specifically focused on SMEs. In order to achieve this objective, the present study has identified the common scopes of MM (manufacturing sector) that have been examined in the context of both large/multinational enterprises and SMEs. These scopes include organizational strategy, smart factory, smart operation, smart product, vertical integration (VI), horizontal integration (HI), employees, leadership, customers, culture, governance, technology, data-driven governance, IT infrastructure, and information systems. In the context of MM stages, research emphasized an initial/basic stage level that enables SMEs to facilitate the adoption of I4.0 in the manufacturing sector.

Keywords: Industry 4.0; SMEs; Maturity Model; Smart Manufacturing; Stages; Dimensions.

2.12 Introduction

In today's world, economic challenges driven by cutting-edge technologies force manufacturing enterprises to improve their agility and responsiveness towards value-chain management in many industrial sectors. Therefore, manufacturing enterprises require assistance of virtual and physical technologies, which provides real-time integration of business and process (Akdil et al., 2018). Implementation of Industry 4.0 (I4.0) requires wide applications in enterprises since the outcomes of I4.0 investments are uncertain due to the lack of knowledge of its concepts (Akdil et al., 2018).

Hence, a maturity model (MM) might be a tool used to identify a large scale of knowledge about an enterprise current state and pave a path/roadmap to pursue I4.0 adoption (Akdil et al., 2018; Elhusseiny & Crispim, 2023).

Moreover, MM enables companies to audit, benchmark, track progress, evaluate strengths, weaknesses, and opportunities regarding to assessment results (Akdil et al., 2018). In other words, MM might provide a guidance for SMEs having a vision for I4.0 adoption in relation to process and practices implemented, allowing a room for improvement through several stages and scopes/dimensions (Elhusseiny & Crispim, 2023).

Thus, the purpose of this research is to conduct a theoretical comparison between I4.0 MM in the manufacturing sector, to determine the main MM scopes and stages studied between models. Moreover, to clarify the similar scopes between all models, which somehow reflects the importance of these common scopes in terms of enterprise's maturity and vision towards I4.0 adoption. Besides, clarifying the required stages/level for enterprises, especially SMEs that might be a guide for I4.0 adoption in the early stages.

The scope of this review is guided by the following research questions:

- (RQ1): what are the similar and different MM scopes/dimensions between I4.0 MM in the manufacturing sector?
- (RQ2): what are the required MM stages of I4.0 implementation in the manufacturing sector for SMEs/newcomers (e.g., enterprises)?

Research published between 2015 and 2022 was reviewed to synthesize the similar MM scopes and stages, as well as the different studied scopes to answer the research questions.

Until now, most MM studies a) focused on large/multinational enterprises, b) SMEs initial stages/levels for newcomers have been studied in only four studies (e.g., MM1, MM3, MM5, MM7 (See

Table:1)), c) some studies (e.g., MM2) missed SMEs financial constraints and lack of knowledge especially in developing countries, d) this review updates the current literature by determining the similar MM scopes and required stages for SMEs.

This theoretical comparison is based on the recent published studies from the following databases: ScienceDirect, Scopus, Google Scholar, and Springer. The search terms were based on recent articles to maturity models, SMEs, and manufacturing sector. [Title/Abstract]: “Maturity model” AND “Scopes” OR “Dimensions” AND “Stages” OR “Levels” AND “Implementation” OR “Adoption” AND “Industry 4.0” AND “SMEs” AND “Manufacturing” OR “Industrial” AND “Logistics” OR “Supply chain”.

The present paper is structured in the following manner. In Section 2, a theoretical comparison of I4.0 maturity models (MM) in the manufacturing sector was conducted. This comparison was based on a comprehensive analysis of relevant scientific articles obtained from existing databases.

The literature review encompassed many scopes and stages of MM, highlighting both similarities and differences among them. Section 3 of the paper provides a comprehensive examination of the various MM models and proposes suitable dimensions and stages/levels of MM specifically tailored for SMEs. Finally, section 4 provides a concise recommendation for potential future research that may arise from the findings presented in this study.

2.13 A Theoretical Comparison of Industry 4.0 Maturity Models

A total of 16 I4.0 MM were reviewed in terms of stages and scopes in the manufacturing sector. The reviewed MM were applied on SMEs (Elhusseiny & Crispim, 2023). The mentioned MM proposed a strategy for large, multinational enterprises as well as SMEs (e.g., MM5) to be as a main enabler of I4.0 implementation (Ganzarain and Errasti, 2016).

Moreover, to assess, evaluate, and measure enterprises’ current position and provide instructions for future enhancements (e.g., MM2, MM3) and the necessary requirements, which needed to be achieved to fulfil I4.0 environment (Schumacher, Erol and Sihn, 2016; Mittal et al., 2018).

Furthermore, highlighting the opportunities and benefits of adopting I4.0, in terms of allowing enterprises of changing the traditional manufacturing environment to a smart manufacturing environment, coping with advanced technological changes, and overcoming their weaknesses by digital transformation (De Carolis et al., 2017). The said maturity models have also summarized the main elements of smart

manufacturing, like smart manufacturing processes, efficiency, zero-wastes, product development, efficient planning, facility management, smart services, efficient logistics management, employee's technological skills, managers skills, process, and quality control.

According to, the studied MM consider the vertical (VI) and horizontal integration (HI) (e.g., Internet of Things (IoT), Big Data Analytics (BDA), Cyber Physical System (CPS)) as the base technologies for I4.0 adoption (Mittal et al., 2018; Ramos, de Freitas Rocha Loures and Deschamps, 2020). Considering, SMEs, digitization, (HI &VI), and advanced ICT will support SMEs integration with suppliers, distributors, and customers (Mittal et al., 2018; Ramos, de Freitas Rocha Loures and Deschamps, 2020; Elhusseiny and Crispim, 2023), allowing them to compete large enterprises and opening the gate for competition in foreign markets (Mittal et al., 2018; Elhusseiny and Crispim, 2023).

The following section will compare the studied sixteen MM in terms of scopes and stages, to clarify the similar and different scopes studied between them. In addition, to determine the common scopes and recommend the necessary stages for SMEs, and newcomers towards I4.0 adoption.

2.13.1 MM Comparison in terms of Scopes

As shown in Table (5), the following MM have studied the fourth-generation industry adoption, some of them have been applied on SMEs in the manufacturing sector like (MM1, MM5, MM7, MM8, and MM13), while the others have been applied on large enterprises. Although, the building design of each of the mentioned models varies in terms of the number of stages as well as scope.

However, it has been observed that there are some common scopes between these models. According to the comparison, the common scopes are: Organizational strategy, Smart factory, Smart Operation, Smart product, Vertical integration (VI), Horizontal integration (HI), Employees, Leadership, Customers, Culture, Governance, Technology, Data-driven/governance, IT-infrastructure, and Information systems.

These similar scopes somehow reflect the main dimensions that have be available in a MM for SME manufactural sector to pave the way for I4.0 adoption. Moreover, Table (6) clarifies the similar maturity scopes and some exemplary maturity items.

2.13.2 MM differences in terms of Scopes

Although, the MM have some similar scopes, however, there are some differences between them like: Data collection, Digital business models, Digitization, Data analytics, Compliance security, Digital product development, Cross-sectional technology criteria, Digitization awareness, Smart services, Services systems, Production process, System Automation, Performance, Resources, Connectivity, Value creation, Competences, Smart working, Supply Chain (SC) collaboration, Information flow, Process transformation, Maturity, and Business process.

This somehow reflects the necessity of digitization for the transformation from traditional manufacturing to a smart manufacturing (SM) process (Frank, Dalenogare and Ayala, 2019). (See Appendix A.2).

Table 5: Maturity Models Comparison in terms of stages and dimensions.

MM	Stages/Levels	Scopes/Dimensions	SMEs	Reference
MM1: IMPULS-Industrie 4.0 Readiness	S1 Outsider S2 Beginner S3 Intermediate S4 Experienced S5 Expert S6 Top Performer	D1 Organizational Strategy D2 Smart Factory D3 Smart Operation D4 Smart Product D5 Data Collection D 6 Employees	Yes	(Mittal et al., 2018; Ramos, de Freitas Rocha Loures and Deschamps, 2020)
MM2: Industry 4.0/Digital operations self-assessment (PwC)	S1 Digital Novice S2Vertical Integrador S3Horizontal Collaborator S4Digital Champion	D1 Digital Business Models & Customer Access D2 Digitization of products & Services D3 Digitization & integration of vertical & horizontal value-chains D4 Data Analytics D5 IT infrastructure D6 Compliance Security D7 Organization, employees & digital culture	N/M	(Geissbauer et al., 2016)
MM3: Industry 4.0 Maturity Model	S1 Measurement of Maturing Items in Enterprise S2 Calculate of Maturity Level.	D1 Strategy D2 Leadership D3 Customers	Yes	(Schumacher, Erol and Sihn, 2016)

	S3 Representation & visualization of MM report	D4 Products D5 Operations D6 Culture D7 People D8 Governance		
MM4: SIMMI 4.0 (System Integration Maturity Model for I4.0)	S1 Basic Level S2 Cross-department digitization S3 Horizontal & vertical integration S4 Full digitization S5 Optimized digitization	D1 Vertical Integration D2 Horizontal Integration D3 Digital Product Development D4 Cross-Sectional Technology Criteria	N/M	(Leyh et al., n.d.)
MM5: Maturity Model in SMEs towards Industry 4.0	S1 Development of I4.0 Vision S2 I4.0 Technological vision informed by network. S3 Polices, Management & training for employees	D1 Strategy D2 Leadership D3 Customers D4 Products D5 Operations D6 Culture D7 People D8 Governance D9 Technology	Yes	(Ganzarain and Errasti, 2016)
MM6: Maturity Model for Digital Transformation	S1 Digitalization awareness S2 Smart networked products S3 Thinking of service systems. S4 The service-oriented enterprise S5 The data-driven enterprise	D1 Digitization Awareness D2 Smart Products D3 Smart Services D4 Services Systems D5 Data-driven	N/M	(Klötzer & Pflaum, 2017)
MM7: Guideline Industrie 4.0	S1 Knowledge S2 Analysis S3 Creativity S4 Evaluation S5 Application	D1 Integration of Sensors D2 No use of Sensors D3 Sensor Readings D4 Data Evaluation & Analysis D5 Product Independency D6 Data Processing in Production D7 No Processing of Data D8 Storage of Documented Data	Yes	(Mittal et al., 2018; Angreani, Vijaya and Wicaksono, 2020)

		D9 Analysing Data		
MM8: Smart Assessment Model	S1 Leadership S2 Process S3 System &Automation S4 Performance	D1 Production Process D2 System & Automation D3 Performance D4 Leadership	Yes	(Lee et al., 2017)
MM9: Actech Industrie 4.0 Maturity Index	S1 Computerization S2 Connectivity S3 Visibility S4 Transability S5 Predictive Capacity S6 Adaptability	D1 Resources D2 Information Systems D3 Organizational Structure D4 Culture	N/M	(Angreani et al., 2020; Schuh et al., n.d.)
MM10: DREAMY (Digital Readiness Assessment Maturity model)	S1 Initial S2 Managed S3 Defined S4 Integrated & Interoperable S5 Digital Originated	N/M	N/M	(De Carolis et al., 2017)
MM11: Methodology for modelling and assessing human activities within cyber-physical systems (CPS)	S1 Problem Setting S2 Scoping S3 Analysis S4 Assessment	D1 Abstraction D2 Decision Making D3 Innovations D4 Social Interaction D5 Human Component D6 CPS Component	N/M	(Fantini et al., 2020)
MM12: 360 Digital Maturity Assessment (360 DMA)	S1 Creation of Awareness S2 Definition of Scope S3 Data Collection S4 Evaluation S5 Debriefing S6 Integrated	D1 Technology D2 Connectivity D3 Value Creation D4 Competences D5 Governance	No	(Colli et al., 2019)
MM13: Framework of the adoption patterns of Industry 4.0	S1 Smart Manufacturing S2 Smart Products S3 Smart Working S4 Smart Supply Chain S5 Base Technologies (I4.0)	N/M	Yes	(Frank, Dalenogare and Ayala, 2019)
MM14: Development of an	S1 Level 0 (in complete) S2 Performed	D1 IT D2 Data Governance	No	(Gökalp et al., 2017)

assessment model for industry 4.0: industry 4.0 maturity model	S3 Managed S4 Established S5 Predictable S6 Optimized	D3 Information Flow D4 Process Transformation D5 Organizational Structure/Strategy		
MM15: Towards a framework for assessing the maturity of manufacturing companies in industry 4.0 adoption	N/M	D1 Strategy D2 Maturity D3 Performance	No	(Mittal et al., 2018)
MM16: Maturity and readiness model for Industry 4.0 strategy	S1 I4.0 Requirements not fulfilled. S2 Automation of data collection S3 Data sharing &integration	D1 Smart Products D2 Smart Services D3 Business Process	No	(Akdil et al., 2018)

Table 6: Common Maturity Scopes and Exemplary Maturity Items.

#	Maturity Dimensions	Exemplary Maturity Items
1	Organizational Strategy	• Strategic planning • I4.0 corporate strategy • Implementing I4.0 roadmap • Adopting business models • Realizing available resources for digitization & smart automation • Flexible communication • Agile management • customer benefits • cooperation within the network • knowledge/ IT skills • Business strategy (IT investments, IoT roadmap, enhancements of products by IoT, developments of new products) • Technology strategy (cyber security, choice of platforms standards) • Networking & integration (HI & VI data sharing, IoT systems)

2.14 Discussion and Findings

As previously mentioned, I 4.0 MMs have similar and different scopes, the similar scopes classify I4.0 environment as follows:

- organizational strategy, which address the strategic planning and control of I4.0 business strategy in terms of IT investments, implementing I4.0 roadmap, cyber security, realizing available resources for digitization, HI & VI (Schuh et al., no date; Ganzarain and Errasti, 2016; Schumacher, Erol and Sihn, 2016; Gökalp, Şener and Eren, 2017; Mittal et al., 2018; Ramos, de Freitas Rocha Loures and Deschamps, 2020).
- smart factory, which aims to establish a highly automated productive environment (e.g., Equipment infrastructure, IT systems like ERP, MES, Digitized machines, Traceability (final products, raw materials), Energy Management (Energy consumption, Energy monitoring), Automation (automated identification, industrial robots, M2M communication), Virtualization (AI for maintenance, AI for production), Flexibilization (Flexible line, additive manufacturing) (Mittal et al., 2018; Frank, Dalenogare and Ayala, 2019; Ramos, de Freitas Rocha Loures and Deschamps, 2020).
- smart operation, which aims for virtual and physical integration (e.g., Information Sharing, Cloud usage, IT security, Decentralization of processes, Modeling & simulation, Interdepartmental collaboration, Data Analytics (Ganzarain and Errasti, 2016; Schumacher, Erol and Sihn, 2016; Mittal et al., 2018; Frank, Dalenogare and Ayala, 2019; Ramos, de Freitas Rocha Loures and Deschamps, 2020).
- smart products, which aims to facilitate the automated and efficient production management (e.g., using ICT functions of product for self-reporting, identification, localization, Online presence, Integrated customer management, Customized products, and Data processing (Ganzarain and Errasti, 2016; Klötzer and Pflaum, 2017; Akdil, Ustundag and Cevikcan, 2018; Mittal et al., 2018; Frank, Dalenogare and Ayala, 2019; Ramos, de Freitas Rocha Loures and Deschamps, 2020).
- Vertical Integration (VI) & Horizontal Integration (HI) which aims to the integration of the different departments inside an enterprise (e.g., production) and outside enterprise like the SC members (e.g., suppliers, manufacturer, and external customers) (Carvajal Carmen L.and Moreno, 2017; Gökalp, Şener and Eren, 2017; Mittal, Romero and Wuest, 2018; Frank, Dalenogare and Ayala, 2019; Schuh and Frank, 2020).

- Employees, which helps to realize digital transformation of employees through employee's awareness, technical skills, and trainings (e.g., Digital skills, ICT competences of employees, Openness of employees to new technology) (Ganzarain and Errasti, 2016; Schumacher, Erol and Sihn, 2016; Mittal, Romero and Wuest, 2018) .
- Leadership, which aims to improvement of management strategies (e.g., Management of digital competences & methods, Existence of central coordination for I4.0 strategy, Leadership & strategy) (Ganzarain and Errasti, 2016; Schumacher, Erol and Sihn, 2016; Lee et al., 2017) .
- customers, which aims for better utilization of customer data, Digitization of sales/services, Customers digital media competences (Ganzarain and Errasti, 2016; Schumacher, Erol and Sihn, 2016).
- culture, which aims to willing to change, openness to innovation, social collaboration, and knowledge sharing (Ganzarain and Errasti, 2016; Schumacher, Erol and Sihn, 2016; Angreani, Vijaya and Wicaksono, 2020; Schuh and Frank, 2020) (for the other dimensions See Appendix B & C).

In terms of stages, four maturity models (MM) mentioned an (outsider/ absence/basic level/ Initial) stage for SMEs (e.g., MM1 (Mittal et al., 2018; Ramos, de Freitas Rocha Loures and Deschamps, 2020), MM3 (Schumacher, Erol and Sihn, 2016), MM5 (Ganzarain and Errasti, 2016), MM7 (Mittal et al., 2018; Angreani, Vijaya and Wicaksono, 2020)). In addition to, MMs that studied large enterprises (e.g., MM4 (Leyh et al., n.d.), MM10 (De Carolis et al., 2017), MM12 (Colli et al., 2019) , MM14 (Gökalp et al., 2017), MM16 (Akdil et al., 2018)).

This demonstrates the importance of the basic stage specifically for the newcomers SMEs that have never utilized any I4.0 projects and are willing to pave a vision of adoption (Akdil et al., 2018). Moreover, it allows enterprises to measure, audit, their maturity stage (Akdil et al., 2018).

Based on the previous discussion, it is proposed the following stages for I4.0 adoption: Level 0: Absence, Level 1 Beginner, Level 2 Existence, Level 3: Survival, Level 4: Maturity. (See table 7).

Table 7: A Proposed Industry 4.0 Maturity Stages for SMEs & Newcomers.

Maturity Stages	Exemplary Maturity Stages	References
Level 0: Absence	Enterprises that do not meet any of I4.0 requirements/lack of I4.0 awareness/ no adoption of digital technology.	(Akdil, Ustundag and Cevikcan, 2018; Mittal et al., 2018)
Level 1 Beginner	Roadmap/vision is available/newcomer.	(Akdil, Ustundag and Cevikcan, 2018; Mittal et al., 2018)
Level 2: Existence	Not fully smart/integration & smart manufacturing at low level/ Digitization is not applied to all operations.	(Akdil, Ustundag and Cevikcan, 2018; Mittal et al., 2018)
Level 3: Survival	Medium level of real-time integration and automation.	(Akdil, Ustundag and Cevikcan, 2018; Mittal et al., 2018)
Level 4: Maturity	High level of digitization/integration/ smart manufacturing.	(Akdil, Ustundag and Cevikcan, 2018; Mittal et al., 2018)

2.15 Conclusion and Future Directions

This review begins with a theoretical comparison between I4.0 Maturity Models (MM) in the manufacturing sector, to identify the similar and different scopes as well as stages studied between models. Then, a theoretical comparison was conducted through a guiding (RQs), to establish a solid finding towards the similar MM scopes and the necessary stages for beginners/newcomers (SMES/Large enterprises).

Results of this review show that: Organizational strategy, Smart factory, Smart Operation, Smart product, Vertical integration (VI), Horizontal integration (HI), Employees, Leadership, Customers, Culture, Governance, Technology, Data-driven/governance, IT-infrastructure, and Information systems, are the main scopes studied between MM. In terms of stages, this review demonstrates the necessity of a basic level/stage-0 for enterprises, which do not develop a roadmap for I4.0. However, they are willing to adopt I4.0 in future. Therefore, there is a space for future topics like customized stages, scopes for SMEs in developing countries within the manufacturing industry in terms of technologies, digitization level in the context of I4.0 adoption.

3. Chapter Three: Assessing Industry 4.0 Adoption in Cairo SMEs: A Study on THE MANUFACTURING Sector.

Abstract

Industry 4.0 (I4.0) enables Small and Medium Enterprises (SMEs) to enhance their competitiveness through advanced Information and Communication Technologies (ICT). This study addresses the lack of tailored I4.0 maturity models (MMs) for SMEs in developing countries by proposing a customized framework for Cairo's manufacturing sector. A two-round Delphi survey involving 19 industrial experts was conducted. The first round assessed existing ICT levels, IT systems, stakeholder involvement, and training needs, while the second round identified the most relevant dimensions for a tailored model. Findings show moderate ICT integration, widespread ERP use, and partial digital transformation among Cairo SMEs. However, the adoption of advanced I4.0 technologies remains limited. The proposed MM incorporates ten validated dimensions like organizational strategy, smart operations, culture and leadership, and organizes them into five developmental stages. This framework provides a structured, context roadmap to support digital transformation among manufacturing SMEs in Cairo and similar developing contexts.

Keywords: Industry 4.0, Cairo SMEs, Manufacturing Sector, Developing Countries, Maturity Model, Delphi Method.

3.1 Introduction

Industry 4.0 (I4.0) is a German initiative targeting the enhancement of value within manufacturing industries and services by utilizing advanced technologies and integrating production systems with product lifecycles and supply chain activities (Müller et al., 2018). I4.0 offers substantial benefits to SMEs, fostering innovation and enabling participation in global markets (Mittal, Khan, et al., 2018; Vanninen et al., 2022).

The successful implementation of I4.0 relies on the use of digital technologies like cyber-physical systems (CPS) to create intelligent manufacturing processes, utilizing technologies such as the Internet of Things (IoT), cloud computing, robotics, virtual reality, big data analytics (BDA), artificial intelligence (AI), and 3D printing (Javaid & Haleem, 2019; S. S. Kamble et al., 2018; Luthra & Mangla, 2018).

The technologies mentioned aim to transform the manufacturing processes and improve efficiency, quality, and responsiveness to market demands. Here are some examples of such technologies as follows:

- *Internet of Things (IoT)*

IoT enables connectivity between physical devices and systems, allowing for real-time data collection and exchange. In manufacturing, IoT can be used for predictive maintenance, asset tracking, and monitoring production processes (Javaid & Haleem, 2019; S. S. Kamble et al., 2018; Luthra & Mangla, 2018).

- *Cyber-Physical Systems (CPS)*

CPS integrates physical processes with digital networks, using sensors, actuators, and control systems to create smart production environments. This allows for automated, real-time adjustments in manufacturing operations (Javaid & Haleem, 2019; S. S. Kamble et al., 2018; Luthra & Mangla, 2018).

- *Big Data Analytics (BDA)*

Big data analytics involves processing large volumes of data to extract insights and inform decision-making. In manufacturing, BDA can optimize supply chain management, improve product quality, and enhance operational efficiency (Javaid & Haleem, 2019; S. S. Kamble et al., 2018; Luthra & Mangla, 2018).

- *Artificial Intelligence (AI)*

AI can analyse data to identify patterns, predict outcomes, and make autonomous decisions. Applications include quality control, demand forecasting, and process optimization (Ganzarain and Errasti, 2016; Schumacher, Erol and Sihn, 2016; Frank, Dalenogare and Ayala, 2019).

- *Cloud Computing*

Cloud computing provides scalable and flexible IT resources over the internet. Manufacturing companies use cloud platforms for data storage, processing, and enabling collaboration across different locations (Javaid & Haleem, 2019; S. S. Kamble et al., 2018; Luthra & Mangla, 2018).

- *Robotics and Automation*

Advanced robotics automates repetitive tasks, increase precision, and improve productivity. Robotics can be used for assembly, material handling, and packaging processes (Frank et al., 2019; Mittal, Khan, et al., 2018).

- *Additive Manufacturing (3D Printing)*

3D printing allows the creation of complex, custom parts layer by layer from digital models. It is used for prototyping, custom manufacturing, and production of lightweight components (Frank et al., 2019; Mittal, Khan, et al., 2018).

- *Virtual Reality (VR) and Augmented Reality (AR)*

VR and AR technologies create immersive experiences for training, maintenance, and design visualization. AR can overlay digital information onto the physical world, aiding in complex assembly tasks (Frank et al., 2019; Mittal, Khan, et al., 2018).

- *Enterprise Resource Planning (ERP) Systems*

ERP systems integrate various business processes and information flows within an organization. They help in managing production, inventory, orders, and financials efficiently (Frank et al., 2019; Mittal, Khan, et al., 2018).

- *Manufacturing Execution Systems (MES)*

MES provides real-time monitoring and control of manufacturing operations. It connects, monitors, and controls complex manufacturing systems and data flows on the factory floor (Frank et al., 2019; Mittal, Khan, et al., 2018).

The said technologies collectively enable smart manufacturing, where processes are interconnected, automated, and optimized through continuous data exchange and advanced analytics. Moreover, these technologies are essential for driving economic development, encouraging industrial growth, and establishing a sustainable supply chain for existing industrial systems (Aboelmaged, 2018; Mittal, Romero, and Wuest, 2018).

Therefore, I4.0 introduces new methods to transform production and manufacturing by integrating information technology with industrial processes and to enhance product and process quality while satisfying global market demands and customer expectations (Häring et al., 2023).

Furthermore, for SMEs as a major driving force and economic backbone of many economies and manufacturing industries (Häring et al., 2023); I4.0 presents significant opportunities for SMEs, enabling them to innovate, enter global markets, and compete internationally (Mittal et al., 2018). These opportunities include digital collaboration, sustainability, flexibility, real-time information, mass-customization, smart manufacturing, cost reduction, and IT integration (Elhusseiny & Crispim, 2021).

Nonetheless, SMEs face many barriers and challenges towards technological adoption; this is due to technical (AL-Shboul, 2019), organizational, technological, and legal barriers (Ghadge et al., 2020).

The successful adoption of I4.0 depends on a maturity model (MM) that identifies and enterprise's current technological state and provides a roadmap for advancement (Angreani et al., 2020) through outlining the dimensions and exemplary maturity item (Carvajal Carmen L. and Moreno, 2017; Elhusseiny & Crispim, 2023).

Researchers like Mittal et al., (2018) and Häring, Pimentel and Teixeira, (2023) have mentioned that MMs are a well-established method for evaluating a company's level of I4.0 adoption. In order to help enterprises assess their current maturity level and develop a roadmap for improvement to reach the desired level of maturity.

Nevertheless, SMEs primarily rely on conventional manufacturing techniques, resulting in their inability to meet the diverse and fluctuating demands of customers. Consequently, adopting I4.0 could provide SMEs with new opportunities to innovate and compete globally (Mittal, Khan, et al., 2018; Touijer & Elabjani, 2025).

The implementation of I4.0 involves MMs and readiness models, which help enterprises assess their current capabilities (Häring et al., 2023) or identify areas for improvement (Angreani et al., 2020). Researchers like Mittal et al., (2018); Angreani, Vijaya and Wicaksono, (2020) Touijer and Elabjani, (2025) have proposed MMs to provide SMEs with a roadmap towards I4.0 adoption. However, most of the existing studies on I4.0 MMs focus on large/multinational companies (e.g., (Ramos, de Freitas Rocha Loures and Deschamps, 2020)) with limited consideration of SMEs' specific needs, particularly their financial and technological constraints in developing countries. In addition to the various numbers of MMs, with their many

dimensions, stages, and requirements which add confusion to SMEs to develop a vision or roadmap for I4.0 adoption (Elhusseiny & Crispim, 2023).

A MM comprises: the input data, the model itself, and how the result, i.e., how the maturity level is presented. The literature is vague regarding the data, but it is important to understand how it is collected (questionnaires, checklists, etc.), and whether it is possible to have a consensual data collection instrument that can be applied to a wide range of maturity models. Regarding the models, various dimensions and indicators that measure them are suggested, some common to each other and others differing (Magdy Elhusseiny & Crispim, 2023).

Understanding, through comparative analysis, what distinguishes the models and the rationale behind them is important to better justify the adoption of a given model. The number of maturity levels presented by the models also varies greatly, apparently, because the authors want to provide more detail on the evolution of technology adoption or, conversely, to offer simpler models. Identifying which is appropriate for the context has not been studied in the literature.

These models have been developed for developed economies, with no reference to emerging economies in developing countries, raising the question of whether these models can be applied to these countries.

This study will seek to address the previously identified gaps through:

a. A comparative study of the maturity models identified in the literature,
b. Their exploratory application in the Cairo region of Egypt, and
c. The development of a model tailored to the specific context of this region.

According to the American Chamber of Commerce in Egypt, Cairo functions as a crucial centre for the country's manufacturing sector. The city's strategic positioning, strong infrastructure, and access to a significant consumer market have attracted both large-scale industries and SMEs (*AmCham Egypt - Egypt4Business Initiative*, n.d.).

Thus, Cairo was considered an appropriate region for this research study. The business managers from diverse sectors like Automotive, Metals & Machinery, Electrical Equipment, Food & Beverage, Textile, Agriculture, and Petrochemicals, who collaborated in this study were consulted using the Delphi method. Therefore, this study aims to address these research questions:

- RQ1: What are the key maturity dimensions applicable to manufacturing SMEs in a developing country context?

- RQ2: How can these dimensions be structured into a practical, stage-based MM to guide their adoption?

The main contribution of this research study is threefold: First, the development of a diagnostically and context-customized I4.0 MM. The artifact addresses acritical gap in the literature, where MM frameworks, often designed for large corporations in developed economies, fail to account for the unique operational and institutional realities of SMEs in developing regions.

Second, the proposed model is composed of 10 empirically validated dimensions and 5-structured maturity levels: Initial, Foundation, Progress, Managed, and Maturity. The model Is Inherently tailored to the manufacturing Cairo SME context.

Third, by grounding the model in the realities of Cairo's manufacturing SME, this study provides a much-needed alternative to generalized frameworks that fail to account for the institutional and operational complexities of companies in developing countries.

3.2 Cairo Manufacturing SMEs Context

To ground this study in its empirical context, this section provides a comprehensive overview of manufacturing SMEs. Based on recent statistics and international benchmarks, it outlines the scale of the sector, the current state of digital adoption, and the primary barriers and enablers shaping its digital transformation. This section provides the real-world foundation that necessitates the development of the customized I4.0 MM proposed in this thesis.

3.2.1 Digitalization in Cairo's Manufacturing SMEs

This section synthesizes empirical data and academic literature to establish the foundational context for this study. It highlights the scale of manufacturing SMEs, their digitalization status, and the main barriers and enablers shaping their I4.0 readiness. This informed contextual framing justifies the need for a contextualized I4.0 MM tailored to emerging SMEs in developing countries (Frank et al., 2019; Ghobakhloo, 2020; Touijer & Elabjani, 2025).

Manufacturing SMEs form a significant portion of Egypt's industrial base, with SMEs accounting for approximately 90% of all enterprises in the sector and employing approximately 70% of the workforce (OECD, 2025). Moreover, a recent national ICT survey (MCIT-CAMPUS, 2019-20) found approximately 70% of formal

SMEs In Egypt use computer for office tasks, while fewer than 30% engage in R&D or innovative-oriented digital use (Kamel, 2021; OECD, 2025).

This stratification reflects a pattern termed "reactive adoption", digital tools applied to Immediate operational Issues rather than strategic transformation (Ghobakhloo, 2020; Müller et al., 2018). Alos, the recent adoption of payments solutions accounts 53% as reported in "2025 Visa-MSMDA" survey (OECD, 2025).

Based on the " Technology-Organization-environment" framework (Baker, 2012), and supported by mixed-method regional studies across MENA (Al Khalifa, 2025), the key obstacles In Cairo manufacturing SMEs towards digitalization are:

- Technical: due to poor Integration with advanced systems, lack of Interoperability, and insufficient infrastructure for IoT or cloud systems (Al Khalifa, 2025).
- Organizational: due to limited financial resources (Aboelmaged, 2018; Al Khalifa, 2025) , lack of digital skills, and resistance to change (Al Khalifa, 2025).
- Environmental: due to digital ecosystem fragmentation (e.g., not digitally integrated with SC partners like suppliers), regulatory complexity, and policy gaps discourage integrated digital upgrades (OECD, 2025).

Despite the said challenges, several factors support SME digitalization in terms of policy frameworks like Egypt vision 2030 and MSME Development Law 2020, which encourage digital adoption, offering formalization Incentives and Industry support (OECD, 2025).

In addition to Institutional capacity-building, through MSMEDA and MCIT's Innovative hubs, which aims to enhance digital literacy and entrepreneurial skills (Al Khalifa, 2025; Kamel, 2021). Furthermore, public-private partnerships (PPPs), like the Visa-MSMDA for digital payment initiatives, demonstrate the necessity of collaboration in overcoming adoption barriers with private investors (OECD, 2025).

In summary, the academic and empirical evidence characterizes Cairo's manufacturing SMEs as operating a low digital baseline, with foundational ICT use but limited strategic or Integrated deployment (Aboelmaged, 2018; Al Khalifa, 2025; OECD, 2025). The dominant mode of digital adoption is reactive, while strategic organizational readiness remains significantly underdeveloped (OECD, 2025).

These insights highlight a critical misalignment with standard I4.0 MMs and demonstrates the necessity of a model that starts from these unique conditions and supports incremental transformation processes.

Therefore, this study proposes a maturity framework that aligns digital adoption with organizational capabilities. By focusing on relevant dimensions for SMEs, validated through the Delphi method, this model assists SMEs in transitioning from initial digital usage to a structured digital maturity.

3.3 Research Design and Approach

This study adopted a multi-stage, mixed-method exploratory research design to develop and validate customized I4.0 MM for manufacturing SMEs. The research was executed in four primary phases moving sequentially from broad theoretical exploration to specific, context-driven model creation and validation.

This approach Is appropriate for complex, emerging topics like I4.0 adoption, where existing theory requires significant contextual adaptation and expert validation to ensure practical relevance (Creswell & Plano Clark, 2017). The overall research process is Illustrated in Figure 5, below.

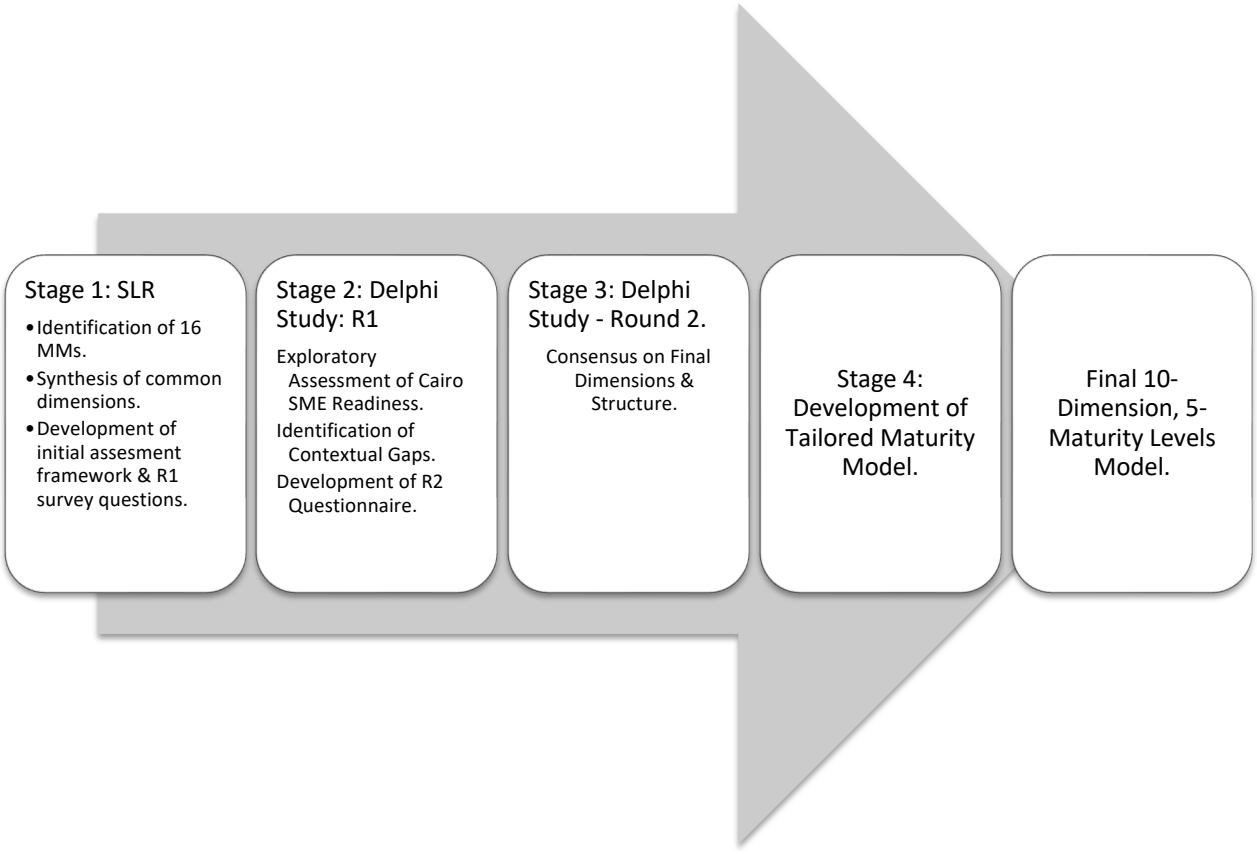


Figure 5: Timeline Illustrating Research Process

Source: Author's Own Work.

The following sections detail the procedures undertaken in each stage of the research design:

3.3.1 Stage 1: Systematic Literature Review (SLR)

The foundational stage of the research study Involved a SLR, following the established protocols for evidence-based management research (Tranfield et al., 2003), to Identify relevant I4.0 MMs and to synthesize their core conceptual components.

A systematic search was conducted in academic databases like Scopus, ScienceDirect and WoS databases trough the following terms: [Title/Abstract]: "Industry 4.0" OR "Fourth industrial revolution" OR "Industry 4.0" AND "Maturity Models" AND "SMEs" AND "Manufacturing Sector" OR "Smart Manufacturing" AND "Logistics" OR "Supply chain". This allowed us to capture literature focusing on frameworks that assess digital maturity in manufacturing contexts.

To ensure the relevance and quality of the selected research studies, strict Inclusion and exclusion criteria were applied (see Table 8).

Table 8: Inclusion and Exclusion Criteria used with explanation.

Inclusion/Exclusion	Criteria	Criteria Explanation
Exclusion	Search engines Not-Related (NR)	NR1- Search engines result that do not have any results matching with the study scope. NR2- titles/abstracts are not related. NR-3 Industry 4.0/SMEs are not related to the manufacturing sector.
	Loosely Related (LR)	LR-1 MMs are generally discussed. LR-2 MMs/readiness models are not applied. LR-3 Deals generally with the maturity of an organization without mentioning a specific field/sector.
Inclusion	Partially Related (PR)	PR-1 conducts an MM in the manufacturing sector. PR-2 proposes MM for Industry 4.0 for large enterprises in the manufacturing sector. PR-3 readiness factors for Industry 4.0 in the manufacturing sector. PR-4 reviewing other MMs concepts and adoption about Industry 4.0 in the manufacturing sector.

	Closely Related (CR)	CR-1 The research paper is mainly dedicated to MMs/readiness models adoption about Industry 4.0 in SMEs within the manufacturing sector.

Source: Author's own work.

The review Included only:

a. peer-reviewed publications proposing maturity or readiness models explicitly for manufacturing sector;
b. models that were applicable or specifically designed for SMEs; and
c. studies where the primary focus was the development or application of I4.0 assessment framework.

This transparent and reproducible search and screening process resulted In the Identification of 16 core I4.0 MMs published between 2016 and 2020. this set was deemed to represent the foundational body of knowledge for this study.

A multi-stage analytical process was conducted to constructed and synthesize the core components of the 16 MMs. The analysis began deductively by systematically extracting all reported dimensions, exemplary maturity Items and maturity levels/stages from each model into a structured spreadsheet. this process yielded a comprehensive but fragmented list, confirming a high degree of heterogeneity in the literature and reinforcing the need for a simplified, SME- relevant framework that captures core dimensions without the resource-heavy assumptions embedded in large-enterprise models (Mittal, Khan, et al., 2018).

In reviewing these 16 MMs, we noted that they include numerous dimensions with exemplary maturity items (as mentioned before). This abundance of dimensions adds to the complexity for both scholars and practitioners in determining the most suitable model or dimensions for implementing I4.0 in enterprises willing to develop a roadmap for I4.0 adoption.

Thus, this research study started with classifying these MMs according to the type of enterprises and identifying the common dimensions studied among these MMs.

To create a unified basis for the Delphi study, this research study classified 16 models and identified common themes. Each model was categorized by its intended scope, dimensions, and exemplary maturity items. Then, all dimensions were thematically grouped to find equivalences (e.g., many models include strategic dimensions variously termed "organizational strategy" or "management & strategy"), dimensions related to technology or smart factory operations, human resources or skills, and data or IT infrastructure.

Through iterative comparison, 11 common dimensions emerged as consistently appearing across multiple models. These common dimensions and their prevalence were documented; for instance, Organizational Strategy appeared in 5 of the 16 models, Smart Factory in 4 models, Smart Operations in 3 models, etc.

Alongside the dimensions, exemplary maturity items were noted for each dimension, in which illustrates the progress in that domain looks like. In total, 55 representative indicators were categorized under the 11 common dimensions. By synthesizing these findings, the literature review output was an initial integrated framework of I4.0 readiness dimensions relevant to manufacturing SMEs. This framework formed the basis for expert evaluation in the next phase. Crucially, focusing on the common dimensions addresses the gap of overly complex or large enterprises-oriented models, by highlighting the core areas that most experts agree are essential for SME digital transformation. Moreover, it also aligns with the study's purpose to simplify the roadmap for SMEs, especially in developing countries context, by concentrating on widely acknowledged dimensions.

To summarize, the reviewed literature on I4.0 MMs reveals an abundance of dimensions and maturity items, which complicates the selection of appropriate model and dimensions for SMEs aiming to adopt I4.0. Moreover, the published MMs poses challenges for scholars and practitioners in pinpointing the most suitable approach for specific organizational contexts. Additionally, most existing MMs are tailored to large and multinational companies, with limited focus on the unique needs and constraints of SMEs, particularly in developing countries.

Therefore, this study addresses a critical research gap by focusing on SMEs in Cairo's manufacturing sector, aiming to identify and tailor common dimensions from existing MMs to suit their specific context. This approach not only simplifies the adoption process for these enterprises but also provides a practical and scalable roadmap for implementation I4.0.

Table 9: Identification of the available Maturity and Readiness Models for I4.0 adoption in the Manufacturing Sector.

Maturity Model	Purpose	Levels/stages	Dimensions	Adoption
MM1: IMPULS-Industries 4.0 Readiness (Mittal et al., 2018; Ramos, de Freitas Rocha Loures and Deschamps, 2020)	To assess the evolution stages to categorize enterprises	L1 outsider L2 beginner L3 Intermediate L4 Experienced L5 Expert L6 Top performer	D1 Organizational Strategy D2 Smart Factory D3 Smart Operation D4 Smart product D5 Data Collection D6 Employees	SMEs

MM2: Industry 4.0/Digital operations self-assessment (PwC) (Ramos, de Freitas Rocha Loures and Deschamps, 2020)	Help enterprises evaluate their current position for future adoption of I4.0	L1 Digital novice L2 Vertical Integrador L3 Horizontal Collaborator L4 Digital Champion	D1 Digital Business Models & Customer Access D2 Digitization of products & Services D3 Digitization & integration of vertical & horizontal value-chains D4 Data Analytics D5 IT infrastructure D6 Compliance Security D7 Organization, employees & digital culture	N/M
MM3: Industry 4.0 Maturity Model (Schumacher et al., 2016)	Change the abstract concepts of smart manufacturing into measurable items in production environments.	L1 Measurement of Maturing Items in Enterprise L2 Calculate of Maturity Level. L3 Representation & visualization of MM report	D1 Strategy D2 Leadership D3 Customers D4 Products D5 Operations D6 Culture D7 People D8 Governance D9 Technology	SMEs
MM4: SIMMI 4.0 (System Integration Maturity Model for I4.0) (Leyh et al., n.d.).	Classify IT systems within I4.0 adoption	L1 Basic Level L2 Cross-department digitization L3 Horizontal & vertical integration L4 Full digitization L5 Optimized digitization	D1 Vertical Integration D2 Horizontal Integration D3 Digital Product Development D4 Cross-Sectional Technology Criteria	N/M
MM5: Maturity Model in SMEs towards Industry 4.0 (Ganzarain and Errasti, 2016).	Enable SMEs to recognize future growth markets	L1 Development of I4.0 Vision L2 I4.0 Technological vision informed by network.	D1 Strategy D2 Leadership D3 Customers D4 Products D5 Operations D6 Culture	SMEs

		L3 Polices, Management & training for employees	D7 People D8 Governance D9 Technology	
MM6: Maturity Model for Digital Transformation (Klötzer & Pflaum, 2017).	Evaluate supply chain and manufacturing performance	L1 Digitalization awareness L2 Smart networked products L3 Thinking in service systems. L4 The service-oriented enterprise L5 The data-driven enterprise	D1 Digitization Awareness D2 Smart Products D3 Smart Services D4 Services Systems D5 Data-driven	N/M
MM7: Guideline Industrie 4.0 (Mittal et al., 2018; Angreani, Vijaya and Wicaksono, 2020).	Provide steps for German SMEs towards I4.0 adoption	L1 Knowledge L2 Analysis L3 Creativity L4 Evaluation L5 Application	D1 Integration of Sensors D2 No use of Sensors D3 Sensor Readings D4 Data Evaluation & Analysis D5 Product Independency D6 Data Processing in Production D7 No Processing of Data D8 Storage of Documented Data D9 Analyzing Data D10 Evaluation D11 Application	SMEs
MM8: Smart Assessment Model (Lee et al., 2017).	Propose a framework to evaluate smart factories	L1 Leadership L2 Process L3 System &Automation L4 Performance	D1 Production Process D2 System & Automation D3 Performance D4 Leadership	SMEs
MM9: Actech Industrie 4.0 Maturity Index (Angreani et al., 2020; Schuh et al., n.d.).	Support enterprises towards I4.0 implementation	L1 Computerization L2 Connectivity L3 Visibility L4 Transability L5 Predictive Capacity L6 Adaptability	D1 Resources D2 Information Systems D3 Organizational Structure D4 Culture	N/M

MM10: DREAMY (Digital Readiness Assessment Maturity model) (De Carolis et al., 2017).	Allow enterprises to evaluate their current digital readiness and identify opportunities towards smart manufacturing adoption	L1 Initial L2 Managed L3 Defined L4 Integrated & Interoperable L5 Digital Originated	N/M	N/M
MM11: Methodology for modelling and assessing human activities within cyber-physical systems (CPS) (Fantini et al., 2020).	Support employees with Cyber Physical System (CPS) integration	L1 Problem Setting L2 Scoping L3 Analysis L4 Assessment	D1 Abstraction D2 Decision Making D3 Innovations D4 Social Interaction D5 Human Component D6 CPS Component	N/M
MM12: 360 Digital Maturity Assessment (360 DMA) (Colli et al., 2019).	Facilitate the contextualization of the assessed enterprises and support them with improvement recommendations	L1 Creation of Awareness L2 Definition of Scope L3 Data Collection L4 Evaluation L5 Debriefing L6 Integrated	D1 Technology D2 Connectivity D3 Value Creation D4 Competences D5 Governance	No
MM13: Framework of the adoption patterns of Industry 4.0 (Frank et al., 2019).	Evaluate the maturity in smart manufacturing	Three stages	D1 Smart Manufacturing D2 Smart Products D3 Smart Working D4 Smart Supply chain D5 Base Technologies	SMEs
MM14: Development of an assessment model for industry 4.0: industry 4.0 maturity model (Gökalp et al., 2017).	Create a base for I4.0 assessment	L1 Level 0 (in complete) L2 Performed L3 Managed L4 Established L5 Predictable L6 Optimized	D1 IT D2 Data Governance D3 Information Flow S4 Process Transformation D5 Organizational Structure/Strategy	No
MM15: Towards a framework for assessing the maturity of	Evaluate the maturity level of enterprises	N/M	D1 Strategy D2 Maturity D3 Performance	No

manufacturing companies in industry 4.0 adoption. (Mittal et al., 2018).	already implementing I4.0.			
MM16: Maturity and readiness model for Industry 4.0 strategy (Akdil et al., 2018).	Provide an index for calculating the readiness of enterprises towards I4.0 adoption.	L1 I4.0 Requirements not fulfilled. L2 Automation of data collection L3 Data sharing &integration	D1 Smart Products & services D2 Smart business process D3 Strategy and organization	NO

This was followed by an Inductive thematic synthesis to identify overlapping constructs and develop a unified set of common dimensions along with their exemplary maturity items (Tranfield et al., 2003). Through an iterative process of comparison and grouping, conceptually similar items were consolidated under higher order themes. This inductive step resulted in 11 common dimensions, which is discussed later (see Table 12) to emerge as the most consistently recurring constructs across the literature.

These 11 common dimensions, identified through synthesis, served as the foundation for constructing the initial expert questionnaire in Delphi Round 1 (R1), providing a theoretically grounded basis for the subsequent empirical validation phase.

This design allowed combining qualitative insights from literature (deductive content analysis of frameworks) with quantitative and consensus-driven inputs from practitioners. This approach is appropriate for emerging, complex topics like I4.0 adoption, where existing theory needs contextual adaptation and expert validation. The methodology ensured a thorough grounding in prior research while leveraging local expert knowledge to produce a practical model for SMEs.

The following sections detail each step, including literature review procedures, selection of MMs, Delphi panel formation, survey instrument design, data analysis techniques and validity considerations (Tranfield et al., 2003).

3.3.2 Stage 2: Delphi Study-Round 1 (Exploratory Assessment)

To validate and refine the framework derived from literature, a Delphi method was employed. The Delphi is a well-suited tool for building consensus among a panel of experts on complex issues, and it has been used in technology adoption research to identify trends and set of standards (Touijer & Elabjani, 2025). Moreover, it allows experts to express their views independently and anonymously (Culot et al., 2020; Neupane & Bhattarai, 2024), reducing the dominance of any single expert and mitigating peer pressure (Neupane & Bhattarai, 2024). The iterative rounds enable experts to reconsider their opinions considering group feedback, thereby effectively prioritizing and validating proposed criteria (Culot et al., 2020; Neupane & Bhattarai, 2024).

In this study, a two-round Delphi survey was conducted with a panel of experts from Cairo's Manufacturing Sector. The Delphi phase had two objectives: (1) exploratory assessment of the current I4.0 readiness and practices among Cairo SMEs (Round 1), and (2) consensus building on the key dimensions and structure of a customized MM (Round 2).

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The iterative rounds enable experts to reconsider their opinions considering group feedback, thereby effectively prioritizing and validating proposed criteria (Culot et al., 2020; Neupane & Bhattarai, 2024).

Following the synthesis of 11 common dimensions form the literature, the second stage involved an exploratory Delphi study. The main objective of R1 was: (1) to gather empirical data on the current state In Cairo's manufacturing SMEs, and (2) to contextually ground and test the relevance of the literature-derived dimensions through practical, operational questions. Table 10 demonstrates R1 survey questions, their sections, and the purpose of each section.

This approach avoids asking experts to rate abstract academic constructs directly and instead validated them through their real-world manifestations (Skulmoski et al., 2007).

Table 10: R1 Survey Questions.

Axis	Purpose	Items	Questions
ICT Level	The purpose of this section is to assess the usage of ICT in Cairo manufacturing SMEs (Elbeltagi et al., 2016; Frank et al., 2019; H. Zaied, 2012; Müller & Voigt, 2018; Nick et al., 2019).	1) SMEs use a well-structured system that enables different departments to be connected. 2) SMEs use software like Enterprise Recourse Planning (ERP) for providing production status. 3) SMEs use electronic advertising. 4) SMEs use IT for customer services. 5) SMEs use IT for tracing order fulfilment and delivery. 6) SMEs offer online/electronic payment services for customers. 7) SMEs purchase materials from suppliers via electronic payment. 8) SMEs use the internet to search for customers. 9) SMEs use internet to search for suppliers. 10) SMEs use the internet to communicate with customers. 11) SMEs use the internet to collect information about customers. 12) SMEs use internet to collect information about competitors. 13) SMEs use IT to advertise products/ services. 14) SMEs use IT only for receiving/managing customer orders. 15) SMEs use the internet only in offering after-sales services for customers. 16) SMEs use electronic catalogues to sell products/ services to customers. 17) SMEs use electronic catalogues in offering after-sales services to customers. 18) SMEs use IT for accessing suppliers' products/ services database. 19) SMEs use IT in Placing/ managing orders with suppliers. 20) Suppliers can access SMEs inventory via Information system (IS). 21) SMEs use electronic catalogues to buy raw materials from suppliers. 22) SMEs use software in product designs e.g., Computer Aided Design (CAD). 23) SMEs use cloud computing for data storage and backup. 24) SMEs IT for monitoring machine and production process. 25) SMEs produce customized products. 26) SMEs uses 3D printing. 27) SMEs use cloud computing for collecting product usage data. 28) SMEs use digitized machines (e.g., sensors).	5-points Likert scale from "Not applicable" to Fully adopted".
Production Digitization level and information transfer.	To evaluate the extent of production digitization and IS Integration of SMEs. Based on established frameworks like Pirola et al., (2019), this section aimed to assess 5 interrelated constructs critical to I4.0	**A) Which is the digitization level of Cairo SMEs production plant?** (Pirola et al., 2019) o Purely physical production system (the production system does not communicate with the IT system, and no information can be collected about the production process	

	readiness: 1) the digitization level of production systems, 2) the presence and continuity of production data collection, 3) the scope & status of digital investments across operational function, 4) the adoption and integration status of key IT systems (e.g., ERP, MES, PLM, WMS, etc.)	○ Low-digitized production system (the production system is connected to the IT system, but it is possible to collect only some information about the production process (machine status) ○ Well-digitized production system (the production system is connected to the IT system and information on the production process (machine status, management parameters, processing parameters) are collected and analytically analyzed) **B) Does Cairo SMEs collect data from the production system?** (Pirola et al., 2019) ○ No, SMEs do not collect data from the production system, and do not know which data to collect ○ No, SMEs do not collect data from the production system, however, some companies know which data to collect ○ Yes, but not in continuous (e.g., only at the end of turn) ○ Yes, in continuous (real-time) ○ Yes, in continuous and data can be viewed remotely (real-time) **C) In which operating units are the Egyptian SMEs planning investments/developing projects for digitization?** (Pirola et al., 2019) ○ Sales & marketing ○ R&D ○ Purchasing ○ Production ○ Quality management ○ Internal maintenance ○ Logistics ○ After-sales-services ○ HR ○ Cybersecurity ○ IT infrastructure **D) Which data on machinery/processes are collected? How are they collected?** (Pirola et al., 2019) ○ Warehouse data ○ Performance in line assembly machines ○ Availability of production machines ○ Waste/production defects ○ Faults/ malfunctions of machinery	

		○ Causes of machinery malfunctions/ assembly ○ Energy consumption **E) Which IT systems are used in Cairo SMEs, and which are integrated with the main information system**? (Pirola et al., 2019) ○ Enterprise Resource Planning (ERP) ○ Manufacturing Execution System (MES) ○ Product Data Management (PDM) ○ Product lifecycle Management (PLM) ○ Customer Relationship Management (CRM) ○ Computer Aided Design (CAD) ○ Document Management ○ Workflow Management ○ E-commerce ○ Warehouse Management System (WMS)	
Supply Chain (SC) collaboration	To examine the extent and depth of SC integration among manufacturing SMEs. Based on the framework of Pirola et al., (2019), this section investigates how digital technologies are employed to facilitate coordination and data exchange with customers, suppliers, distributors, and wholesalers.	**What is the degree of integration with customers and suppliers?** (Pirola et al., 2019) ○ No integration ○ Electronic Data Interchange (EDI) (e.g., sharing information between SC partners). ○ Fully integrated information system (IS)	
I4.0 Knowledge and Awareness	To assess the respondents are aware of foundational I4.0 technologies and explore whether SMEs have developed, or are in process of developing, formal strategic framework to guide I4.0 adoption.	1. Do you know what industry 4.0 is? ○ Yes ○ No 2. Do you know what IoT (internet of things) is? ○ Yes ○ No 3. Do you know what CPS is (cyber physical system)? ○ Yes ○ No 4. Do you know what big data analytics is? ○ Yes ○ No 5. Do you know what Additive manufacturing is? ○ Yes ○ No 6. Do you know what cloud computing technologies are?	Binary

		○ Yes ○ No 7. Has an industry 4.0 been defined as the mentioned sector? ○ Yes ○ No 8. If an industry 4.0 strategy has been introduced in the Egyptian SMEs, which support tools/ analysis are used? (Pirola et al., 2019) ○ A strategy has not been defined but we would like to define it ○ The strategy is under definition. ○ A strategy has been defined, but not an action plan ○ A well-defined strategy exists, with an action plan ○ Other: —————————— 9. Is there a roadmap for planning the activities for the introduction of industry 4.0 solutions for Egyptian SMEs? (Pirola et al., 2019) ○ A roadmap does not exist ○ A roadmap does not exist, but we are going to define it ○ A roadmap is under definition ○ A roadmap exists and we are starting with the implementation phase ○ A roadmap exists and it is fully implemented	
Main drivers for I4.0 adoption and stakeholders.	To identify the primary factors motivating of adopting I4.0 among SME. this section assessed expert agreement with 12 potential drivers, including cost reduction, process efficiency, competitive advantage, customer satisfaction, and market expansion (Elbeltagi et al., 2016; Horváth & Szabó, 2019a). Moreover, this section identifies the necessary stakeholders to facilitate I4.0 adoption.	1. Digital technologies reduce inventory cots. 2. Digital technologies reduce operational costs. 3. Digital technologies reduce marketing costs. 4. Digital technologies reduce documentation process. 5. Using Digital technologies reduces human work. 6. Digital technologies improve the company's competitive advantages (e.g., new products/services, customized products, better customer services, etc. 7. Digital technologies allow customers to customize their products. 8. Digital technologies increase the company's market share. 9. Digital technologies increase the company's business efficiency. 10. Digital technologies improve the company's information quality. 11. Digital technologies improve the company's quality of following up with customer claims and complaints. 12. Digital technologies improve company's quality in reduction of transaction errors. **2) What are the main barriers for implementing an industry 4.0 strategy in your company?**	5-Likert scale from "Strongly Agree" to "Strongly Disagree"

		○ Lack of human knowledge ○ Lack of efficiency in value chain and product/services quality ○ Lack of cyber security ○ Decision making deficiencies ○ Unskilled employees and managers ○ Inadequate organizational structure ○ Financial constraints ○ Demobilization ○ Limited use of IT by SMEs ○ Organization resistance to change ○ Absence of legal and regulatory systems ○ Governmental regulations **3) Whose stakeholders are crucial to the success of industry 4.0 technologies adoption? Please, select at least "3" from the following list:** ○ Government ○ Universities ○ Banks ○ Financial organizations ○ International community support funds ○ Technology Support companies ○ Technology Supply companies ○ Egyptian chamber of commerce ○ Supply chain members, e.g., suppliers ○ Supply chain members, e.g., customers ○ Consulting companies ○ Third party partner, e.g., product and manufacturing design partner, freight consolidation, transportation, digital services providers, etc.	
Required Training skills for managers and employees.	To identify the required skills for both managers and employees, in which these are required for digital transformation.	As an expert in your field, please support the research with the necessary training skills needed in human power for I4.0 adoption: 1. What types of training programs do you recommend for improving managers' skills? 2. What types of training programs do you recommend for improving employee's skills?	Open-ended questions.

3.3.3 Expert Panel selection and characteristics

A purposive sampling strategy was used to recruit a panel of experts possessing rich, relevant knowledge in both manufacturing and digital transformation. experts were selected according to stringent criteria to ensure high-quality insights like: (1) current or recent tenure in a top-management level; (2) a minimum of 9 years of experience in the manufacturing sector; (3) a relevant academic degree; and (4) demonstrated familiarity with technical and strategic aspects of technology adoption (see Table 10).

The recruitment process utilized Industry associations, professional networks, and personal contacts within Cairo manufacturing community. A total of 30 individuals from various industries were invited to participate. Of these 22 initially agreed, but 3 were excluded due to incomplete or insufficient responses in the first round. This resulted in a final Delphi panel of 19 experts.

Previous literature suggests that a panel size of 10-20 is effective for Delphi Studies on specialized topics (Culot et al., 2020; Skulmoski et al., 2007; Touijer & Elabjani, 2025). Thus, the size of 19 falls within this range and provided a robust basis for consensus. The expert panel was purposefully composed to capture a broad representation of the manufacturing sector in Cairo.

Table 10 provides an overview of the experts, including their sectors, job roles, and experience. The experts spanned seven industries: Automotive, Metals & Machinery, Electrical Equipment, Food &Beverages, Textile, Agriculture, and Petrochemicals. Each of the said sectors is significant in the local economy (World Bank, 2023), and having experts from each ensures that the maturity model would be relevant across different manufacturing domains.

Table 11: Anonymized Overview of the Delphi-Experts.

Experts	Job-position	Sector type	Area of Expertise	Academic Degree	Years of Experience
E1	CEO	Agriculture	Sales & Business Mgt.	MSc.	10
E2	Head of Production	Automotive	Business Mgt.	MSc.	15
E3	Head of Production		Operation Mgt..	BSc.	12
E4	Head of Operations	Electrical Equipment's	Electromechanical Eng.	MSc.	14
E5	CEO		Production.	MSc.	5
E6	CEO	Food & Beverages	Mechanical Eng.	MSc.	More than 15
E7	Head of Operations		Production Mgt.	MSc.	More than 15
E8	CEO		Sales & Business Mgt.	PhD.	18
E9	Head of Operations		Operations & Logistics Mgt.	MSc.	12
E10	Head of Sales		Sales & Business Mgt.	PhD.	20
E11	CEO & Chairperson of SMEs industries federation association.		Business Mgt. & Development.	PhD.	20
E12	CEO	Metals & Machinery	Sales & Business Mgt.	MSc. & ITI	9
E13	Head of Operations		Operations Mgt.	MSc.	15
E14	Vice of Operations	Petrochemicals	Industrial Eng.	MSc.	15
E15	CEO		Production & Sales	MSc.	15
E16	Head of Operations		Logistics Mgt.	BSc.	9
E17	General Manager	Textile	Sales & Business Mgt.	MSc.	17
E18	CEO		Sales & Business Mgt.	MSc.	More than 15
E19	CEO		Industrial Sales Eng.	MSc.	10

The Round 1 questionnaire was designed as an exploratory instrument to assess the current state of digital readiness. To bridge the gap between the theoretical dimensions from stage 1 and actual (on-the-ground/real) practice, the questionnaire was structured into 5-sections. Each section was designed to collect data that would serve as empirical Indicators for one or more of the 11 literature-derived dimensions.

The content was developed by adapting survey Items from the 16 MMs identified in the literature, ensuring a clear linage from theory to question. Besides, the key areas of inquiry about SMEs' digital readiness, and additional literature on SME digitization like Elbeltagi et al., (2016); Frank et al., (2019); H. Zaied, (2012); Müller & Voigt, (2018); Nick et al., (2019); Pirola et al., (2020).

The Round 1 survey was structured as follows: (see Appendix D)

- **Section-1:** Background Information: this section includes the basic profiling questions like expert's industry sector, size of enterprise, and other demographic information.
- **Section-2:** Current ICT Level: Includes questions evaluating the general level of ICT usage (e.g., whether SMEs uses well-structured Information systems that connect different departments, extent of Internet use in operations, and digital communication practices) this section gauged the overall digital Infrastructure and connectivity present in SMEs.
- **Section-3:** Main IT Systems in Use: this part delved into specific software and systems deployed, like ERP, MES, CRM, etc. It identified which core systems are commonly implemented and integrated in SMEs.
- **Section-4:** Training and Skills Needs: questions here explored the human capital aspect in terms of skill set of managers and employees or expertise hindering I4.0 adoption. Understanding the workforce readiness is crucial, since adopting new technologies often requires new competencies.
- **Section-5:** Stakeholder Involvement: this section examined which stakeholders (Internal or external) are needed in the enterprise's digital transformation. For example, the role of technology providers, government initiatives in supporting I4.0 adoption.

Before deployment, the questionnaire was reviewed for clarity by two independent academics and piloted with two Industry experts, leading to some refinements. The full questionnaire used in R1 is provided in (see Table 11) (Appendix -D).

Furthermore, the content was developed by adopting survey Items from the 16 MMs identified in the literature, ensuring a clear lineage from theory to question. The following table (see Table 12) below Illustrates

the mapping between the questionnaire sections and the common dimensions they were designed to Investigate.

Table 12: A summarized mapping between Survey sections and Common Dimensions.

Questionnaire Section	Key Inquiry	Primary Dimensions Investigated
Section-2: Current ICT Level	Use of integrated systems, internet, digitalization.	Information systems, Technology, Smart operations, and Customers.
Section-3: Main IT Systems in Use	Adoption of specific software (ERP, MES, CRM)	Smart factory, Information systems, and Technology.
Section-4: Training and Skills Needs	Skills gaps, training needs for managers/employees.	Employees, and Leadership management.
Section-5: Stakeholder Involvement	Role of government, partners, etc.	Organizational strategy, culture

Source: Author's own work.

3.3.4 Data Collection Procedure

The first round took place from October 2022 to March 2023, aligned with the study's objectives. moreover, we were engaged with each expert Individually. The primary mode of data collection was in-person for those experts who were accessible; in other cases, video conferencing (via Zoom) was used to reach experts at their convenience. In each section, we first explained the study's purpose and assured confidentiality. then expert either filled out the questionnaire or answered verbally while we recorded responses. On average, each round 1 session lasted from 60-90 minutes, as many experts provided detailed information or explanations along with ticking boxes. The mixed approach of hand-delivered surveys and real-time discussion helped clarify any ambiguous questions and ensured rich input. The anonymity of individual responses was maintained in analysis (experts were assigned codes E1, E2, ... E19), but during this round many experts were comfortable discussing experiences openly in the one-on-one setting. All participants gave Informed consent before proceeding, and the study protocol was explained to them.

3.3.5 Stage 3: Delphi Study-Round 2 (Expert Validation & Consensus)

The exploratory R1 confirmed a significant gap between the comprehensive dimensions found in the literature and the operational realities of SMEs. This finding necessitated a second, prescriptive Delphi round designed to build expert consensus on a final, tailored set of dimensions. The purpose of this, is to leverage

the Iterative nature of the Delphi method to validate, prioritize, and collaboratively refine the initial framework, ensuring the final model was both theoretically grounded and practically relevant (Culot et al., 2020).

3.3.6 Round 2 Survey Instrument Design

The second-round questionnaire was designed as a focus, quantitative instrument to achieve consensus. It was structured around the 11 common dimensions and their 55 exemplary maturity Items that were synthesized from the literature in stage 1.

To ensure a shared context and Informed judgment, the Instrument provided each expert with a brief, anonymized summary of the key findings from R1, a clear statement of the purpose of round 2 to finalize the core components of the model, and a concise definition for each of the 11 proposed dimensions, accompanied by examples if needed.

3.3.7 Stage 4: Development, Operationalization, and Presentation of the Customized Model

The final stage of this research involved the customization of the tailored I4.0 model. This process is grounded in a design science research approach (DRS) paradigm, which focuses on creating innovative solutions to real-world problems through the design of purposeful artifacts (Hevner & Park, 2004). The output of this stage is a set of interrelated artifacts designed to address the identifies research gap.

The development process was guided by synthesis of the findings from the literature review and the Delphi study to construct the tailored I4.0 MM. This ensures the final artifacts were not only theoretically, but also contextually tailored to the specific realities of SMEs (Becker et al., 2009; Skulmoski et al., 2007).

The design of the final model was determined by quantitative weight consensus of the maturity dimensions achieved in the R2 Delphi. This process was instrumental in transforming a general, literature-derived framework into a focused, SME-specific one.

The Delphi process deliberately filtered the initial framework. The reduction form 11 literature-derived dimensions to 10 expert-validated dimensions, and from 55 exemplary items to a more focused set of 32, is a critical outcome. This was not merely a reduction but contextual refinement, where the expert panel eliminated components that were either too complex, too resource-intensive, or strategically irrelevant for SME context. The resulting dimensional structure is therefore inherently SME-specific, as it is composed exclusively of elements that practitioners (in reality) deemed essential.

This process yielded the primary contributions of this study, which can be classified using the DSR framework (March & Smith, 1995):

- **Constructs:** the 10 validated dimensions and 32 exemplary items represent the core constructs - the specific concepts that are essential for understanding and implementing I4.0 In SME context.
- **Model:** the tailored 10-dimensions and 5-level maturity model itself is the central artifact. It is a model that represents the relationships between the constructs and describes a realistic, incremental pathway for SME development
- **Method:** the scoring and normalization protocol developed in this study represents a method-a specific set of steps for applying the model to assess maturity.

3.3.8 Operationalizing the Maturity Levels and Scoring Protocol

with the core components finalized, the model was operationalized as a practical assessment tool as follows:

- **Adoption of a 5-level maturity scale:** the model employs a 5-level maturity scale (Level0: Initial to Level 4: Maturity). This structure is grounded in the foundational Capability Maturity Model (CMM), which provides the theoretical logic for a staged, evolutionary progression where each level builds upon the capabilities of the last (Becker et al., 2009).
- **Application of the quantitative scoring method**: The quantitative data from the R1 Delphi was used to calculate a baseline maturity score for SMEs. This required a consistent scoring protocol to convert diverse survey responses into a unified (0-4) scale. As detailed latter (In section: 3.6.6).

The final maturity score for each dimension was calculated by taking the arithmetic mean of all the normalized item scores mapped to it. The use of "statistical aggregation of group responses" is a key feature of the Delphi method, which allows for quantitative analysis and interpretation of expert's judgements (Skulmoski et al., 2007).

3.3.9 Delphi Round-2: Consensus on Key Dimensions and Model Structure

The second Delphi round aimed to achieve expert consensus on the unified maturity model framework essentially to validate and refine the list of dimensions and their exemplary maturity items. given the complexity and number of dimensions in existing models, round-2 was designed to simplify and tailor the

model to the SME context based on expert judgement. by the end of this round, the goal was to finalize a set of core dimensions (with definitions and exemplary maturity items) that are both theoretically sound (grounded in literature) and practically relevant (validated by practitioners), as well as to outline the maturity stages to be used in the customized model.

The second-round questionnaire was more focused and structured than Round-1. it was prepared after analysing Round -1 results and compiling the initial set of 11 common dimensions and their exemplary maturity items. The survey instrument provided the experts with background information to ensure a common understanding. This included a brief recap of round-1 findings (e.g., general observations on current ICT adoption), the purpose of Round-2 (to co-create a tailored MM for Cairo's SMEs), and an explanation of what a MM entails (a framework to evaluate how far a company has progressed in digital transformation.

Importantly, the survey listed each proposed dimension (e.g., organizational strategy, smart factory, smart operations, ... etc.) accompanied by a clear definition distilled from the content analysis and an example of what a high-maturity practice in that dimension might look like. this information helped ensure that all experts interpreted the dimensions in the same way when rating them (see Appendix F)

The questionnaire was organized in two sections: section-1 asked experts to confirm their sector, and section 2presented the list of dimensions to be rated. each dimension was posed as a statement or item to evaluate its essentiality for inclusion in the MM. experts were instructed to rate each dimension on a five-point Likert scale ranging from *"Strongly Disagree" to "Strongly Agree"*

Round-2 was conducted between April and June 2024 with the same group of experts. all 19 original experts agreed to continue into round-2, which was important for maintaining consistency and leveraging the shared knowledge built in round-1.

3.4 Results

3.4.1 Maturity Model Dimensions

- Common I4.0 MMs Dimensions

Based on the identification of research keywords, search terms, and inclusion and exclusion criteria, this research utilized content analysis and identified the common dimensions with 55 exemplary maturity items

studied within I4.0 MMs in the manufacturing sector. These dimensions are: Organizational Strategy, Smart Factory, Smart Operation, Smart Product, Employees, Leadership, Customers, Culture, Technology, Data-Driven/Governance, and Information Systems (see Table 13).

Table 13: I4.0 Common Dimensions in the Manufacturing Sector.

#	Dimension	MM	Definition	Exemplary Maturity Item	Reference
1	Organizational strategy	Studied in 5 MMs: (MM1, MM3, MM5, MM13, MM15)	Organizational strategy, which encompasses the strategic planning and management of I4.0 business strategies, involves IT investments, implementing the I4.0 roadmap, cybersecurity, leveraging available digitization resources, and vertical and horizontal integration (VI & HI).	Organizational level (strategy structure. Management resources allocation, digital awareness, integrated departments) IT knowledge Technology strategy (e.g., cyber security) Networking & Integration Realizing available resources for digitization Roadmap for I4.0 Implementing I4.0 Roadmap	(Schuh et al., no date; Ganzarain and Errasti, 2016; Schumacher, Erol and Sihn, 2016; Gökalp, Şener and Eren, 2017; Mittal et al., 2018; Ramos, de Freitas Rocha Loures and Deschamps, 2020)
2	Smart Factory	Included in 4 MMs: (MM1, MM5, MM7)	Smart factory seeks to create a highly automated production environment, encompassing equipment infrastructure, IT systems such as ERP and MES, digitized machinery, traceability of both final products and raw materials, energy management (including consumption and monitoring), automation (such as	Automated production environment Equipment infrastructure IT systems VI (ERP, MES, Digitized machines) Traceability (final products, raw materials)	(Mittal et al., 2018; Frank, Dalenogare and Ayala, 2019; Ramos, de Freitas Rocha Loures and

			automated identification, industrial robots, and M2M communication), virtualization (utilizing AI for maintenance and production), and flexibilization (flexible production lines and additive manufacturing).	Energy Management (Energy consumption, Energy monitoring) Automation (automated identification, industrial robots, M2M communication) Virtualization (AI for maintenance, AI for production) Flexibilization (Flexible line, additive manufacturing)	Deschamps, 2020)
3	Smart Operation	Covered in 4 MMs: (MM1, MM3, MM5)	Smart operation, which focuses on integrating virtual and physical elements, encompasses information sharing, cloud usage, IT security, process decentralization, modeling and simulation, interdepartmental collaboration, and data analytics.	Information Sharing Cloud usage IT security Decentralization of processes Modeling & simulation Interdepartmental collaboration Data Analytics	(Ganzarain and Errasti, 2016; Schumacher, Erol and Sihn, 2016; Mittal et al., 2018; Frank, Dalenogare and Ayala, 2019; Ramos, de Freitas Rocha Loures and Deschamps, 2020)
4	Smart Products	Examined in 3 MMs: (MM1, MM3, MM5, MM13)	Smart products, designed to enable automated and efficient production management, include utilizing ICT functions for self-reporting, identification, localization, online presence, integrated customer	New data driven services (e.g., self-reporting, identification, localization) Online presence Integrated customer management Customized products	(Ganzarain and Errasti, 2016; Klötzer and Pflaum, 2017; Akdil, Ustundag

			management, customized products, and data processing.	Digitization of products/services systems Product integration Defined roadmap for smart products. Data processing R&D	and Cevikcan, 2018; Mittal et al., 2018; Frank, Dalenogare and Ayala, 2019; Ramos, de Freitas Rocha Loures and Deschamps, 2020)
5	Employees	Addressed in 5 MMs: (MM2, MM3, MM5)	Employees who drive the digital transformation process are developed through awareness programs, technical skills enhancement, and training. This includes fostering digital skills, ICT competencies, and openness to new technologies.	Digital skills ICT competences of employees Openness of employees to new technology	(Ganzarain and Errasti, 2016; Schumacher, Erol and Sihn, 2016; Mittal, Romero and Wuest, 2018)
6	Leadership Management	Addressed in 3 MMs: (MM3, MM5)	Leadership, which aims to improve management strategies (e.g., Management of digital competences & methods, Existence of central coordination for I4.0 strategy, Leadership & strategy).	Management of digital competences & methods Existence of central coordination for I4.0 strategy Leadership & strategy	(Ganzarain and Errasti, 2016; Schumacher, Erol and Sihn, 2016; Lee et al., 2017)
7	Customers	Mentioned in 2 MMs: (MM3, MM5)	Customers aim to better utilize customer data, digitize sales and	Utilization of customer data Digitization of sales/services	(Ganzarain and Errasti, 2016;

			services, and enhance customers' digital media competencies.	Customers digital media competences	Schumacher, Erol and Sihn, 2016)
8	Culture	Explored in 3 MMs: (MM3, MM5)	Culture, which prioritizes adaptability, openness to innovation, social collaboration, and knowledge sharing.	Knowledge sharing Open innovation & cross-company collaboration ICT value inside the company Democratic leadership	(Ganzarain and Errasti, 2016; Schumacher, Erol and Sihn, 2016; Angreani, Vijaya and Wicaksono, 2020; Schuh and Frank, 2020)
9	Technology	Investigated in 4 MMs: (MM1, MM5, MM13)	Technology in the context of I4.0 encompasses the use of modern ICT, including IoT, CPS, BDA, cloud computing, adaptive robotics, AI, embedded systems, additive manufacturing, sensors and actuators, and RFID. It also involves the utilization of mobile devices, integration of ICT for vertical and horizontal processes, and ensuring cybersecurity.	Existence of modern ICT (IoT, CPS, BDA, cloud-computing, adaptive robotics, AI, embedded sys, additive manufacturing, sensors & actuators, RFID) Utilization of mobile devices ICT integration (VI&HI) Cyber-security	(Ganzarain and Errasti, 2016; Schumacher, Erol and Sihn, 2016; Akdil, Ustundag and Cevikcan, 2018; Mittal et al., 2018; Colli et al., 2019; Angreani, Vijaya and Wicaksono, 2020)
10	Data Governance	Discussed in 2 MMs:	Data governance in the context of I4.0 involves big data analytics	BDA Data collection and usage	(Ganzarain and Errasti,

		(MM3, MM5).	(BDA) and the collection and utilization of data.		2016; Gökalp, Şener and Eren, 2017; Angreani, Vijaya and Wicaksono, 2020)
11	Information Systems	Discussed in 3 MMs: (MM9, MM15)	Information systems within the I4.0 framework include data analysis, contextualized data delivery, robust IT infrastructure, and (HI & VI).	Data analysis Contextualized data delivery Resilient IT infrastructure HI&VI	(Lee et al., 2017; Angreani, Vijaya and Wicaksono, 2020)

- Divergent I4.0 MMs Dimensions

The study found several divergent dimensions in I4.0 MMs beyond the common dimensions. These divergent dimensions reflect the multi-faceted approaches taken by different researchers to address specific aspects of I4.0 adoption. Below are the detailed definitions and exemplary maturity items for these divergent dimensions (see Table 14).

Table 14: Divergent I4.0 MMs dimensions.

#	Dimensions	Definition	Exemplary Maturity Items	Reference
1	Data collection	Data collection is crucial for implementation I4.0, focusing on how data is gathered, managed, and utilized within the manufacturing environment. This encompasses the availability and utilization of data-driven insights to inform decision-making processes.	• Availability of data driven • Share of revenue • Share of data used	(Mittal et al., 2018; Ramos, de Freitas Rocha Loures and Deschamps, 2020)
2	Digital business models and customer access	This dimension explores the transformation of traditional business models through digital solutions, facilitating enhanced customer access and engagement.	• Digital solutions • Applications	(Ramos, de Freitas Rocha Loures and

				Deschamps, 2020)
3	Digitization and integration of VI and HI	This dimension addresses the degree of digital integration both within the enterprise (vertical) and across the supply chain (horizontal), aiming to streamline processes and improve efficiency.	• Fully adopted processes • Semi-integrated processes	(Ramos, de Freitas Rocha Loures and Deschamps, 2020)
4	Data analytics	Data analytics focuses on the enterprise's capability to process and interpret data to generate actionable insights, predicting trends and optimizing operations.	• Basic analytical capabilities • Predictive analytics	(Ramos, de Freitas Rocha Loures and Deschamps, 2020)
5	IT-infrastructure	IT infrastructure encompasses the foundational technological architecture required to support I4.0 initiatives, including hardware, software, and network capabilities.	• IT-architecture	(Ramos, de Freitas Rocha Loures and Deschamps, 2020)
6	Compliance security	This dimension involves ensuring that digital solutions adhere to industry standards and regulatory requirements to safeguard data and operations.	• Traditional in-house structure • Optimizing value-chain compliance	(Ramos, de Freitas Rocha Loures and Deschamps, 2020)
7	Organizational, employees and digital culture	This dimension focuses on fostering a culture that supports digital transformation, emphasizing collaboration, digital proficiency, and adaptability among employees.	• Collaboration	(Ramos, de Freitas Rocha Loures and Deschamps, 2020)
8	Vertical integration	Vertical integration pertains to integrating I4.0 technologies at the lowest levels of the enterprise, ensuring seamless data flow across systems like ERP, PLM, CAD	• Focuses on the components of the lowest level of an enterprise (e.g., ERP, PLM)	(Leyh et al., n.d.)
9	Horizontal integration	Horizontal integration focuses on ensuring smooth information flow across different departments and	• Information flows across the enterprise and beyond the enterprise borders	(Leyh et al., 2016)

		external entities, enhancing coordination and efficiency.		
10	Digital product development	This dimension involves integrating advanced technologies to support continuous product development and lifecycle management across the supply chain.	• Supporting the product development continuously along the SC using advanced technologies	(Leyh et al., 2016)
11	Cross-sectional technology criteria	This dimension assesses the extent of technology usage across various fields of I4.0 requirements, including IoT, BDA, and cloud computing.	• Assessing the extent to which technologies are used across different fields of I4.0 based requirements (e.g., IoT, BDA, cloud computing)	(Leyh et al., 2016)
12	Digitization Awareness	Digitization awareness entails understanding and planning for digital transformation, including developing roadmaps and portfolios for digital products.	• Defined product roadmap • Portfolio for digital products • Framework for smart products	(Klötzer & Pflaum, 2017)
13	Services systems	This dimension focuses on the strategic development of service systems, integrating digital tools to enhance service delivery and customer engagement.	• Roadmap for services systems • Strategic ecosystem • Digital enterprise	(Klötzer & Pflaum, 2017)
14	Production processes	Production processes involve the digitization of core manufacturing activities, including product development, process planning, control, facility, and logistics management.	• Product development • Process planning • Process control • Facility management • Logistics management	(Lee et al., 2017)
15	System and automation	This dimension evaluates the extent of system integration and automation within the enterprise, focusing on IT systems and facility automation.	• Information system • Facility automation	(Lee et al., 2017)
16	Performance	Performance assessment measures the impact of I4.0 adoption on key performance indicators (KPIs), such as efficiency, defect reduction, and economic benefits.	• Benefits of I4.0 adoption: (economic, social, and environmental benefits) • Impact of efficiency: (employee efficiency, order fulfillment rate, cost, lead-time consumption, defect reduction, reduction in time for decision-making, impact of inventory requirements)	(Lee et al., 2017; Akdil, Ustundag and Cevikcan, 2018)

17	Resources	This dimension involves evaluating the adequacy of resources, including digital competencies, automated data acquisition, and decentralized data processing.	• Digital competences • Automated data acquisition • Decentralized processing of data	(Angreani et al., 2020; Schuh et al., n.d.)
18	Connectivity	Connectivity assesses the integration of data-sharing protocols, IT security, and structured data management within the enterprise.	• Data sharing • IT security • Data structuring	(Colli et al., 2019)
19	Value creation	Value creation measures the extent to which data is leveraged for order management, forecasting, and operational optimization.	• Data usage for orders • Forecasting	(Colli et al., 2019)
20	Competences	This dimension evaluates the ability of employees to engage in continuous learning and training, focusing on developing digital competences necessary for I4.0 adoption.	• Digital competences • Training • Learning	(Colli et al., 2019)
21	Smart working	Smart working refers to the application of advanced technologies like remote operation, production monitoring, and augmented/virtual reality to streamline workplace efficiency.	• Production monitoring • Remote operation • Augmented and virtual reality	(Frank et al., 2019)
22	Supply chain collaboration	This dimension focuses on digital platforms that enable seamless collaborations among supply chain partners, including suppliers, distributors, and wholesalers.	• Digital platforms with other companies • Digital platforms with suppliers • Digital platforms with distributors/wholesalers	(Frank et al., 2019)
23	Information flow	Information flow emphasizes the need for an integrated and automated information system to ensure smooth data exchange across different functional areas.	• Integrated/ automated information flow	(Gökalp et al., 2017)
24	Process transformation	Process transformation involves reengineering core business processes such as planning, acquisition, sales, and production to align with I4.0 principles.	• Planning • Acquisition • Sales and distribution • Production	(Gökalp et al., 2017)
25	Maturity	Maturity includes assessing the infrastructure for IoT, analytical skills,	• Infrastructure for IoT: (equipment infrastructure, IT systems, security systems, technology adopted)	(Akdil et al., 2018)

		and absorptive capacity necessary for achieving and sustaining I4.0 readiness.	• Analytical skills: (ability to analyze big data (BD), awareness of BD, reasons to use BD, self-awareness sys., real-time change abilities, effective use of BD) • Absorptive capacity: (employee training system, knowledge management sys., awareness of the skills required for IoT)	
26	Business process	Business process evaluates the maturity and readiness of enterprise business processes for transformation in line with I4.0 objectives, focusing on strategic alignment.	• N/M	(Akdil et al., 2018)

3.4.2 A Synthesized Framework: Justification for the Selected Maturity Dimensions

This research study adopts a structured set of common dimensions as the foundation for Its I4.0 proposed MM, purposefully excluding the broader and fragmented list of divergent dimensions. The selection of the common dimensions to be the base for the proposed MM Is grounded in a systematic and methodological way (Tranfield et al., 2003).

The common dimensions were chosen based on four Interrelated considerations:

- *Frequency and Consensus in Literature:*

The selected dimensions represent concepts that appear most frequently across widely cited I4.0 MMs. This highlights their broad academic consensus on their relevance and importance in assessing digital transformation readiness. Their Inclusion enhances the credibility, generalizability, and comparability of the proposed framework.

- *Dimensional Clarity Through Thematic Synthesis:*

Unlike the divergent dimensions, which reflect a wide range of concepts and overlapping constructs, the common dimensions result from a thematic synthesis that distils diverse source into a cohesive set of higher-order categories. This method ensures that the model captures the essence of I4.0 transformation without duplicating similar concepts under different labels.

- *Streamlining Dimensions for Analytical Rigor:*

A key reason for adopting the common dimensions lies in the effort to develop a model that is both analytically robust and structurally coherent. The extensive set of divergent dimensions identified in the literature often includes overlapping, or narrowly defined constructs that can dilute the clarity and utility of a maturity framework. For example, "Data collection", "Data Analytics", and "Value creation" are functionally sequential elements within a broader data lifecycle. Treating these as independent maturity dimensions would result in conceptual duplication and inflate the model's complexity without adding substantive analytical value (Tranfield et al., 2003).

- Practical usability for SMEs:

The consolidated set of common dimensions results in a more manageable and actionable framework (Tranfield et al., 2003) (with a set of essential comprehensive dimensions) for users like SMEs. A model with 10 dimensions clearly defined, provides a practical tool for self-assessment and strategic planning towards I4.0 mature adoption. The streamlined structure of the common dimensions provides a clear, step-by-step roadmap that is both comprehensive and accessible.

Table 14 demonstrates the results of this research study's thematic synthesis, conducted in the line with systematic review methodologies (Tranfield et al., 2003). While the divergent dimensions are drawn from previously published models (as mentioned before), the act of grouping them under common dimensions represents an original analytical contribution of this study. This explains why this study selected the common dimensions (see Table 14).

Table 14: Thematically Related Divergent Dimensions.

#	Common Dimension	Thematically Related Divergent Dimensions
1	Organizational strategy	Digitization Awareness, Process transformation, Business process.
2	Smart Factory	Production processes, System and automation, Smart working.
3	Smart Operation	Digitization and integration of VI and HI, Vertical integration, Horizontal integration, Information flow.
4	Smart Products	Digital product development, Services systems.
5	Employees	Organizational, employees and digital culture, Competences.
6	Leadership Management	Digitization Awareness, Resources, Maturity
7	Customers	Digital business models and customer access.
8	Culture	Organizational, employees and digital culture.
9	Technology	Cross-sectional technology criteria, Maturity

10	Data Governance	Data collection, Data analytics, Value creation.
11	Information Systems	IT-infrastructure, Connectivity.

Source: Author's own work.

3.4.3 First Round Delphi Results:

The data from the first Delphi round was applied to sixteen published I4.0 MMs to analyze how well Cairo SMEs algin with existing frameworks. However, the comparative analysis revealed that that none of the published MMs could be fully applicable due to; financial constraints that limit investments in advanced technologies (e.g., IoT, BDA, CPS), gaps in leadership commitment and strategic vision for digital transformation, limited IT infrastructure preventing full integration of smart manufacturing operations, and skilled workforce shortage, hindering the adoption of new technologies.

To demonstrate this process, we will refer to "*MM 13: Framework of the Adoption Patterns of Industry 4.0"* (Frank et al., 2019). (for the other models see Appendix E).

The data was entered into each dimension to identify which dimensions and sub-dimensions are relevant in the manufacturing sector.

Based on sections 2 and 3 of the Delphi survey, the results indicate:

- D1: Smart Manufacturing

Eighteen experts confirmed that all SMEs use enterprise resource planning (ERP) systems across sectors like automotive, metals, electrical equipment, food and beverage, textiles, petrochemicals, and agriculture.

ERP is fully integrated in the automotive, metals, and textile sectors. Additionally, 8 experts reported the use of manufacturing execution systems (MES) in the automotive, textile, and food and beverage sectors.

Energy consumption and monitoring data are collected manually in the metals and electrical equipment sectors (according to 2 experts) and continuously through information systems in the agricultural sector (as noted by 1 expert). It is also collected intermittently via IS in the textile and food and beverage sectors (4 experts). However, in the automotive and petrochemical sectors, energy data is neither collected nor used (4 experts).

- D2: Smart Products

Passive smart products are employed and monitored via information systems in the automotive, textile, metals, electrical equipment, petrochemicals, agricultural, and food and beverage sectors (as stated by 15

experts). Furthermore, 8 experts mentioned that textile, petrochemical, and food and beverage sectors utilize mobile devices for remote operations.

- D3: Smart Working

This dimension involves monitoring production and machine processes using information systems (IS) and information technology (IT). However, no sectors are currently using collaborative robots or augmented/virtual reality technologies.

- D4: Smart Supply Chain

In sectors like automotive, metals, electrical equipment, petrochemicals, and food and beverages, 9 experts highlighted the use of IT systems by SMEs to access supplier databases for procuring raw materials. Additionally, electronic data interchange (EDI) is used to share information among supply chain partners: between main distributors in the automotive and petrochemical sectors, between all customers in the metals sector, between main suppliers in the electrical equipment, textiles, and food and beverage sectors, and between main customers in the agricultural sector

- D5: Base Technologies

Most SMEs adopt cloud computing for data storage and backup (as mentioned by 18 experts). However, it is important to note that these SMEs lack other I4.0 base technologies such as IoT, Big Data, and CPS.

a) Main Information Technologies (IT) Systems Used in SMEs:

This study identified the main IT systems integrated within the manufacturing environment of SMEs:

- Enterprise Resource Planning (ERP): Utilized by all SMEs.
- Warehouse Management Systems (WMS): Considered a main IT system, as noted by 19 experts.
- Document Management Systems: Also highlighted by 19 experts as a primary IT system.
- Customer Relationship Management (CRM): Used in automotive, metals, electrical equipment, textile, agricultural, petrochemicals, and food & beverage sectors (10 experts).
- Product Lifecycle Management (PLM) and Computer-Aided Design (CAD): Employed in automotive, metals, electrical equipment, textile, agricultural, petrochemicals, and food & beverage sectors (9 experts).
- E-commerce Systems: Utilized by all the mentioned sectors (12 experts).
- Manufacturing Execution Systems (MES): Adopted by automotive, textile, and food & beverage sectors (7 experts).

- Product Data Management (PDM): Adopted by all sectors (13 experts).
- Workflow Management Systems: Employed only in metal and electrical equipment sectors (2 experts).

Moreover, on the one hand some experts highlighted and quoted the importance of IT systems as follows:

"ERP is non-negotiable at this point. It's the digital baseline for SME competitiveness"- Expert 4.

"CRM and e-commerce tools are growing fast, especially among SMEs trying to reach customers online; but Integration remains shallow"- Expert 8.

"It's encouraging to see PLM and CAD products even in textiles and food sectors; as It shows a shift toward design-led thinking, not just production"- Expert 12.

"ERP systems have become the backbone of operational management in most SMEs-we've almost reached full Integration In automotive sector"- Expert 3.

"Agricultural Is surprising ahead in energy data tracking; perhaps due to pressure from export partners of sustainability certifications"- Expert 15.

"Mobile devices are helping textile and food SMEs extend control beyond the shopfloor, especially for remote operations and quality checks"-Expert 6.

On the other hand, experts mentioned some drawbacks like:

"There's a good use of IS to monitor machines, but technologies like collaborative robots or AR are still seen as futuristic luxuries here"- Expert 10.

"No one is using AR In Egyptian SMEs yet- it's not a priority when basic connectivity Is still Incomplete"- Expert 5.

"SMEs In sectors like automotive and petrochemicals have started using IT to access supplier databases, but full Integration Is still a far work in progress"- Expert 2.

"Cloud computing is widely used, mostly for storage and backup, also; there's little awareness about IoT and CPS"- Expert 1.

"Some specialists and academics talk about bigdata, but none of these SMEs have the infrastructure or skills to actually use it"- Expert 17.

"MES Is still limited to a few sectors. Many companies hesitate because of cost and uncertainty about ROI"- Expert 7.

"It's concerning that some sectors don't collect energy data at all-how can we talk about optimization without measurement?"- Expert 9.

The ICT level among SMEs in the manufacturing sector demonstrates a robust integration of various advanced systems. All SMEs are equipped with ERP systems, which are especially well-integrated in the automotive, metals, and textile sectors. However, there is moderate adoption of MES, particularly in the automotive, textile, and food and beverage industries.

Energy consumption data collection varies significantly across sectors. In the metals and electrical equipment sectors, data is typically collected manually, while the agricultural sector employs continuous IS for this purpose. The textile and food and beverage sectors utilize intermittent IS for energy data collection, indicating a mixed approach to energy monitoring. Notably, the automotive and petrochemical sectors do not engage in systematic energy data collection.

In terms of smart products, passive smart products monitored through IS are implemented across several sectors, including automotive, textiles, metals, electrical equipment, petrochemicals, agriculture, food and beverage. Additionally, sectors such as textile, petrochemical, and food and beverage utilize mobile devices to facilitate remote operations.

The dimension of smart working primarily involves monitoring production and machine processes using IS and IT, but there is no current adoption of collaborative robots or augmented/virtual reality technologies in any sector.

For smart supply chains, information technology systems are used to access supplier databases in sectors like automotive, metals, electrical equipment, petrochemicals, and food and beverages. EDI is also employed to share (some) information among supply chain partners (e.g., distributors, suppliers, and customers), demonstrating a moderate level of ICT integration in supply chain management.

Cloud computing is widely adopted for data storage and backup across most SMEs in the sector, though more sophisticated I4.0 base technologies such as IoT, Big Data, and CPS are generally lacking.

Additionally, the study identifies other key IT systems integrated within these enterprises. These include WMS, Document Management Systems, CRM, PLM, CAD, e-commerce systems, and PDM, indicating an extensive range of ICT tools in use. However, Workflow Management Systems are notably only used in the metals and electrical equipment sectors, reflecting a somewhat specialized application.

Overall, SMEs in the manufacturing sector exhibit a moderate ICT adoption, with comprehensive use of ERP systems and moderate integration of IT systems for smart manufacturing and supply chain operations. Nonetheless, there is significant room for improvement in adopting more advanced I4.0 technologies to

further enhance their digital transformation efforts. Additionally, the study examined the necessary qualifications for managers and employees, as well as the stakeholders essential for facilitating I4.0 adoption.

The analysis of these qualifications was conducted through word counts. Experts recommend several training programs for managers to improve their skills, including strategic planning, negotiation skills, Master of Business Administration (MBA), digital marketing skills, project management, and Six Sigma diplomas/courses. Moreover, based on expert insights, employees are advised to develop a range of competencies such as effective communication skills, digital skills, knowledge of safety and security protocols, participation in technical training workshops, and obtaining educational qualifications. This is particularly important in Egypt, where a substantial portion of the labour force lacks formal education.

Additionally, experts have identified the key stakeholders essential for the adoption of I4.0 as follows:

- Government (cited by 18 experts),
- Supply chain members including suppliers (12 experts)
- Customers (12 experts),
- Consulting companies (11 experts),
- Financial organizations (6 experts),
- Third-party partners (e.g., product and manufacturing design partners, freight consolidation, transportation, and digital services providers) (6 experts).

Table 15: R1 Delphi Survey Experts Responses.

Axis	Items	Responses
ICT Level	1. SMEs use a well-structured system that enables different departments to be connected. 2. SMEs use software like Enterprise Recourse Planning (ERP) for providing production status. 3. SMEs use electronic advertising. 4. SMEs use IT for customer services. 5. SMEs use IT for tracing order fulfilment and delivery. 6. SMEs offer online/electronic payment services for customers. 7. SMEs purchase materials from suppliers via electronic payment. 8. SMEs use the internet to search for customers. 9. SMEs use internet to search for suppliers. 10. SMEs use the internet to communicate with customers. 11. SMEs use the internet to collect information about customers. 12. SMEs use internet to collect information about competitors. 13. SMEs use IT to advertise products/ services. 14. SMEs use IT only for receiving/managing customer orders. 15. SMEs use the internet only in offering after-sales services for customers. 16. SMEs use electronic catalogues to sell products/ services to customers. 17. SMEs use electronic catalogues in offering after-sales services to customers. 18. SMEs use IT for accessing suppliers' products/ services database. 19. SMEs use IT in Placing/ managing orders with suppliers. 20. Suppliers can access SMEs inventory via Information system (IS). 21. SMEs use electronic catalogues to buy raw materials from suppliers. 22. SMEs use software in product designs e.g., Computer Aided Design (CAD). 23. SMEs use cloud computing for data storage and backup. 24. SMEs IT for monitoring machine and production process. 25. SMEs produce customized products. 26. SMEs uses 3D printing. 27. SMEs use cloud computing for collecting product usage data. 28. SMEs use digitized machines (e.g., sensors).	1. Not fully adopted (7 Experts), Fully adopted (5 experts). 2. NFA (8 Experts), FA (8 experts) 3. NFA (1 Expert), FA (11 experts) 4. NFA (6 Expert), FA (6 experts) 5. NFA (3 Expert), FA (10 experts) 6. NFA (1 Expert), FA (13 experts) 7. NFA (4 Expert), FA (11 experts) 8. NFA (6 Expert), FA (8 experts) 9. NFA (5 Expert), FA (10 experts) 10. NFA (6 Expert), FA (12 experts) 11. NFA (7 Expert), FA (9 experts) 12. NFA (9 Expert), FA (7 experts) 13. NFA (2 Expert), FA (13 experts) 14. NFA (2 Expert), FA (12 experts) 15. NFA (6 Expert), FA (9 experts) 16. NFA (1 Expert), FA (16 experts) 17. NFA (2 Expert), FA (10 experts) 18. NFA (6 Expert), FA (0 experts) 19. NFA (9 Expert), FA (5 experts) 20. NFA (0 Expert), FA (0 experts) 21. NFA (5 Expert), FA (10 experts) 22. NFA (4 Expert), FA (9 experts) 23. NFA (3 Expert), FA (12 experts) 24. NFA (6 Expert), FA (7 experts) 25. NFA (7 Expert), FA (11 experts) 26. NFA (0 Expert), FA (3 experts) 27. NFA (4 Expert), FA (10 experts) 28. NFA (3 Expert), FA (14 experts)

Production Digitization level and information transfer.	**A) Which is the digitization level of Cairo SMEs production plant?** (Pirola et al., 2019) ○ Purely physical production system (the production system does not communicate with the IT system, and no information can be collected about the production process ○ Low-digitized production system (the production system is connected to the IT system, but it is possible to collect only some information about the production process (machine status) ○ Well-digitized production system (the production system is connected to the IT system and information on the production process (machine status, management parameters, processing parameters) are collected and analytically analysed) **B) Does Cairo SMEs collect data from the production system?** (Pirola et al., 2019) ○ No, SMEs do not collect data from the production system, and do not know which data to collect ○ No, SMEs do not collect data from the production system, however, some companies know which data to collect ○ Yes, but not in continuous (e.g., only at the end of turn) ○ Yes, in continuous (real-time) ○ Yes, in continuous and data can be viewed remotely (real-time) **C) In which operating units are the Egyptian SMEs planning investments/developing projects for digitization?** (Pirola et al., 2019) ○ Sales & marketing ○ R&D ○ Purchasing ○ Production ○ Quality management ○ Internal maintenance ○ Logistics ○ After-sales-services ○ HR ○ Cybersecurity ○ IT infrastructure	A) The digitization level of SMEs is a Low-digitized production system (the production system is connected to the IT system, but it is possible to collect only some information about the production process (machine status) (18 Experts) B) The data collected from the production system: ○ Yes, but not in continuous (e.g., only at the end of turn) (7 experts) ○ Yes, in continuous (real-time) (4 experts) ○ Yes, in continuous and data can be viewed remotely (real-time) (8 experts). C) In terms of investments projects for digitization, Egyptian SMEs ongoing investments are mainly in the following operating units: ○ Sales & Marketing, production, quality management (14 Experts) ○ Research and development (R&D) (13 Experts) ○ Purchasing (12 Experts) ○ Internal maintenance (12 Experts) ○ Logistics (11 Experts) "transportation is the main outsourced logistical activity" ○ IT infrastructure (8 Experts) ○ After sale-services (8 Experts) "mainly in automotive sector" ○ Cyber security (2 Experts) "it was observed the lack of investments in cyber-security and HR projects throughout all conducted sectors" ○ HR (3 Experts) **D) Which data on machinery/processes are collected? How are they collected?** *(Yes, in continuous and connected with the company IS)* ○ Warehouse data (10 experts). ○ Performance in line assembly machines (10 experts). ○ Availability of production machines (11 experts).

	D) Which data on machinery/processes are collected? How are they collected? (Pirola et al., 2019a) o Warehouse data o Performance in line assembly machines o Availability of production machines o Waste/production defects o Faults/ malfunctions of machinery o Causes of machinery malfunctions/ assembly o Energy consumption **E) Which IT systems are used in Cairo SMEs, and which are integrated with the main information system**? (Pirola et al., 2019a) o Enterprise Resource Planning (ERP) o Manufacturing Execution System (MES) o Product Data Management (PDM) o Product lifecycle Management (PLM) o Customer Relationship Management (CRM) o Computer Aided Design (CAD) o Document Management o Workflow Management o E-commerce o Warehouse Management System (WMS)	o Waste/production defects (6 experts). o Faults/ malfunctions of machinery (8 experts). o Causes of machinery malfunctions/ assembly (7experts). o Energy consumption (3 experts). E) **Which IT systems are used in Cairo SMEs, and which are integrated with the main information system**? o ERP (19 experts) o MES (7 experts) o PDM (13 experts) o PLM (9 experts) o CRM (10 experts) o CAD (9 experts) o Document Management (19 experts) o Workflow Management (2 experts) o E-commerce (12 experts) o WMS (19 experts)
Supply Chain (SC) collaboration	**What is the degree of integration with customers and suppliers?** (Pirola et al., 2019a) o No integration o Electronic Data Interchange (EDI) (e.g., sharing information between SC partners). o Fully integrated information system (IS)	o Electronic Data Interchange (EDI) (e.g., sharing information between SC partners). (3 experts reported EDI with main customers; 6 experts reported EDI with main supplier, and 5 experts reported EDI with main distributors). o Fully integrated information system (IS) (1 expert reported fully Integration with main customers)
I4.0 Knowledge and Awareness	1. Do you know what industry 4.0 is? • Yes • No 2. Do you know what IoT (internet of things) is? • Yes • No	1) yes (3); No (16) 2) yes (8); No (11) 3) yes (3); No (16) 4) yes (5); No (14) 5) yes (5); No (14) 6) yes (18); No (1)

	3. Do you know what CPS is (cyber physical system)? • Yes • No 4. Do you know what big data analytics is? • Yes • No 5. Do you know what Additive manufacturing is? • Yes • No 6. Do you know what cloud computing technologies are? • Yes • No 7. Has an industry 4.0 been defined as the mentioned sector? • Yes • No 8. If an industry 4.0 strategy has been introduced in the Egyptian SMEs, which support tools/ analysis are used? (Pirola et al., 2019a) o A strategy has not been defined but we would like to define it o The strategy is under definition. o A strategy has been defined, but not an action plan o A well-defined strategy exists, with an action plan o Other: —————————————— 9. Is there a roadmap for planning the activities for the introduction of industry 4.0 solutions for Egyptian SMEs? (Pirola et al., 2019a) o A roadmap does not exist o A roadmap does not exist, but we are going to define it o A roadmap is under definition o A roadmap exists and we are starting with the implementation phase o A roadmap exists and it is fully implemented	7) yes (2); No (17) 8) A strategy has not been defined but we would like to define it (17 Experts); 1 expert reported that the strategy is under definition; and 1 expert reported that strategy has been defined, but not an action plan. 9) A roadmap does not exist as reported by (19 experts).
Main drivers for I4.0 adoption and stakeholders.	1) Digital technologies reduce inventory cots. 2) Digital technologies reduce operational costs. 3) Digital technologies reduce marketing costs. 4) Digital technologies reduce documentation process. 5) Using Digital technologies reduces human work. 6) Digital technologies improve the company's competitive advantages (e.g., new products/services, customized products, better customer services, etc. 7) Digital technologies allow customers to customize their products.	1) Strongly agree (9) 2) Strongly agree (12) 3) Strongly agree (7) 4) Strongly agree (14) 5) Strongly agree (7) 6) Strongly agree (11) 7) Strongly agree (15) 8) Strongly agree (15) 9) Strongly agree (10)

	8) Digital technologies increase the company's market share. 9) Digital technologies increase the company's business efficiency. 10) Digital technologies improve the company's information quality. 11) Digital technologies improve the company's quality of following up with customer claims and complaints. 12) Digital technologies improve company's quality in reduction of transaction errors. **2) What are the main barriers for implementing an industry 4.0 strategy in your company?** o Lack of human knowledge o Lack of efficiency in value chain and product/services quality o Lack of cyber security o Decision making deficiencies o Unskilled employees and managers o Inadequate organizational structure o Financial constraints o Demobilization o Limited use of IT by SMEs o Organization resistance to change o Absence of legal and regulatory systems o Governmental regulations **3) Whose stakeholders are crucial to the success of industry 4.0 technologies adoption? Please, select at least "3" from the following list:** o Government o Universities o Banks o Financial organizations o International community support funds o Technology Support companies o Technology Supply companies o Egyptian chamber of commerce o Supply chain members, e.g., suppliers o Supply chain members, e.g., customers o Consulting companies	10) Strongly agree (11) **2) The main barriers for implementing an industry 4.0 strategy in your company** o Lack of human knowledge (13 experts) o Lack of efficiency in value chain and product/services quality (5 experts) o Lack of cyber security (None of experts mentioned that barrier) o Decision making deficiencies (8 experts) o Unskilled employees and managers (13 experts) o Inadequate organizational structure (2 experts) o Financial constraints (12 experts) o Demobilization (3 experts) o Limited use of IT by SMEs (5 experts) o Organization resistance to change (16 experts) o Absence of legal and regulatory systems (5 experts) o Governmental regulations (5 experts) **3) The main stakeholders that are crucial to the success of industry 4.0 technologies adoption:** o Government (18 experts) o Universities (3 experts) o Banks (2 experts) o Financial organizations (6 experts) o International community support funds (3 experts) o Technology Support companies (2 experts) o Technology Supply companies (2 experts) o Egyptian chamber of commerce (5 experts) o Supply chain members, e.g., suppliers (12 experts) o Supply chain members, e.g., customers (12 experts) o Consulting companies (11 experts) o Third party partner, e.g., product and manufacturing design partner, freight consolidation, transportation, digital services providers, etc. (11 experts)

	○ Third party partner, e.g., product and manufacturing design partner, freight consolidation, transportation, digital services providers, etc.	
Required Training skills for managers and employees.	As an expert in your field, please support the research with the necessary training skills needed in human power for I4.0 adoption: **1. What types of training programs do you recommend for improving managers' skills?** **2. What types of training programs do you recommend for improving employee's skills?**	**1. What types of training programs do you recommend for improving managers' skills?** ○ Strategic planning skills (11-word counts) ○ Negotiation skills (9-word counts) ○ MBA (7-word counts) ○ Digital Marketing skills (6-word counts) ○ Project Management skills/courses (5-word counts) ○ six-sigma diploma/courses (4-word counts) **2. What types of training programs do you recommend for improving employee's skills?** ○ communication skills (12-word counts) ○ computer skills (11-word counts) ○ safety & security skills (9-word counts) ○ technical skills (8-word counts) ○ education (3-word counts) ○ technical trainings workshops (3-word counts)

3.4.4 Cairo Manufacturing SMEs Classification according to MMs levels

The data collected from the first Delphi round are used for evaluating the ICT readiness of Manufacturing SMEs (as mentioned before) concerning published I4.0 MMs. Experts were surveyed on dimensions like technology adoption, operational practices, and energy management, guided by criteria from the 16 published MMs.

Responses were analysed to assess conformance to the stages of maturity outlined in these models. The analysis (number of agreements by experts) revealed that foundational ICT tools, such as ERP and MES systems, are predominant at the early maturity stages.

The number of experts' agreement highlighted that while these foundational tools are widely used, more advanced technologies like IoT, BDA, and CPS are notably absent. This absence limits most SMEs to the initial/foundational maturity level, which is defined as basic digitization level, although there is variance among sectors as follows; (for more illustration see Appendix).

a. Textile sector: Demonstrates foundational adoption with ERP and MES systems for monitoring material and energy consumption, lacking I4.0 base technologies like IoT, BDA, and CPS.
b. Automotive sector: Displays moderate digitization with ERP systems and partial MES usage but limited energy management integration with smart manufacturing capabilities.
c. Metals & Machinery Sector: Utilizes ERP for monitoring passive smart products but relies on manual energy data collection and limited digital tools.
d. Electrical Equipment Sector: Engages in basic digitization through ERP systems with limited automation of energy data.
e. Food & Beverage Sector: Employs ERP, MES, and mobile devices for remote operations, yet lacks comprehensive digital integration.
f. Agricultural Sector: Exhibits fragmented technology use and maintained cyber security and uses applications for tracking and monitoring, however, lacks adoption of IoT or CPS.

3.4.5 Development of a Customized MM for Cairo, Egypt

Based on the findings from the second round of the Delphi survey, a customized MM for Cairo SMEs in the manufacturing sector was developed (see Table 20) and (Figure 9). The proposed model offers a

structured pathway for SMEs in Cairo's manufacturing sector to systematically progress towards comprehensive digital transformation, ensuring the effective and sustainable adoption of Industry 4.0 technologies. This model provides a practical guide for enhancing digital capabilities. (see Table 6).

- Second Round Delphi Results:

Customization of an MM for Cairo is based on the common dimensions identified earlier. We consider that the divergent dimensions (to be continued after the section on divergent dimensions is written). Therefore, the common dimensions identified in published studies on I4.0 in the manufacturing sector, along with their 55 exemplary items, were transformed into itemized scale items for the second round of the Delphi study (to answer RQ2).

The scale ranged from 'strongly agree' (=5) to 'strongly disagree' (=1), with the objective of determining the most appropriate dimensions for SMEs.

A Microsoft Forms online survey was distributed to the 19 experts (by email) who participated in the initial round. The dimensions and exemplary maturity items, with an average mean score of 4 or higher, were included in the model. A comprehensive descriptive analysis of the second Delphi round is provided in (Appendix-F). The findings reveal that, among the common dimensions and 55 exemplary items, only the 10 dimensions with 32 exemplary with a mean score ≥ 4 were included in our customized model (see Table 16).

Table 16: R2 Delphi Weights.

#	Dimension	Exemplary Maturity Items	Weight
1	Organizational strategy	• Organizational level (strategy, structure, management, resources allocation, digital awareness, integrated departments) • IT Knowledge • Realizing available resources for digitization	• 4.47 • 4.42 • 4
2	Smart factory	• Automated Production Environment • Equipment Infrastructure • IT systems • VI (ERP, MES, Digitized machines) • Traceability (final products, raw materials) • Energy Management (Energy consumption, Energy monitoring)	• 4 • 4.26 • 4.36 • 4.78 • 4.05 • 4

3	Smart operations	• Cloud usage • IT security • Interdepartmental Collaboration • Data Analytics	• 4.26 • 4.05 • 4 • 4
4	Smart products	• New data driven services (e.g., self-reporting, identification, localization) • Online presence • Integrated customer management • Customized products • Digitization of products/services systems • Data processing • R&D	• 4.21 • 4.47 • 4.10 • 4.05 • 4.05 • 4 • 4.15
5	Employees	• Digital skills	• 4
6	Leadership Management	• Management of digital competences	• 4.05
7	Customers	• Utilization of customer data • Digitization of sales/services • Customers digital media competences	• 4.05 • 4.15 • 4.15
8	Culture	• Open to innovation • Supply chain Collaboration	• 4.10 • 4.05
9	Technology	• Utilization of mobile devices • ICT integration (VI&HI)	• 4.5 • 4.05
10	Information systems	• Data analysis • Resilient IT infrastructure • Protection of intellectual property	• 4 • 4 • 4

Source: Author's Own Work.

3.4.6 Maturity Levels

In addition to the dimensional structure, a key component of any MM is the set of maturity levels or stages that describes the evolutionary progress of an organization (Mittal, Khan, et al., 2018). Moreover, MMs are structured frameworks for assessing and guiding organizational development, particularly in domains involving complex capabilities like information systems, and digital transformation (Becker et al., 2009).

The theoretical foundation for this study is the CMM, which was introduced by Paulk et al., (1993) , a framework that later evolved into the more comprehensive Capability Maturity Model Integration (CMMI) (CMMI, 2010).

The CMMI framework operationalizes this through a staged model of capability evolution, defining discrete maturity levels. the model's logic Is built on two core principles: (1) a focus on mastering specific key process areas at each stage, and (2) a strict "prerequisite" logic, which states that an organization's overall maturity is constrained by Its lowest-performing dimension (CMMI, 2010; Paulk et al., 1993).

While the original CMMI does not provide a specific mathematical equation to compute maturity, previous studies like Baker, (2012); Schumacher et al., (2016) have proposed quantitative adaptations to operationalize the staged logic through numerical scoring and aggregation. This could allow companies to determine and clarify the level of maturity and find room for improvement (Baker, 2012; March & Smith, 1995; Schumacher et al., 2016).

Following this quantitative adaptation approach, this study operationalizes the model by first, mapping experts' assessments to a (0-4) maturity scale (Baker, 2012). The scores for individual items are then aggregated to the dimension level using the following arithmetic mean (Baker, 2012) to identify the maturity level for each maturity dimension.

This quantitative approach allows for transparency, objectivity, and comparability across dimensions and facilitates classification into maturity levels as mentioned by previous studies like (Akdil et al., 2018; Mittal, Romero, et al., 2018; Schumacher et al., 2016). The specific maturity levels used to categorize scores be defined below.

Based on literature, our customized model employs a five-level maturity scale to classify SME readiness. Many existing models used between 4 to 6 levels (see Table 9); a five-level maturity scale was chosen here as a balanced approach, providing enough granularity to distinguish different degrees of maturity without over-complicating the assessment as recommended by Akdil et al., (2018); Mittal, Khan, et al., (2018).

The five levels represent a scale from minimal to fully optimized I4.0 adoption, defined as follows: (Level 1 being the lowest maturity and Level 4 being the highest, for ease of presentation, though some resources label a "Level 0" we will refer to Level 0-4 for clarity), (see Table: 17):

- **Level 0: Initial:** the enterprise has very limited or has no adoption of I4.0 technologies. There is a lack of awareness or strategy regarding digital transformation, and processes remain predominantly

manual. The company might not have any significant IT systems beyond basic software. This corresponds to an organization that has not started its I4.0 journey (Akdil et al., 2018; Mittal, Khan, et al., 2018).

- **Level 1: Foundation:** the enterprise has recognized the importance of digital transformation and is in the planning or experimentation stage. A preliminary roadmap or vision for I4.0 may exist, and the company is a *"newcomer"* to these concepts. Some basic technologies or systems are adopted (e.g., ERP system), but implementation is minimum. Organizationally, there may be isolated digital initiatives and initial training efforts (Akdil et al., 2018; Mittal, Khan, et al., 2018).
- **Level 2: Progressing:** the SME has made notable progress in digitization, implementing I4.0 solutions in various operations, though not comprehensively. There is partial integration: some shopfloor processes are smart or connected, but others remain traditional. This stage can be described as "not-fully smart" as digitization is not applied to all operations (Akdil et al., 2018; Mittal, Khan, et al., 2018).
- **Level 3: Managed:** the enterprise is at a moderate to high level of digital Integration. Most processes are digital or automated to some extent, and there are considerable real-time data flow and Integration between systems (VI & HI). Advanced technologies like IoT sensors, robotics, or analytics are used in daily operations, however, not at the cutting-edge level of the most advanced global corporations (Akdil et al., 2018; Mittal, Khan, et al., 2018).
- **Level 4: Maturity:** the SME demonstrates full maturity in I4.0 adoption, with high levels of digitization and integration across all dimensions (Akdil et al., 2018; Mittal, Khan, et al., 2018).

Table 17: Maturity Levels Scoring Range.

Maturity Level	Score Range	Description	References
Level 0: **Initial**	0.00 < 1.00	No capability present: the company has not yet addressed the requirements or process.	(Akdil et al., 2018; Mittal, Khan, et al., 2018).
Level 1: **Foundation**	1.00 - < 2.00	Capabilities are planned or minimally implemented. company recognizes the need of digitalization and has taken initial steps.	(Akdil et al., 2018; Mittal, Khan, et al., 2018).

Level 2: Progressing	2.00 - < 3.00	Progressing; partial integration (capabilities may be functional but not integrated)	(Akdil et al., 2018; Mittal, Khan, et al., 2018).
Level 3: Managed	3.00 - < 4.00	Systems are connected, data flow and performance are monitored, cross-functional coordination exists. (partial to near-complete implementation).	(Akdil et al., 2018; Mittal, Khan, et al., 2018).
Level 4: Maturity	4.00	Fully mature; all systems are fully embedded in operations, continuously improved. (all items are fully implemented)	(Akdil et al., 2018; Mittal, Khan, et al., 2018).

To quantitively assess the maturity level of each of the 10 dimensions, it was necessary to convert and unify the diverse range of expert responses from the Delphi survey into a single, consistent measurement scale. The first-round survey employed multiple questions formats, including 5-Likert type scales, four-points categorical scales, and binary (Yes/No) items.

Thus, a direct averaging of these disparate scales would be methodologically invalid, as it would conflict with different units of measurement and lead to bias.

Therefore, a normalized protocol was designed to translate every survey item onto a unified (0-4) cardinal scale, where each Integer corresponds directly to a defined maturity level (0 = Initial, 1 = Foundational, 2 = Progressing, 3 = Managed, and 4 = Maturity) (Akdil et al., 2018; Mittal, Khan, et al., 2018).

This process ensures that the subsequent calculation of the mean score for each dimension is mathematically sound, transparent, and directly interpretable in the context of the maturity framework (Becker et al., 2009).

3.5 R1 Survey Questions and Corresponding Maturity Dimensions:

Table 18 demonstrates raw data points drawn from Delphi R1 survey results, involving the 19 experts. The data is primarily involved and attached into the 16 literature MMs (see Appendix E).

Table 18: Corresponding Maturity Dimensions Questions.

#	Dimension	Related R1 Questions
1	Organizational strategy	• Existence of a defined I4.0 strategy. • Existence of a roadmap for planning I4.0 activities. • Investments in cyber security. • Integration between departments (VI). • EDI with customers (HI). • EDI with suppliers (HI).
2	Smart factory	• Use of digitized machines (e.g., sensors). • IT is used for monitoring machines & production process. • Use of MES. • Use of WMS. • Degree of digitization level. • Data collection items.
3	Smart operations	• Integrate between departments via structured system. • Use of EDI with suppliers. • IT usage for tracking & order fulfillment. • Monitoring machines.
4	Smart products	• Production of customized products. • Use of software for designs (e.g., CAD). • Use of product lifecycle management (PLM). • Investments in R&D. • 3D printing.
5	Employees	• Lack of human knowledge • Investments in HR projects/training.
6	Leadership Management	• Unskilled managers. • Decision making deficiencies.
7	Customers	• Usage of electronic catalogues to sell products/services. • Usage of the internet to communicate with customers. • Usage of IT (e.g., social media) for advertising. • Use of CRM systems. • Use of EDI with customers.

8	Culture	• Organizational resistance to change. • Access to company databases for suppliers.
9	Technology	• Usage of cloud computing. • Investments in IT infrastructure. • Investments in cybersecurity. • Adoption of 3D printing
10	Information systems	• Main IT systems are used: ERP, WMS, Doc. Mgt. CRM • Fully integrated IS with suppliers/customers.

Source: Author's own work.

After normalizing survey data, the following table demonstrates item-by-item breakdown of the maturity score calculation for each of the 10 dimensions of the customized I4.0 MM. The scores are derived from the first-round Delphi survey conducted with a panel of 19 experts from the Cairo manufacturing sector (as previously mentioned).

The calculation process followed a consistent normalization protocol to convert various survey scales into a unified (0-4) maturity scale (as previously mentioned). The final score for dimension is the arithmetic mean of all the normalized Item scores mapped to it (see Table 19).

Table 19: R1 Survey Items, Raw Data, Final Dimension Score, and Maturity Level.

#	Dimension	Survey Items/Questions	Score Data	Item Score	Mean Score
1	Smart Operations	Integration between departments	4.2	4.2	3.77
		EDI with suppliers	3.80	3.80	
		IT usage for tracking & order fulfillment	3.75	3.75	
		Monitoring machines	3.31	3.31	
2	Customers	Electronic catalogues to sell products/services	4.13	4.13	3.27
		Internet to communicate with customers	4.25	4.25	
		Use of IT for customer services	3.63	3.63	
		Use of CRM	1.94	1.94	
		EDI with customers	2.4	2.4	
3	Smart Factory	Use of digitized machines (e.g., sensors)	4.24	4.24	2.94
		IT is used for monitoring machines & production process	3.31	3.31	
		Use of MES	2.13	2.13	
		Use of WMS	2.13	2.13	
		Degree of digitization level	95% "Low-digitized"	2.10	
		Average of 7 Data collection items (Q17)	3.70	3.70	

4	Smart Products	Production of customized products	4.19	4.19	2.69
		Use of CAD	2.19	2.19	
		Use of PLM	2.25	2.25	
		Investment in R&D	3	3	
		3D printing	1.81	1.81	
5	Leadership Management	Unskilled managers	68%	1.28	1.8
		Decision Deficiencies	42%	2.32	
6	Information systems	Use of ERP	68%	2.72	2.01
		Use of MES	10%	0.4	
		Use of WMS	68%	2.72	
		Use of Document Management	2.19	2.19	
7	Technology	Adoption of cloud computing	4.5	4.5	2.13
		Investments in IT infrastructure	2.81	2.81	
		Investments in cybersecurity	10%	0.4	
		Adoption of 3D printing	1.81	0.81	
8	Organizational Strategy	Has an I4.0 strategy been defined?	10% yes	0.4	1.99
		Is there a roadmap for I4.0?	0 % yes	0.00	
		Investments in cyber security	1.88	0.91	
		Integration between departments (VI)	3.44	3.44	
		EDI with customers (HI)	2.4	2.4	
		EDI with suppliers (HI)	3.8	3.8	
9	Employees	Investments in HR	16%	0.64	0.96
		Lack of knowledge	68%	1.28	
10	Culture	Organizational resistance to change	84% of experts agree	0.64	0.64

Source: Author's Own work.

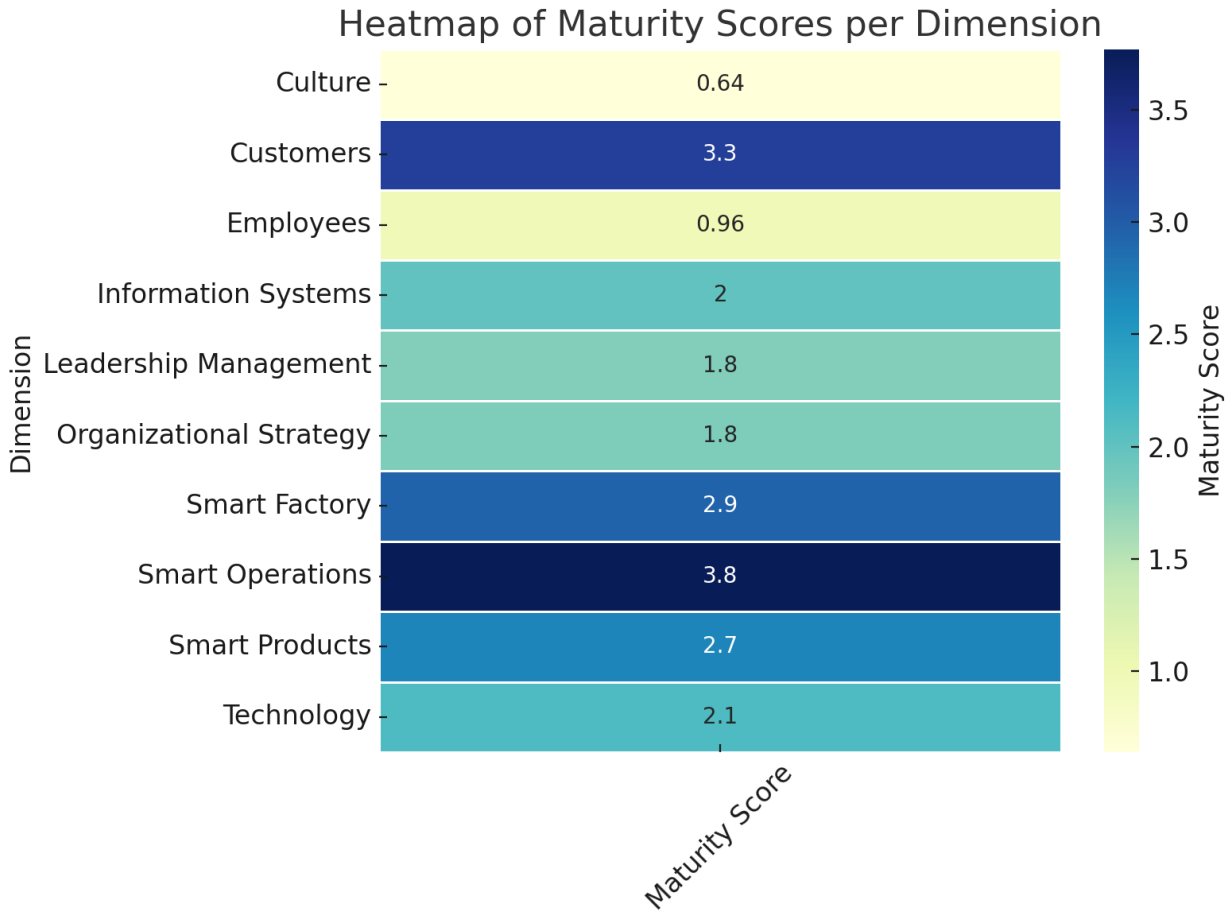


Figure 6: Cairo Manufacturing SMEs Maturity Levels.

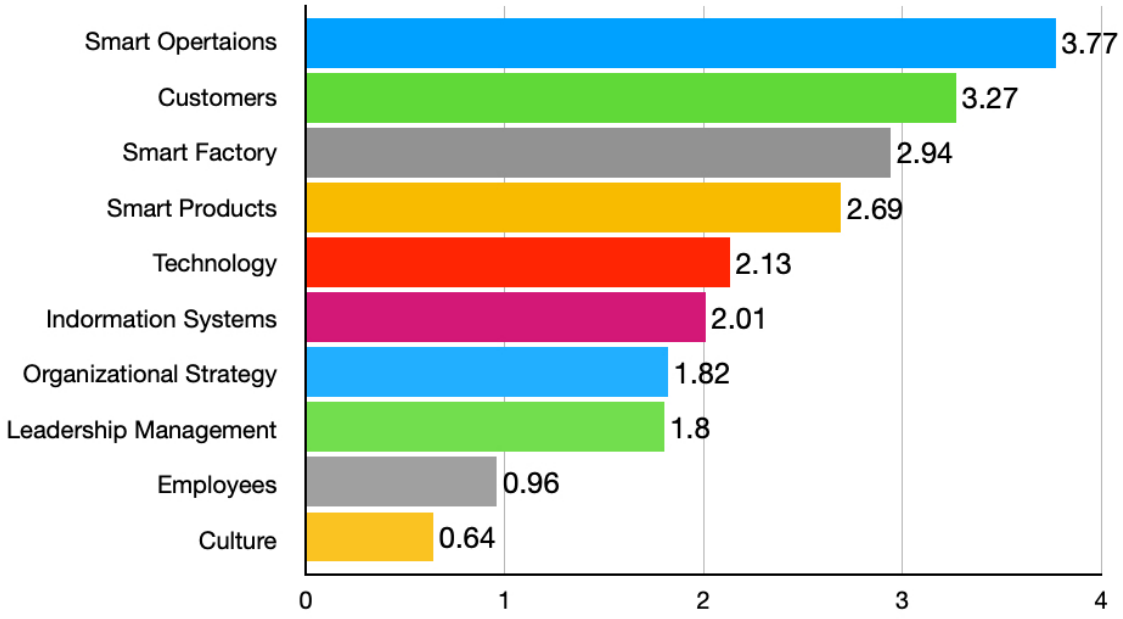


Figure 7: Maturity Level/Dimension

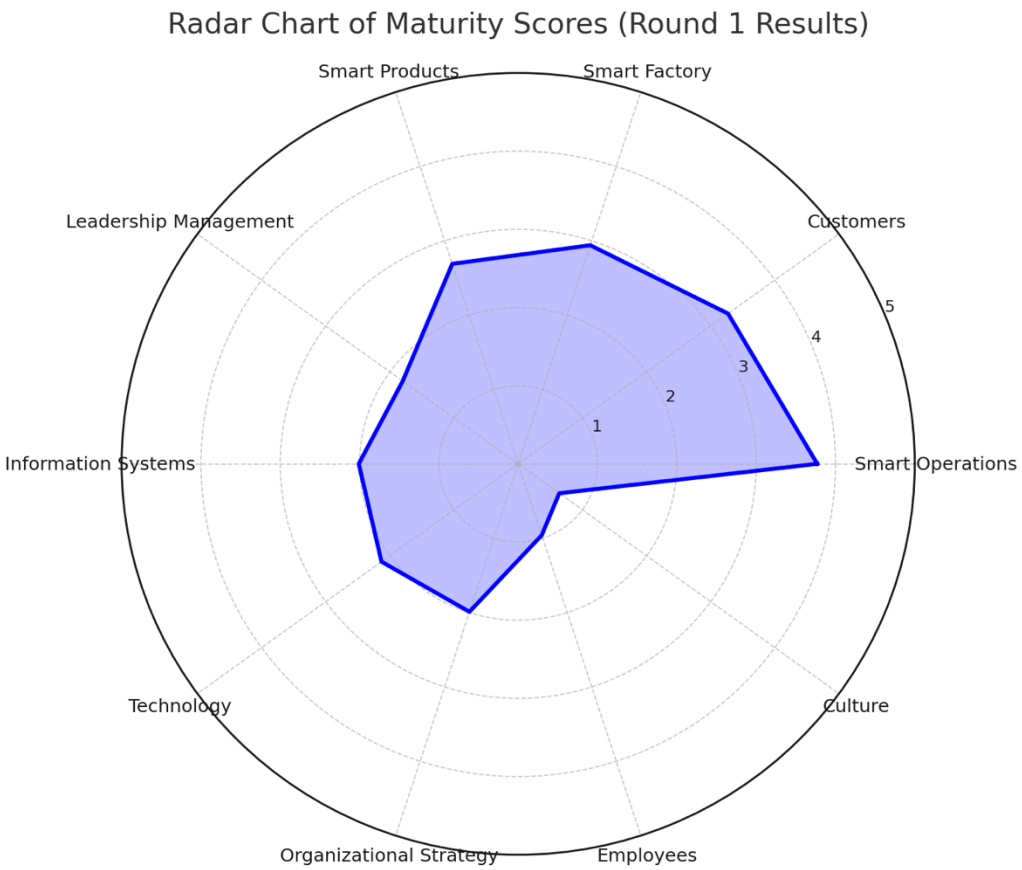


Figure 8: Rader Chart of the Maturity Levels/Dimension.

3.5.1 Discussion-R1 Insights

The results of R1, as summarized in Table (9), demonstrate how Cairo SMEs align with existing I4.0 MMs. While some foundational practices are present, the experts' assessments reveal that most SMEs remain at an early stage of maturity, with uneven progress across the maturity dimensions.

Table 19 highlights relatively stronger performance in terms of Smart operations, Customers, and Smart factory. For instance, ERP systems were widely adopted across multiple sectors, particularly in automotive, textiles, metals, and machinery. These practices reflect SMEs' prioritization of efficiency, customer responsiveness, and order fulfilment. This suggests that SMEs pursue digitalization primarily to streamline operations and strengthen customer relationships, rather than as part of a broader transformation agenda.

In the context of this study, the results reveal significant weaknesses in Organizational strategy, Leadership management, Employees, and Culture. SMEs lack a well-defined digital strategy and structured resource allocation towards I4.0. Moreover, employees' digital skills and training opportunities are limited, as evidenced by their low scores in this area. Cultural openness to innovation is also weak, reflecting resistance to change and a lack of trust in digital initiatives. These findings highlight a soft dimension gap, as technical systems are adopted selectively, while the human, cultural, and strategic enablers of I4.0 remain underdeveloped.

Moreover, the baseline for Cairo manufacturing SMEs aligns with evidence from other developing country contexts. Mittal, Khan, et al., (2018) observed that Indian SMEs often integrate basic ICT systems but lack the strategic and human capital structures necessary for deeper digital transformation. Similarly, (Sony & Naik, 2020) found that SMEs in emerging economies face persistent barriers related to cost, infrastructure, and workforce readiness. Egyptian studies, such as (Aboelmaged, 2018; Moussa & Tarek, 2023), also highlighted the digital skills gaps and the lack of governmental support for SMEs. Therefore, the results of R1 reflect a broader pattern; SMEs in emerging economies selectively adopt operational technologies but significantly lag behind in leadership, strategy, and human development.

Table 19 demonstrate the need for a customized manufacturing (MM) model specifically tailored to Cairo manufacturing SMEs. While internationally recognized frameworks like Acatech or IMPULS emphasize advanced technologies such as CPS, IoT, and BDA, these benchmarks often prove unrealistic for SMEs lacking even basic digital skills and strategic vision.

By aligning the model with local realities, such as the widespread adoption of ERP systems but limited investment in training and cultural awareness, the customized model ensures that maturity is defined in achievable, context-sensitive stages. This approach prevents Cairo SMEs from being misclassified as immature and instead provides them with a practical roadmap for gradual advancement.

Furthermore, the R1 Delphi results reveal that Cairo manufacturing SMEs exhibit an overall digital maturity score of 2.2, corresponding to "Level 2: Progressing" on the (0 to 4) maturity scale. This indicates that while foundational capabilities are established, the focus is now on developing more repeatable and standardized digital processes.

The strongest dimensions are Smart operations (3.77) and Customers (3.27), both positioned at "Level 3: Managed". This reflects a relatively high degree of maturity in processes integration and the use of

digital tools for customer interaction. Following these are Smart factory (2.94), Smart products (2.69), and Technology (2.13), which are firmly in the “Level 2: Progressing” category.

Conversely, critical weaknesses exist at the human and organizational levels. Employees (0.96) and Culture (0.64) are at “Level 0: Initial”, highlighting significant deficiencies in workforce digital skills and a strong organizational resistance to change. Other key enabling dimensions, including Leadership management (1.8) and Organizational strategy (1.82), remain at “Level 1: Foundation”, indicating that strategic planning and governance for digital transformation are still in their infancy. Information systems (2) are just entering the “Progression” stage.

In essence, the findings indicate a significant disparity in maturity levels. While operational and customer-facing technologies are progressing, this progress is hindered by a lack of strategic direction, leadership, and investment in human capital. To achieve higher maturity levels, SMEs must prioritize cultural change management, workforce development, and the establishment of a formal I4.0 strategy (Elhusseiny & Crispim, 2021; Frank et al., 2019).

Table 20: I4.0 Tailored MM for Cairo Manufacturing SMEs.

#	Dimension	Exemplary Maturity Items	Level 0: Initial	Level 1: Foundation	Level 2: Progress	Level 3: Managed	Level 4: Maturity
1	**Organizational Strategy**	Organizational level (strategy, structure, management, resources allocation, digital awareness, integrated departments), IT Knowledge, Realizing available resources for digitization.	Enterprises that fail to comply with any of the I4.0 requirements, lack awareness of I4.0, or fail to adopt digital technologies. (e.g., manual process, no digital strategy or I4.0 vision plans).	The roadmap and vision are available for newcomers. (e.g., basic digital awareness; initial vision for I4.0.)	Not all operations are fully integrated with smart manufacturing and digitization. Moreover, there is still room for improvement in terms of smart manufacturing and integration (in lower levels) (e.g., Partial digital strategy; some digitization initiatives).	Medium level integration and automation capabilities. (e.g., Integrated digital strategy; medium level of execution).	High level of digitization, and smart manufacturing. (e.g., Full digital strategy; extensive integration and execution).
2	**Smart Factory**	Automated Production Environment, Equipment Infrastructure, IT systems, VI (ERP, MES, Digitized machines), Traceability (final products, raw materials), Energy	No automation or digitalization in place.	Basic automation; standalone systems.	Initial digitization in some processes; limited integration.	Medium level of automation and integration (e.g., ERP, MES, digitized machines).	Highly automated and integrated production environment.

		Management (Energy consumption, Energy monitoring)					
3	**Smart Operations**	Cloud usage, IT security, Interdepartmental Collaboration, Data Analytics.	Manual operations; no digital tools.	Introduction of basic digital tools (e.g., cloud usage).	Some inter-departmental collaboration; limited IT security measures.	Effective interdepartmental collaboration; good IT security practices.	High-level smart operations; extensive use of data analytics and interdepartmental collaboration.
4	**Smart Products**	New data driven services (e.g., self-reporting, identification, localization), Online presence, Integrated customer management, Customized products, Digitization of products/services systems, Data processing, R&D	No implementation of smart products.	Initial plans for smart products; basic online presence.	Some smart products; basic data-driven services.	Integrated customer management and customized products; good online presence.	Advanced smart products with extensive data-driven services and R&D.
5	**Employees**	Digital skills	No digital skills among employees.	Basic digital skills; initial training programs.	Improving digital skills through continuous training.	Employees possess good digital skills; regular updates and training.	Highly skilled employees; advanced training programs.
6	**Leadership Management**	Management of digital competences	No digital leadership or strategy.	Initial digital leadership efforts; basic management	Developing digital leadership; some management of competences.	Strong digital leadership; good management of digital competences.	Excellent digital leadership and competences management.

				of digital competences.			
7	**Customers**	Utilization of customer data, Digitization of sales/services, Customers digital media competences.	No digital interaction with customers.	Initial digitization of sales/services; basic use of customer data.	Good digitization of sales/services; better customer data utilization.	Extensive digitization; integration of digital media competences.	Highly digitized customer interactions; advanced use of customer data.
8	**Culture**	Open to innovation, Supply chain Collaboration.	Resistance to change; no innovation focus.	Beginning to open to innovation; initial supply chain collaboration.	Openness to innovation; moderate supply chain collaboration.	Strong culture of innovation; extensive collaboration.	Highly innovative culture with robust supply chain collaboration.
9	**Technology**	Utilization of mobile devices, ICT integration (VI&HI).	No modern ICT usage.	Basic ICT systems in place; initial use of mobile devices.	Some ICT integration; good use of mobile devices.	Extensive ICT integration (VI&HI); strong usage of mobile devices.	Highly integrated ICT systems (VI&HI); advanced use of mobile devices.
10	**Information Systems**	Data analysis, IT infrastructure, Protection of intellectual property.	Manual data handling; no formal systems.	Basic data analysis tools; initial IT infrastructure.	Moderate data analysis capabilities; developing IT infrastructure.	Good data analysis; resilient IT infrastructure.	Advanced data analysis; highly resilient and secure IT infrastructure.

Source: Author's Own work.



Figure 9: I4.0 Tailored MM for Cairo Manufacturing SMEs (In terms of Dimensions weights).

3.6 Discussion

In this section, we delve deeper into the primary research gaps previously identified. providing detailed discussions and answers. The purpose is to pave the way for the adoption of the proposed generic MM, allowing SMEs to I4.0 paradigm transition. In addition, to build a robust groundwork for both theoretical and practical application.

Our discussion and responses are structured around existing literature and the primary collected data, offering a comprehensive perspective on I4.0 adoption in SMEs within the manufacturing context.

- **Research gap 1: The Complexity of I4.0 MMs**

The literature review indicates that current I4.0 MMs in the manufacturing sector encompasses a wide variety of dimensions and stages, all designed to evaluate enterprises' readiness and progression in adopting I4.0 technologies (Akdil et al., 2018; Ganzarain & Errasti, 2016; Gökalp et al., 2017; Mittal, Khan, et al., 2018; Schumacher et al., 2019).

These models assess various dimensions, providing a detailed roadmap for organizations to digitize and innovate their processes and services. However, the diversity in these models reflects the complexity of the I4.0 transition and highlights the different focal points and methodologies that can be employed (Magdy Elhusseiny & Crispim, 2023; Touijer & Elabjani, 2025).

Moreover, the SLR confirmed that the most I4.0 MMs (e.g., (De Carolis et al., 2017; Gökalp et al., 2017; Mittal, Khan, et al., 2018a; Schumacher et al., 2016)) are designed for large, resource-rich companies in developed economies. These models Implicitly assumed that most companies, regardless of size or economic context, can follow the similar transformation trajectories (De Carolis et al., 2017; Mittal, Romero, et al., 2018; Ranz & Schumacher, 2019; Schumacher et al., 2016; Touijer & Elabjani, 2025).

However, the Delphi findings strongly rebut this logic, foundational technologies like ERP, MES, ...etc., were moderately adopted, but the pillars of I4.0 like IoT, CPS, BDA were largely absent among SMEs. This mirrors the concerns raised by (Frank et al., 2019; Magdy Elhusseiny & Crispim, 2023), who argued that applying developed economies frameworks to SMEs in emerging economies produces a significant gap.

Furthermore, the reviewed models like (Colli et al., 2019; De Carolis et al., 2017; Fantini et al., 2020; Klötzer & Pflaum, 2017; Leyh et al., n.d.; Mittal, Romero, et al., 2018; Ramos et al., 2020; Schuh & Frank, 2020) assume the presence of digital skills, strategic planning capabilities, and a supportive Institutional environment, these conditions are rarely met in Egypt's SMEs landscape (*SME and*

Entrepreneurship Policy in Egypt, 2025). In addition, models like PwC (Ramos et al., 2020) emphasizes HI & VI as mid-level milestone, however, Cairo SMEs in this study had not yet become progressed in full Integration across the supply chain. Similarly, the Schumacher et al., (2016) model builds upon a staged capability logic, where early digital literacy, automation, and CPS readiness are presumed prerequisites. In contrast, Cairo SMEs remain highly reliant on manual paper-based processes, with foundational technological adoption.

Moreover, none of the 16 reviewed MMs systematically address contextual constraints like: (1) week institutional support for digitalization, (2) lack of affordable digital infrastructure, (3) cultural resistance to change, (4) lack of digital training skills, and (5) the role of stakeholders' engagement.

As such, applying any of these existing MMs without adaptation would result In Inaccurate assessments, Inappropriate benchmarks, and potentially misleading strategic recommendations.

Therefore, this research study confirms that none of the currently available I4.0 MMs are suitable for direct application in the Egyptian manufacturing SME context. Even those models that claim SME relevance like the ones by (Mittal, Romero, et al., 2018) or the SIMMI 4.0 by (Leyh et al., 2016) are established for European industrial ecosystems like Germany, where SMEs benefit from national digitization polices, public funding, and digital Infrastructure not available in developing economies like Egypt.

- **Research gap 2: Contribution of a Customized, empirically validated MM**

This research study contributes to the literature by proposing a customized, 10-dimensions MM for Cairo manufacturing SMEs. the proposed model Integrates dimensions validated through empirical data collected from two rounds of Delphi survey with 19 Industry experts. this ensures that the framework Is both evidence-based and contextually appropriate.

The model guides SMEs through 5-progressive maturity levels (Initial, foundational, progress, managed, and maturity) adopting concepts from prior frameworks (Akdil et al., 2018; Mittal, Khan, et al., 2018; Tranfield et al., 2003), while accounting for the social, economic and technological constraints facing resource-limited SMEs.

Unlike the published MMs proposed in existing literature, which assume a baseline of technological Infrastructure and strategic readiness (e.g., (Frank et al., 2019; Schumacher et al., 2016)), this study critically demonstrates that such assumptions are not valid for emerging economies context. The R1 Delphi results revealed the limited presence of core I4.0 technologies like IoT, CPS, and BDA, thereby questioning

the direct applicability of those models. Consequently, the development of a customized SME-specific model was not only necessary but methodologically justified.

The structure and content of the proposed MM were refined through a SLR synthesis of 16 existing MMs and triangulated with experts Input, following (Tranfield et al., 2003).

In addition to the synthesized SLR, the weight of 10 final dimensions was retained based on consensus (mean ≥ 4.00) in Delphi R2. Each dimension Is presented below showing both its theoretical foundation in the literature and its empirical validation through survey data.

The first Delphi round provided the data to conduct an exploratory assessment of the actual state of ICT adoption level. The findings were quantified by mapping all experts' responses to a normalized (0-4) scale and calculating a mean score for each of the 10 dimensions of the proposed model. This was concluded to Identify the actual maturity of Cairo SMEs.

These results are summarized in Table 21 as follows:

Table 21: Summary of Cairo SMEs Maturity Levels.

#	Dimension	Maturity Level Mean Score	Maturity Level
1	Smart Operations	3.77	Level 3: Managed
2	Customers	3.27	Level 3: Managed
3	Smart Factory	2.94	Level 2: Progressing
4	Smart Products	2.69	Level 2: Progressing
5	Information systems	2.01	Level 2: Progressing
6	Technology	2.13	Level 1: Foundation
7	Organizational Strategy	1.82	Level 1: Foundation
8	Leadership Management	1.8	Level 1: Foundation
9	Employees	0.94	Level 0: Initial
10	Culture	0.64	Level 0: Initial

The maturity scores (previously mentioned), provide a clear diagnostic of SME digitalization in Cairo, which is presented below, showing both its theoretical foundation in the literature and its empirical validation through Delphi survey:

- **Organizational Strategy:** Models like MM1, MM3, and MM5 emphasize the strategic role of defining and I4.0 roadmap, cyber security, and resources mobilization. However, the necessity for a clear strategic direction is underscored by the survey results, where only 2 experts reported that their SMEs had an implemented I4.0 strategy, and a striking 19 experts indicated the

absence of a formal roadmap for planning I4.0 activities. This fundamental lack of strategic clarity, coupled with "Organizational resistance to change", identified as a main barrier by 16 experts, and "Inadequate organizational structure", noted by 2 experts, highlighting the reason why the Organizational Strategy dimension is foundational in the model. It aims to guide SMEs in defining a vision and allocating resources effectively for digitization. Moreover, this places most SMEs at Level 1 maturity validating the Inclusion of Organizational Strategy as a foundational component in the customized model.

- **Smart Factory:** The concept of Smart factories in MM1, MM4, and MM5 involve advanced automation, energy monitoring, digitized machines, and integrated IT systems, while the survey data reveals a nascent but present foundation for the smart factory concept. Experts reported that the digitization level of production system Is generally "Low-digitized" as mentioned by 18 experts, Indicating connectivity to IT but only limited data collection. However, digitized machines for production/assembly are used (as mentioned by 13 experts), and IT Is used for monitoring machines/processes (as mentioned by 6 experts). continuous data collection from production machines (as mentioned by 11 experts) and energy consumption (as mentioned by 6 experts) is already occurring via IS to varying degrees. These insights suggest a fragmented and low-automotive environment, which is below the HI and VI levels expected by literature models. This empirical state justifies the "Smart Factory" dimension focusing on leveraging and enhancing this existing automation and monitoring efforts.
- **Smart Operations:** MM3 and MM5 require cloud usage, decentralized control, and interdepartmental collaboration. While this dimension addresses the Integration of VI and HI, cloud usage for storage and backup is notably high (as mentioned by 18 experts). Information sharing is facilitated by interdepartmental integration (as mentioned by 5 expert) and EDI with SC partners (8 experts) with suppliers, (6 experts) with distributors. However, "Lack of cyber security", identified as a main barrier (as mentioned by 13 experts), this demonstrates the critical need for the IT-Security aspect within this dimension.
- **Smart Products:** this dimension emphasized in MM1, MM3, and MM13, involves self-reporting products, customization, and online presence. Although the current level of "customized product production" as mentioned by 11 experts and the use of design software (as mentioned by 9 experts) indicate an Initial capacity for digital product aspects. The weak integration between

products and digital platforms indicates that most SMEs are still in the early stages of smart product development.

- **Employees:** both MM2 and MM3 stress the development of digital competences and leadership support for digital transformation. While the human capital emerged as a critical factor, with 13 experts mentioning "Lack of human knowledge" and 13 experts mentioning "unskilled employees and managers" as major barriers. the recommended training programs (e.g., communication skills (12-word count), computer skills (11-word count), technical skills (8-word count), directly address the need to improve digital competences. Thus, this dimension emphasis is skill development and training to bridge this crucial gap identified by experts.
- **Leadership Management:** complementing the focus on employees, the "Leadership Management" dimension is vital for driving transformation. The survey highlighted the need for leadership skills, with experts recommending training in strategic planning (11-word count), negotiation skills (9-word count), and project management skills (5-word count). This empirical evidence supports the dimension's role in cultivating the necessary leadership capabilities to steer I4.0 Initiatives.
- **Customers:** the data Indicates significant existing digital interaction with customers. electronic catalogues are fully adopted (as mentioned by 16 experts), and the internet is used for communication (as mentioned by 12 experts). CRM systems are used (as mentioned by 6 experts), while searching for customers are used (as mentioned by 8 experts) and collecting information about them are practiced (as mentioned by 9 experts), deeper utilization of customer data requires development. The "Customer" dimension leverages these existing digital channels and guides SMEs towards more advanced, data-driven customer strategies.
- **Culture:** collaboration is an underlying theme, with interdepartmental integration (as mentioned by 5 experts) and EDI used with SC partners (previously mentioned). Although specific measures for knowledge sharing or open innovation were not explicitly quantified, the "Culture" dimension is included to address the organizational readiness, openness to new technology, and collaborative spirit required for successful I4.0 adoption, particularly given the high rate of organizational resistance (as mentioned by 16 experts) as a barrier.
- **Technology:** the empirical data provides a clear picture of the current technology landscape. Foundational IT systems like ERP (as mentioned by 13 experts), WMS (as mentioned by 13

experts), and Document Management (as mentioned by 12 experts) are widely used. cloud computing is highly adopted (as mentioned by 12 experts), reported usage (as mentioned by18 experts). However, adoption of more advanced technologies specifically mentioned in I4.0 context, such as MES (as mentioned by 2 experts), PLM (as mentioned by 4 experts), CAD (as mentioned by 4 experts), and the explicit note of IoT, BDA, M2M communication, and CPS are not used. Moreover, the "Technology" dimension in our model is crucial for guiding SMEs in identifying, adopting, and integrating these modern ICTs strategically.

- **Information Systems:** this dimension works closely with technology, focusing on the integration and robustness of IT systems. The data shows that while many individual systems are in use (as listed under Technology), the overall integration between departments is low, the Information systems dimension emphasizes building a connected and resilient IT infrastructure that supports data flow and advanced applications, addressing this integration observed gap.

In terms of maturity levels, they further highlighted asymmetries within the digital transformation journey:

- **Strategic deficits (Level 1.1-1.13):** Organizational strategy (1.1), Culture (1.3), and Information systems (1.4) scored the lowest, reflecting systemic gaps in vision, planning, and cross-functional Integration. Moreover, only 2 experts reported that their companies had an I4.0 strategy, and 16 highlighted organizational resistance as a critical barrier.
- **Operational Progress (Level 2.0-2.2):** Smart factory (2.1), Smart products (2.0), and Customers (2.2) showed higher maturity levels. SMEs were using ERP, producing customized products, and employing e-catalogues, yet these were Isolated digital Improvements rather than signs of cohesive transformation.
- **Leadership and workforce Gaps:** Although many SMEs Invested In technology, leadership capacity and workforce digital skills were lagging. A significant number of experts cited a lack of strategic training and digital competence among employees (13 experts mentioned "lack of human knowledge"; 13 also reported "unskilled workforce").

The Cairo SME landscape is characterized by a “hollow core and fragmented periphery” with ad-hoc digital adoption lacking foundational support (Schumacher et al., 2016; Vial, 2019).

- **Theoretical and Practical Contributions**

Theoretically, this research study challenges the monolithic framing of digital transformation as a pave way for I4.0 adoption. Instead, it repositions I4.0 adoption as a contingent and context-sensitive process. while published models present Idealized trajectories, this study provides an alternative that reflects the actual technical constraints of SMEs in developing countries. the empirical validation of the model through Delphi adds credibility, transforming It from a conceptual proposal into a practitioner-ready diagnostic tool.

practically, the model delivers a roadmap that guides through 5-maturity levels: Initial, foundation, progress, managed, and maturity. It outlines clear interventions at each level, emphasizing foundational development (e.g., strategic planning, IT Integration, workforce training before scaling to more complex digital tools.

For policymakers, the results demonstrate that investment in digital Infrastructure must be complemented by capacity building in leadership, employee skills, and organizational culture. The model also offers a benchmarking framework for national or sectoral assessments of digital readiness.

Furthermore, unlike many models based solely on literature like those proposed by (Akdil et al., 2018; Ganzarain & Errasti, 2016; Mittal, Romero, et al., 2018; Ramos et al., 2020) or single-case validations like models proposed by (Lee et al., 2017; Schuh & Frank, 2020), this model was developed with local experts through a structured Delphi survey, enhancing both its contextual resonance and methodological rigor. Where, R1 served as an exploratory diagnosis, while R2 provided consensus weight of maturity dimensions. This iterative approach allowed for both bottom-up identification and top-down refinement, ensuring that each dimension is not only theoretically but empirically necessary.

3.7 Conclusions and Future Directions

This study explores the adoption of I4.0 in manufacturing SMEs through an exploratory investigation. It begins by reviewing existing I4.0 MM and, based on a Delphi survey with 19 industrial experts, proposes a tailored maturity model for these SMEs. The research significantly contributes to the literature on I4.0 adoption in the context of manufacturing SMEs.

By systematically reviewing existing models, it identifies key dimensions crucial for adoption and proposes customized generic MM. This study also addresses the critical gaps by providing a framework that addresses the unique challenges and constraints faced by SMEs in developing countries.

- **Theoretical and Practical Contributions:**
    - **First: Theoretical Contributions:**

This research enhances the theoretical understanding of I4.0 adoption in manufacturing SMEs by identifying common dimensions across existing maturity models. The integration of expert insights via the Delphi method strengthens the proposed model's theoretical foundation by assessing current ICT levels in SMEs and offering a framework to facilitate Industry 4.0 adoption.

a. Identification of Critical Dimensions for SMEs:

This research identifies the key dimensions critical for Industry 4.0 adoption, tailored to the needs of SMEs. These dimensions include organizational strategy, smart factory, smart operations, smart products, employees, leadership, customers, culture, technology, data governance, and information systems. Unlike most models offering generalized frameworks, this study presents a focused, detailed set of dimensions specifically relevant to SMEs, enriching the literature with nuanced perspectives on digital transformation for smaller enterprises.

b. Tailored Maturity Model:

A tailored MM has been proposed, addressing the challenges SMEs face in developing regions. The model comprises five maturity stages: Initial, Foundation, Progress, Managed, and Maturity. This sequence considers the limited resources and technological readiness of SMEs, filling a crucial gap in literature often biased toward large/multinational enterprises.

c. Validation through Delphi Method:

The Delphi method ensures the empirical validity of expert opinions on the proposed dimensions and maturity model. Engaging industry experts from sectors such as automotive, metals, electrical equipment, food and beverages, textiles, agriculture, and petrochemicals provide practical insights to refine theoretical constructs. This methodological rigor enhances the credibility of the findings and the innovative approach to adapting global Industry 4.0 frameworks for local customization.

- **Second: Practical Contributions**

a. Practical Roadmap for SMEs:

The study offers a step-by-step roadmap for SMEs to assess and enhance their I4.0 maturity levels. It serves as a practical tool, helping SMEs pursue incremental digital transformation and ensuring effective resource use for sustainable development. For Cairo-manufacturing SMEs and other developing regions, this roadmap guides the implementation phases of I4.0 technologies.

b. Emphasis on Training and Skills Development:

The study emphasizes the importance of skill development and training programs in strategic planning, digital marketing, project management, and enhancing technical skills for managers and employees. Identifying these training needs provides actionable recommendations for SMEs in developing regions to effectively drive and manage digitization initiatives.

c. Stakeholder Engagement:

The paper identifies the importance of stakeholders in facilitating I4.0 adoption, including governmental support, supply chain partners integrations (e.g., EDI), consulting firms, and financial institutions, in supporting I4.0 adoption. These contributions, according to experts' opinions, allow a successful digital transformation for manufacturing SMEs.

Moreover, by focusing on Cairo's manufacturing sector, this research updates the literature with context-specific findings that address the challenges and opportunities in developing countries. It extends the applicability of I4.0 maturity models to regions and enterprises that have been underrepresented in previous studies, offering a localized perspective that enriches the global discourse on digital transformation.

The study's findings reveal a moderate level of ICT adoption among Cairo SMEs, with extensive use of ERP systems but limited integration of more advanced technologies like IoT, Big Data, and CPS. These insights update the literature by providing a realistic picture of the current state of digital readiness in developing regions, highlighting areas for improvement and targeted intervention.

Additionally, our use of the Delphi method to validate the relevance of these dimensions with experts provides a novel approach to customizing global I4.0 frameworks to fit the specific needs of SMEs. This methodological contribution enhances the reliability and applicability of our findings.

Overall, this research provides a comprehensive framework and practical guidelines that can significantly enhance the ability of SMEs to adopt I4.0 technologies. Future research should expand on this

foundation by exploring the long-term impacts of I4.0 adoption and adapting the model to other developing regions, thus contributing to the broader discourse on digital transformation and industrial development on a global scale.

3.8 Study Limitations

- Despite the methodological rigor and contextual relevance of this study, some limitations should be acknowledged.
- First, the geographical focus of the study was limited to manufacturing SMEs, which may affect the generalizability of the findings. Although Cairo represents a central manufacturing hub in Egypt, regional disparities in infrastructure, policy support, and digital capabilities may influence the relevance of the proposed model in Middle East and North Africa (MENA) economies.
- Second, the Delphi method expert-driven validation of the model's dimensions and maturity items, provides rich, context-specific finding relevant for Cairo manufacturing SMEs or those in developing countries with similar characteristics. However, the validation of the identified dimensions requires a more in-depth study that includes quantitative data gathered from international index like Smart Industry Index (SIRI) or OECD for further assessments.
- Furthermore, the study prioritized I4.0 and did not extend into broader thematic scope like Industry 5.0 (I5.0), which includes sustainability and resilience. We recommend that future research expand the model by incorporating environmental and ethical indicators aligned with I5.0 to explore SMEs transitions from I4.0 to I5.0 maturity stages.
- Finally, the study reflects the state of technology and adoption patterns as of the time of data collection (2024). Given the rapid pace of innovation like advances in AI and digital technologies, some model components may require continuous updating to remain aligned with evolving industry standards and requirements.

4. Chapter Four: Towards a Digitalized Tourism Model: A Conceptual Framework.

4.1 Introduction

The rapid advancement of technology has significantly transformed the global tourism industry, presenting both opportunities and challenges for small and medium-sized enterprises (SMEs), particularly in emerging economies (Aras & Büyüközkan, 2023; Hafeez et al., 2025). In Egypt, a country where tourism plays a crucial role in its economy, there is a pressing need for digital transformation (Elziaty et al., 2024). Despite its economic challenges, tourism SMEs are encountering substantial difficulties in adopting the necessary information technologies and practices to thrive in a digital marketplace (Sangnak, 2025; Santarsiero et al., 2024; Skare et al., 2023).

Previous studies, such as those conducted by Abdurrahman et al., (2024); Boonmee et al., (2025); Skare et al., (2023), have highlighted the absence of well-developed and applied maturity models (MMs) within the tourism sector, particularly in developing nations. These models predominantly rely on generic theoretical constructs, such as the Technology, Organization, Environment (TOE) framework or the Technology Acceptance Model (TAM), without adequately addressing the unique challenges and capabilities faced by SMEs within the tourism industry (Abdurrahman et al., 2024; Boonmee et al., 2025; Skare et al., 2023).

This research primarily focuses on this gap, raising the critical issue of the absence of a maturity model that can effectively capture the complexity and inter-related dimensions at the SME level, particularly within the tourism sector (A. Hermann et al., 2024; Marino-Romero et al., 2024).

Consequently, the purpose of this chapter is to present a proposed context-based MM for Egyptian tourism SMEs, which will facilitate the assessment of their digital readiness. The proposed model is grounded on six maturity dimensions: Organizational Strategy & Leadership (Avelar et al., 2024; A. Hermann et al., 2024), Technology & Infrastructure (Arroyabe et al., 2024; Tajeddini et al., 2026), People & Culture (Abdo et al., 2025; Abdurrahman et al., 2024b; Marino-Romero et al., 2024; Sangnak, 2025), Smart Operations & Processes (Abdurrahman et al., 2024b; Arranz et al., 2023; A. Hermann et al., 2024; Sahibzada et al., 2025; Skare et al., 2023), Customer & Services Experience (Enshassi et al., 2025), and Stakeholder

Engagement (Magdy Elhusseiny & Crispm, 2025; Mittal, Khan, et al., 2018a; Mujahed et al., 2024; Sangnak, 2025b).

Each of the aforementioned dimensions encompasses validated capabilities derived from recent literature studies.

The research is guided by 2 main research questions:

- RQ1: What are the critical dimensions and capabilities that determine digital maturity in the tourism sector within Egyptian SMEs?
- RQ2: How can a practical MM be structured to assess, benchmark, and guide digital transformation in tourism SMEs?

To address these research questions, we developed a structured questionnaire aligned with the proposed dimensions, capabilities, and maturity classifications. The questionnaire employs a five-level scale based on established models in the digital transformation literature (Akdil et al., 2018; Mittal, Khan, et al., 2018; Schumacher et al., 2019).

4.2 Digitalization in Tourism

Digitalization in tourism refers to the integration of digital technologies into the value creation, delivery, and consumption of tourism services (Bethune et al., 2022). Moreover, it is the application of ICT to enhance efficiency, customer satisfaction, and competitiveness (Bethune et al., 2022). The digitalization of tourism has evolved in three major phases, including; (1) digitization of information, which includes the transition from paper brochures to online brochures and websites, (2) digital transformation of processes which is characterized by online booking engines, CRM systems, and dynamic pricing tools, and (3) smart tourism ecosystems which integrate IoT, AI, and real-time data sharing to create adaptive, personalized, and immersive services (Bingöl & Yang, 2025; Collado-Agudo et al., 2023; Mantovani et al., 2024; Yap et al., 2025).

The emergence of smart destinations has been influential; the Gandia case study in Spain demonstrates that the integration of ICTs into urban infrastructures, governance, and services is essential to tourism development (Inversini et al., 2024). Moreover, large tourism companies have increasingly deployed advanced digital technologies like IoT, big data, (Inversini et al., 2024) AR/VR, and blockchain (Önder & Treiblmaier, 2018).

Emerging technologies like the metaverse illustrates the new frontier of tourism digitalization (Ledesma-Chaves et al., 2024). As a study of Spanish SMEs showed that the adoption of metaverse applications is primarily motivated by business satisfaction; as it enhances customer and organizational satisfaction rather than direct performance expectations (Ledesma-Chaves et al., 2024). Which include perceived usefulness, ease of use, and compatibility, echoing constructs from the technology acceptance model (TAM) (Ledesma-Chaves et al., 2024; Schorr, 2023).

Tourism large companies are increasingly implementing a variety of cutting-edge digital technologies for e.g., the IoT, which enables applications like occupancy sensors, smart rooms, and energy optimization (Mantovani et al., 2024; Yap et al., 2025). Artificial intelligence (AI), regarded as an innovative tool, can effectively support chatbots, demand forecasting, and customer service robots. (Ivanov & Webster, 2020). BDA, which are regularly used in large enterprises for demand forecast, customer profiling, and market analysis (Mariani, 2019). Also, emerging technologies like AR and VR are employed in virtual heritage tours and destination previews (Inversini et al., 2024).

However, tourism SMEs face difficulties in their digital transformation processes. As SMEs face financial constraints, which, restrict their ability to invest and implement in advanced technologies (Elhusseiny & Crispim, 2021; Maldonado-Guzmán et al., 2017; Mittal, Khan, et al., 2018; Oduro, 2020). Besides, the lack workforce digital skills and organizational resistance to change, hinder their progress towards digitalization (Elhusseiny & Crispim, 2021; Maldonado-Guzmán et al., 2017; Mittal, Khan, et al., 2018; Oduro, 2020).

In addition, recent studies (e.g., Sangnak's, (2025)) emphasized that the absence of governmental support, inadequate training, and poor ICT connectivity are the primary barriers hindering the effective utilization of digital tools for a sustainable development (Sangnak, 2025b).

The said barriers deeply resonate with the challenges faced by Egyptian tourism SMEs; as recent studies like (Abdo et al., 2025; Elziaty et al., 2024) mentioned due to the limited resources, shortage of efficient digital skills, and deficiencies in ICT infrastructure; SMEs face major difficulties towards digitalization (Aboushouk & Elsawy, 2020; Elziaty et al., 2024).

4.3 Methodology

Egypt has been chosen as the context for this chapter due to several compelling reasons. Firstly, the tourism sector is recognized as a significant contributor to the Egyptian economy (Abdo et al., 2025; *Tourism in Egypt 2023 - Discover Egypt's Monuments - Ministry of Tourism and Antiquities*, 2023; *Tourism Sector Contributed 24% of Egypt's GDP Last Year, Making an "Extraordinary Recovery" | WTTC- Business Today*, 2024). In 1960, this sector generated approximately $20 billion, while in 2020, it reached an impressive $412 billion (*World Development Indicators | DataBank*, n.d.).

Secondly, Statista data indicates that the tourism and hospitality industry alone contributed approximately $12.6 billion to the Egyptian economy in 2018 (*Egypt: Contribution of Travel and Tourism to GDP 2012 to 2028 | Statista*, n.d.). Thirdly, the tourism sector employed a substantial number of individuals, with 2.16 million employees in 2021 (*World Development Indicators | DataBank*, n.d.). Fourthly, it is projected that this sector will continue to contribute by $9.5 billion to the Egyptian economy by 2028 (*Tourism Industry in Egypt - Statistics & Facts | Statista*, n.d.).

Despite the acknowledged sufficiency of the tourism sector for Egypt, it is evident that this sector lacks the adoption of digitalization, particularly among SMEs (Abdo et al., 2025; Magdy Elhusseiny & Crispm, 2025).

SMEs encounter several challenges that impede their digitalization adoption. These challenges stem from financial constraints (Abdo et al., 2025; Elziaty et al., 2024), a shortage of digital-skilled labour (*Arab Finance - AI in Egyptian Tourism: Unlocking Innovation, Overcoming Challenges*, n.d.; Magdy Elhusseiny & Crispm, 2025), cybersecurity concerns, cultural barriers, a lack of governmental support, and a lack of customer readiness to fully engage with digital platforms (Abdo et al., 2025).

Therefore, the primary purpose of this chapter is to propose a conceptual framework that could serve as a roadmap and facilitate the adoption of digitalization by tourism SMEs as a substantial economic sector, ultimately fostering innovation.

4.3.1 Questionnaire development

Based on the analysis provided in the previous empirical study (chapter 3), on I4.0 MMs for manufacturing SMEs and the recent literature on digital transformation in tourism and hospitality sector, the following key capabilities are required for implementing digitalization in tourism companies.

These capabilities are organized into six key categories or dimensions that form the foundation of the conceptual model (see Table 22) as follows:

1) Organizational Strategy & Leadership

This dimension assesses the extent to which tourism SMEs incorporate digital transformation into their overarching strategic frameworks (Avelar et al., 2024; A. Hermann et al., 2024; Santarsiero et al., 2024). It underscores the significance of leadership commitment, governance mechanisms, and alignment with organizational objectives and digital initiatives. (Avelar et al., 2024; A. Hermann et al., 2024; Santarsiero et al., 2024).

According to previous studies like Avelar et al., (2024); A. Hermann et al., (2024); Santarsiero et al., (2024) it encompasses six key capacities: a well-defined digital strategy for digitalization adoption, clearly defined responsibilities for digital transformation, management support, investments, and effective management of digital competencies. (Avelar et al., 2024; A. Hermann et al., 2024; Santarsiero et al., 2024).

2) Technology & Infrastructure

This dimension evaluates the presence of cutting-edge technologies that can support core and advanced operations within tourism companies. It includes both the adoption of foundational IT and the integration of advanced technologies. (Arranz et al., 2023; Arroyabe et al., 2024; Tajeddini et al., 2026).

Previous studies, e.g., Arranz et al., (2023); Arroyabe et al., (2024); Mittal, Khan, et al., (2018); Tajeddini et al., (2026), highlighted that the said dimension encompasses four key capabilities: the utilization of ERP, WMS, and CRM systems. Moreover, the adoption of cutting-edge technologies such as IoT, BDA, and Cloud computing is crucial. Additionally, it requires a robust and secure IT infrastructure, mobile devices, and e-commerce utilization platforms (Arranz et al., 2023; Arroyabe et al., 2024; Tajeddini et al., 2026).

3) People & Culture

This dimension emphasizes the human and cultural factors that either facilitate or impede the adoption of digital technologies (Magdy Elhusseiny & Crispm, 2025). It necessitates employees' digital skills, training programs, culture that embraces change and innovation (Magdy Elhusseiny & Crispm, 2025).

Previous studies, like Abdo et al., (2025); Abdurrahman et al., (2024); A. Hermann et al., (2024); Marino-Romero et al., (2024); Sangnak, (2025); Santarsiero et al., (2024) have identified four key capabilities for this dimension: digital skills among employees, openness to innovation, collaboration across

departments, and effective training programs. (Abdo et al., 2025; Abdurrahman et al., 2024; A. Hermann et al., 2024; Marino-Romero et al., 2024; Sangnak, 2025; Santarsiero et al., 2024).

4) Smart Operations & Processes

This dimension focuses on digitizing, automating, and optimizing internal operations, as well as inter-organizational workflows. It highlights the importance of leveraging real-time data and fostering collaboration to improve efficiency. (Bag et al., 2020; Frank et al., 2019; Müller, Buliga, et al., 2018).

5) Customer & Services Experience

This dimension assesses the effective use of digital technologies to improve customer interactions, services, and the development of innovative digital products or experiences. (Enshassi et al., 2025; Magdy Elhusseiny & Crispm, 2025; Tajeddini et al., 2026).

This dimension encompasses some capabilities, like digitizing sales, services, marketing. Moreover, from the said dimension capabilities are also data utilization, integrated CRM systems, and developed innovative data-driven services (e.g., online booking). (Enshassi et al., 2025; Tajeddini et al., 2026).

6) Stakeholders Engagement

This dimension defines how tourism companies collaborate with third-party entities, including financial institutions, consultants, government bodies, and other supply chain partners, to facilitate and enhance their digital transformation efforts (Abdurrahman et al., 2024; Magdy Elhusseiny & Crispm, 2025; Mujahed et al., 2024; Sangnak, 2025).

Table 22: Dimensions, Capabilities for Tourism MM.

#	Dimension	Capabilities	References
1	**Organizational strategy & Leadership**	a) Clear digital strategy and roadmap for I4.0 adoption. b) Defined roles and responsibilities for digital transformation. c) Management's support for digital initiatives. d) Investment in digital technologies and innovation. e) Effective management of digital competences.	(Avelar et al., 2024; A. Hermann et al., 2024; Santarsiero et al., 2024)

2	**Technology & Infrastructure**	a) Use of foundational IT systems like ERP, WMS, and CRM. b) Adopting advanced I4.0 technologies like IoT, BDA, and cloud computing. c) Presence of a resilient and secure IT-infrastructure. d) Utilization of mobile devices and e-commerce platforms.	(Arranz et al., 2023; Arroyabe et al., 2024; Tajeddini et al., 2026)
3	**People & Culture**	a) Digital skills and competencies among employees and managers. b) Openness to innovation and a culture of continues learning. c) Collaboration within and across departments. d) Effective training programs for staff to enhance digital competencies.	(Abdo et al., 2025; Abdurrahman et al., 2024; A. Hermann et al., 2024; Marino-Romero et al., 2024; Sangnak, 2025; Santarsiero et al., 2024)
4	**Smart Operations & Process**	a) Digitization and automation of core business processes. b) Real-time monitoring of operations using IS. c) Efficient supply chain collaboration with partners. d) Data collection and analysis to optimize operations.	(Abdurrahman et al., 2024; Arranz et al., 2023; Avelar et al., 2024; A. Hermann et al., 2024; Mujahed et al., 2024; Sahibzada et al., 2025; Skare et al., 2023)
5	**Customer & Services Experience**	a) Digitization of sales, services, and marketing. b) Use of data to understand customer behaviour and personalize services. c) Integrated customer management systems. d) development of new data-driven services and experiences (e.g., mobile applications, online booking, feedback, etc.,).	(Enshassi et al., 2025; Magdy Elhusseiny & Crispm, 2025; Tajeddini et al., 2026)

6	**Stakeholders Engagement**	a) Collaborations with government and other key stakeholders for support. b) Partnerships with financial organizations, consulting firms, and third-part partners. c) Using EDI to share information with supply chain partners (e.g., suppliers, distributors, and customers).	(Abdurrahman et al., 2024; Magdy Elhusseiny & Crispm, 2025; Mujahed et al., 2024; Sangnak, 2025)

Based on this explanation, we developed a structured questionnaire that can be a valuable tool for Egyptian tourism SMEs. This questionnaire aims to assess their maturity in various dimensions and help them adopt digitalization.

Additionally, since we intend to develop a conceptual MM for tourism SMEs, this questionnaire is designed to be a data collection instrument for researchers and practitioners to be empirically applied. It will also serve as a tool for future studies to develop a tailored MM for tourism SMEs (see Table 23).

Table 23: Questionnaire Design.

Section 1: General Information

This section aims to gather crucial background information about the participating tourism SMEs. The primary purpose of this data is to provide context for the digital maturity assessment, enabling researchers to analyse the findings based on some factors like company size, region, and other relevant information.

- Company Name (optional):
- Services sector:
  - Hospitality.
  - Tour Operator.
  - Travel Agency.
  - Other (Please Mention).
- Region of provided services:
  - Cairo.
  - Alexandria.
  - Luxor.
  - Aswan.
  - Siwa Oasis.
  - Sharm El-Shiek.
  - Hurghada.
  - Sainai.
  - Other (Please Mention).

- Which market does your company primarily serve?
  - Domestic.
  - Regional (Middle East & North Africa).
  - European countries.
  - Other (Please Mention).
- To what extent does your company "currently" have digital presence?
  - No digital presence.
  - A basic presence (e.g., a website).
  - Only social media (e.g., Facebook, Instagram).
  - Advanced (e.g., enabling online payment, booking, sales).
- What is the main motivation for your company to adopt new (advanced) technologies?
  - Improve operational efficiency.
  - Reduce costs.
  - Enhance customer experience.
  - Competitive advantage.
  - Other (Please Mention)
- Do you have dedicated IT team?
  - No.
  - Yes.
  - Outsourcing (Please Mention).
- What are the main barriers/challenges that hinder your company to adopt advanced technology?
  - Financial constraints.
  - Lack of digital skills (employees/managers).
  - Resistance to change.
  - Other (Please Mention).
  - ICT infrastructure.

- Lack of governmental support.

- Whose stakeholders are crucial to the success of cutting-edge technologies adoption? Please, select at least "3" from the following list:

- Government
- Universities
- Banks
- Financial organizations
- International community support funds
- Technology Support companies
- Technology Supply companies
- Supply chain members
- Consulting companies
- Third party partner, e.g., transportation, digital services providers, etc.

Section 2: Main Dimensions and Capabilities

This section outlines a set of critical dimensions, along with the necessary capabilities required to achieve maturity within each dimension. The primary purpose is to facilitate the adoption of cutting-edge technologies and digitization in tourism companies.

For each dimension, please rate the adoption of each capability using the provided scale. The scale ranges from “Not implemented” (0) to “Fully implemented across the organization” (5).

			Likert scale (0-4)				
#	**Dimension**	**Capabilities**	**Not implemented (0)**	**Planned but not implemented (1)**	**Partially implemented (2)**	**Fully implemented in some areas (3)**	**Fully implemented across the organization (4)**
1	Organizational strategy & Leadership	a) Clear digital strategy and roadmap for I4.0 adoption. b) Defined roles and responsibilities for digital transformation. c) Management's support for digital initiatives. d) Investment in digital technologies and innovation. e) Effective management of digital competences.					

2	Technology & Infrastructure	a) Use of foundational IT systems like ERP, WMS, and CRM. b) Adopting advanced I4.0 technologies like IoT, BDA, and cloud computing. c) Presence of a resilient and secure IT-infrastructure. d) Utilization of mobile devices and e-commerce platforms.					
3	People & Culture	a) Digital skills and competencies among employees and managers. b) Openness to innovation and a culture of continues learning. c) Collaboration within and across departments. d) Effective training programs for staff to enhance digital competencies.					
4	Smart Operations & Process	a) Digitization and automation of core business processes. b) Real-time monitoring of operations using IS. c) Efficient supply chain collaboration with partners. d) Data collection and analysis to optimize operations.					

5	Customer & Services Experience	a) Digitization of sales, services, and marketing. b) Use of data to understand customer behaviour and personalize services. c) Integrated customer management systems. d) development of new data-driven services and experiences (e.g., mobile applications, online booking, feedback, etc.,).					
6	Stakeholders Engagement	a) Collaborations with government and other key stakeholders for support. b) Partnerships with financial organizations, consulting firms, and third-part partners. c) Using EDI to share information with supply chain partners (e.g., suppliers, distributors, and customers).					

4.3.2 Data collection

The primary method employed in this chapter is a structured questionnaire, which is designed to evaluate the current digital maturity of tourism SMEs in Egypt. This instrument is used to quantify the extent of a company's capabilities across the aforementioned dimensions (Avelar et al., 2024).

The questionnaire is a suitable research tool because it enables the collection of important background data, maturity assessment, and the use of the Likert scale, which facilitates quantitative data analysis and clearly understand companies' digitalization progress (Abdurrahman et al., 2024; Sahibzada et al., 2025; Sangnak, 2025).

This questionnaire is dedicated for collecting data from top-management levels at tourism enterprises via online forms. This will facilitate data collection method and allow for the assessment of the maturity level for each maturity dimension and measure the readiness of the participated companies in adopting digitalization. Furthermore, this questionnaire could be analysed using structured equation modelling (SEM) as used in previous research studies like Abdurrahman et al., (2024); Sahibzada et al., (2025); Sangnak, (2025).

4.3.3 Maturity levels definitions

In addition to its dimensional structure, a crucial component of any MM is a set of maturity levels or stages that depict a company's evolutionary progress (Mittal, Khan, et al., 2018). Furthermore, these maturity levels are designed to evaluate and guide companies on their digital maturity journey (Becker et al., 2009; Mittal, Khan, et al., 2018).

As previously explained in chapter 3, the tourism sector lacks maturity models (Boonmee et al., 2025; Skare et al., 2023). Previous studies mostly rely on the TOE and TAM theories (Abdurrahman et al., 2024). Therefore, this chapter will use a five-level maturity scale to categorize and assess the digitalization readiness of SMEs. The proposed maturity levels are based on previous research studies, such as those used in the context of Industry 4.0. (e.g., Akdil et al., (2018); Magdy Elhusseiny & Crispm, (2025); Mittal, Romero, et al., (2018); Schumacher et al., (2016).

The five-level represents a scale from lowest digitalization adoption (level 0) to fully optimized digitalization (level 5) (see Table 24); which demonstrates maturity levels scores as follows:

Table 24: Maturity Levels definition for tourism SMEs.

Maturity Level	Definition	Maturity Score	References
Level 0 – Initial	At this stage, a company scores (0) or very close to it across all six dimensions. This indicates that a company has a basic digital presence, like a basic website and software, yet lacks significant IT systems and full integration for online booking or payment.	(0 > 1)	(Akdil et al., 2018; Magdy Elhusseiny & Crispm, 2025; Mittal, Romero, et al., 2018).
Level 1 – Foundation	A company at this stage start recognizing the significance of digital transformation and has a basic digital presence, like a reliable website and social media profiles. However, lack the adoption of integrated systems like ERP.	(1 > 2)	(Akdil et al., 2018; Magdy Elhusseiny & Crispm, 2025; Mittal, Romero, et al., 2018).
Level 2 – Progressing	Companies should adopt a proactive digital strategy, integrate key operational systems and utilize social media for marketing. Furthermore, collaboration across departments is emerging, and basic training programs are introduced to enhance employees' digital competencies, although these programs are not yet standardized.	(2 > 3)	(Akdil et al., 2018; Mittal, Romero, et al., 2018).
Level 3 – Managed	An organization possesses a dependable innovation culture, integrated IT systems, and a clearly defined roadmap for digitalization.	(3 > 4)	(Akdil et al., 2018; Mittal, Romero, et al., 2018).
Level 4 – Maturity	A company optimized every aspect of its operations to reach its maximum level of maturity. Moreover, it has effectively adopted AI and VI for	(4 ≥ 5)	(Akdil et al., 2018; Mittal, Romero, et al., 2018).

	better and advanced experience, as well as commitment to digital transformation		

4.3.4 A Roadmap for tourism SMEs to adopt the proposed maturity model

In this section, we will present a roadmap illustration using artificial data (not real data) to clarify how this proposed model can be implemented for tourism SMEs.

Previous studies (as shown in Table 25) proposed a step-by-step guideline for applying a roadmap. Following these guidelines, we propose a similar guideline for SMEs to apply our proposed model.

Table 25: Tourism Maturity Model Roadmap Steps.

Roadmap Steps	Description	References
Step-1	Proposes a roadmap for SMEs that includes assessing maturity, aligning with their strategic objectives, and gradual digital transformation.	(Aras & Büyüközkan, 2023; Hafeez et al., 2025; Othen et al., 2025; Re et al., n.d.)
Step-2	Calculated the maturity score of core dimensions (strategy, leadership, technology, customers, etc.) used in MMs.	(Aras & Büyüközkan, 2023; Hafeez et al., 2025; Othen et al., 2025; Re et al., n.d.)
Step-3	Prioritization of focus areas based on resources constraints and strategic needs	(Aras & Büyüközkan, 2023; Hafeez et al., 2025; Othen et al., 2025; Re et al., n.d.)
Step-4	Roadmap development	(Aras & Büyüközkan, 2023; Hafeez et al., 2025; Othen et al., 2025; Re et al., n.d.)
Step-5	Implementation & capability building	(Aras & Büyüközkan, 2023; Hafeez et al., 2025; Othen et al., 2025; Re et al., n.d.)
Step-6	Monitoring & reassessment	(Aras & Büyüközkan, 2023; Hafeez et al., 2025; Othen et al., 2025; Re et al., n.d.)

The Tourism Digital Maturity Model (TDMM) presented in this chapter offers a framework for Egyptian SMEs to evaluate their current digital maturity level based on the specified dimensions. Furthermore, it serves

as a practical guide, providing a structured digital transformation roadmap to assist them in their journey (see Fig.10)

The following steps provide a systematic guide for implementation as follows:

- **Step 1: Initial Assessment:** using the questionnaire developed in this chapter; a company began to evaluate each of the six maturity dimensions capability across a 5-point Likert scale (Level 0 to Level 4) (Aras & Büyüközkan, 2023; Hafeez et al., 2025; Othen et al., 2025; Re et al., n.d.). This step enables a company to identify the current digital maturity level for each dimension, and its overall maturity level (Schumacher et al., 2019).
- **Step 2: Gap Analysis:** once the maturity levels are calculated, a company should conduct a dimension-by-dimension gap analysis. This will be conducted through comparing current scores to the highest maturity level (Aras & Büyüközkan, 2023; Hafeez et al., 2025; Othen et al., 2025; Re et al., n.d.). This step will allow a company to identify its specific capabilities where performance is lagging (Schumacher et al., 2019).
- **Step 3: Capabilities Prioritization:** Due to financial constraints and limited resources, companies may not be able to simultaneously enhance all dimension capabilities (Aras & Büyüközkan, 2023; Hafeez et al., 2025; Othen et al., 2025; Re et al., n.d.). Consequently, companies will prioritize their capabilities based on their available resources (Aras & Büyüközkan, 2023; Hafeez et al., 2025; Othen et al., 2025; Re et al., n.d.).
- **Step 4: Development of a Customized Roadmap:** Companies should develop a customized digital transformation plan using the maturity scores and prioritization insights to guide their development of a customized roadmap (Aras & Büyüközkan, 2023; Hafeez et al., 2025; Othen et al., 2025; Re et al., n.d.).
- **Step 5: implementation:** SMEs implement the customized roadmap using both internal and external resources (Aras & Büyüközkan, 2023; Hafeez et al., 2025; Othen et al., 2025; Re et al., n.d.).
- **Step 6: Monitoring, Re-assessment, and Continues Improvement:** SMEs should establish a regular review plan, such as quarterly, semi-annually, or annually, to assess their improvement across various dimensions (Aras & Büyüközkan, 2023; Hafeez et al., 2025; Othen et al., 2025; Re et al., n.d.).

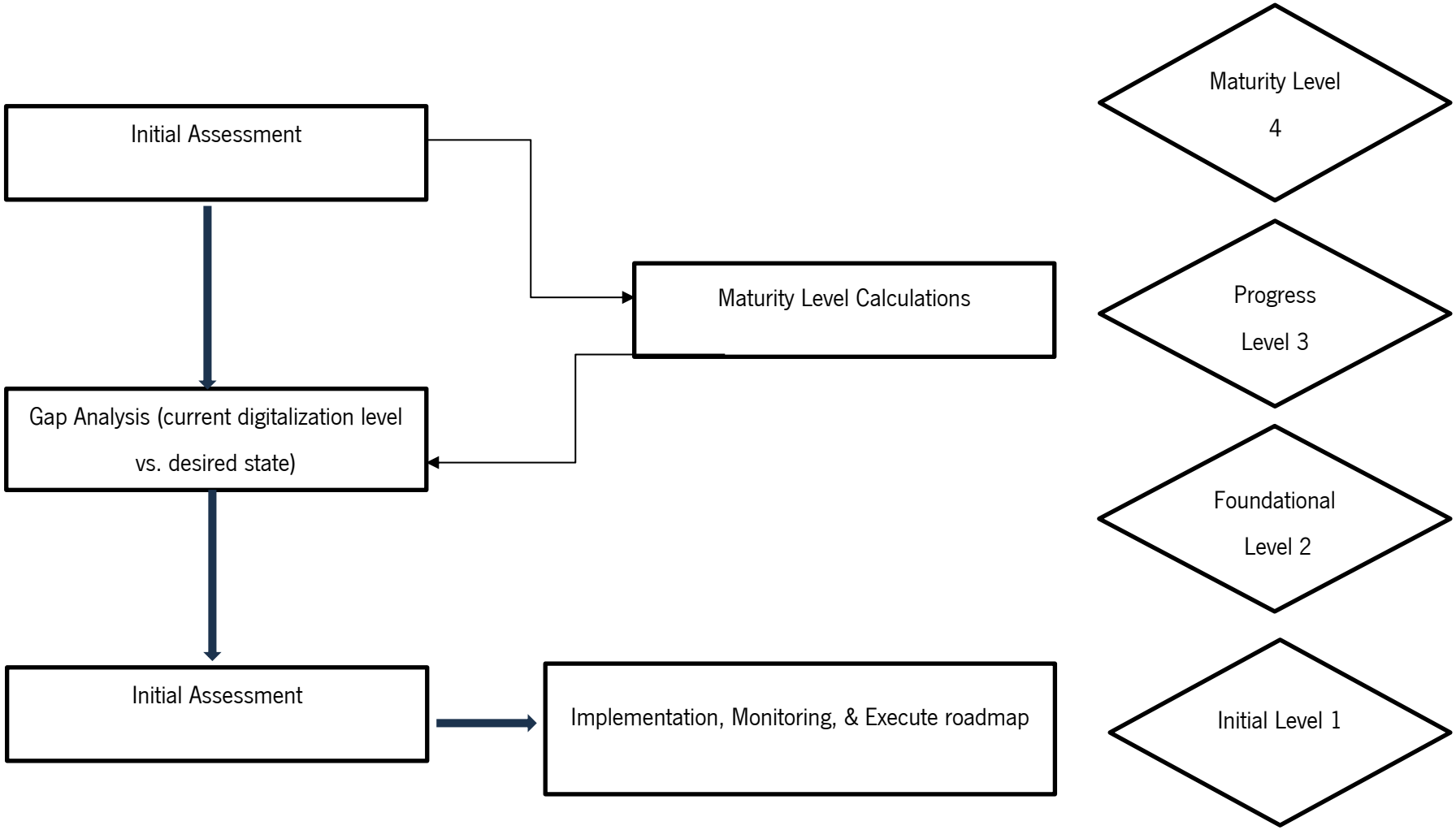


Figure 10: Tourism Maturity Model RoadMap

Furthermore, this section will provide an illustrative example using artificial data of how the model is applied. This will help SMEs understand how to implement the proposed model:

Assume that a top manager has completed the proposed questionnaire, which includes the previously mentioned six dimensions and their capabilities (scored from 0 to 4).

- Step 1: Scores by dimensions:

Table 26: Illustrative Questionnaire Example.

Dimension	Capabilities	Capability Score	Average Scores/dimension
Organizational strategy & Leadership	• Clear digital strategy and roadmap for I4.0 adoption. • Defined roles and responsibilities for digital transformation. • Management's support for digital initiatives. • Investment in digital technologies and innovation. • Effective management of digital competences.	• 3 • 2 • 2 • 3 • 2	• 2.4
Technology & Infrastructure	• Use of foundational IT systems like ERP, WMS, and CRM. • Adopting advanced I4.0 technologies like IoT, BDA, and cloud computing. • Presence of a resilient and secure IT-infrastructure. • Utilization of mobile devices and e-commerce platforms.	• 3 • 0 • 3 • 2	• 2

People & Culture	• Digital skills and competencies among employees and managers. • Openness to innovation and a culture of continues learning. • Collaboration within and across departments. • Effective training programs for staff to enhance digital competencies.	• 1 • 1 • 2 • 1	• 1.25
Smart Operations & Process	• Digitization and automation of core business processes. • Real-time monitoring of operations using IS. • Efficient supply chain collaboration with partners. • Data collection and analysis to optimize operations.	• 2 • 3 • 2 • 2	• 2.25
Customer & Services Experience	• Digitization of sales, services, and marketing. • Use of data to understand customer behaviour and personalize services. • Integrated customer management systems. • development of new data-driven services and experiences (e.g., mobile applications, online booking, feedback, etc.,).	• 3 • 3 • 2 • 3	• 2.75

Stakeholders Engagement	• Collaborations with government and other key stakeholders for support. • Partnerships with financial organizations, consulting firms, and third-part partners. • Using EDI to share information with supply chain partners (e.g., suppliers, distributors, and customers).	• 2 • 1 • 1	• 1.33

- Step 2: overall maturity score calculation:

$$Overall\ Maturity\ score = \frac{\sum average\ maturity\ score/dimension}{no.of\ maturity\ dimensions}$$

$$= \frac{2.4 + 2 + 1.25 + 2.25 + 2.75 + 1.33}{6} = 1.99$$

- Step 3: Determine the maturity level:

Using the defined thresholds of maturity levels; therefore, this company has a foundational maturity level (Level 1).

- Step 4: Gap Analysis:

Based on the previous calculations; the lowest maturity dimensions are:

a. People & culture with maturity score 1.25;
b. Stakeholder engagement with maturity scores 1.33;
c. Technology & infrastructure with maturity score 2.

- Based on the calculated scores; the company decided to prioritize actions; which includes:

a. Developing and lunching digital skills training programs;
b. Adopting partnership collaborations with stakeholders;
c. Investing in IT systems.

4.4 Conclusion and Future Research Directions

This chapter introduces a TDMM to measure and facilitate the digital transformation of SMEs in tourism sector. The proposed model is based on multi-dimensional model, six integrated dimensions are analysed: organizational strategy & leadership (Avelar et al., 2024; A. Hermann et al., 2024), technology & infrastructure (Arroyabe et al., 2024; Tajeddini et al., 2026), people & culture (Abdo et al., 2025; Abdurrahman et al., 2024; Marino-Romero et al., 2024; Sangnak, 2025), smart operations & processes (Abdurrahman et al., 2024; Arranz et al., 2023; A. Hermann et al., 2024; Sahibzada et al., 2025; Skare et al., 2023), customer & services experience (Enshassi et al., 2025), and stakeholder engagement (Mujahed et al., 2024).

The model, utilizing a structured questionnaire and a five-level maturity scale, offers a comprehensive framework for evaluating the current state of digital adoption and identifying strategic priorities to enhance digital capabilities (Magdy Elhusseiny & Crispm, 2025; Mittal, Khan, et al., 2018; Schumacher et al., 2016)

The key contribution of this chapter is the interpretation of the model into an operational step-by-step guide. This roadmap allows SMEs to move from static assessment towards action-oriented transition which matches the digital interventions with internal capabilities and externally environment.

Although previous studies like Boonmee et al., (2025); Skare et al., (2023) primarily focused on internal factors for digital transformation, this research emphasizes the profound connection between tourism's digital transformation and the broader institutional and ecosystemic context. For instance, the introduction of stakeholder involvement as a fundamental dimension of maturity is significant (Boonmee et al., 2025; Skare et al., 2023). Its inclusion in the model enhances our understanding of the systemic nature of tourism digitalization in emerging markets (Aras & Büyüközkan, 2023). This system encompasses external enablers such as government policies, financial incentives, and inter-supply chain collaboration (Abdo et al., 2025).

Furthermore, to our best knowledge, previous research primarily concentrated on the adoption of MMs in the manufacturing sector (L. Kumar & Sharma, 2025; Magdy Elhusseiny & Crispm, 2025; Touijer & Elabjani, 2025), leaving a substantial gap in its application within service-based organizations operating in developing countries.

Our proposed model provides a conceptually grounded and relevant framework. However, it has some limitations that could be explored in future research.

First, further studies may strengthen our model by examining it with a broader and more diverse sample of tourism-based SMEs. This might be achieved statistically, for instance, through structural equation modelling (SEM).

Second, scholars are recommended to longitudinally validate the model to identify how maturity changes or progressed with time. This could be performed in multiple directions or services like tourism, hospitality, and transportation; to create valuable benchmarks.

Third, the model could be improved by including an environmental and sustainability aspects. This would bring digital maturity into line with international trends like sustainable tourism and climate adaptation.

5. Chapter Five: Research Conclusions, Limitations, and Future Directions.

6.1. Summary of the Research Work

This doctoral research study investigated the adoption of Industry 4.0 (I4.0) technologies among Cairo manufacturing small and medium enterprises (SMEs). The study aimed to (a) synthesize the barriers and opportunities facing SMEs in adopting I4.0, (b) distill the essential maturity dimensions studied across existing I4.0 maturity models (MMs), (c) validate which of those dimensions are essential for Cairo manufacturing SMEs, (d) structure the essential dimensions into a progressive, context-fit MM for actionable SME digital transformation, and (e) extend the maturity lens to the tourism sector by specifying its critical dimensions and capabilities.

Through a comprehensive methodological framework, including a systematic literature review, critical MMs evaluation, and two-rounds Delphi, this research culminated in the development and operationalization of a tailored I4.0 MM.

The study began by synthesizing the main barriers and opportunities faced by SMEs globally, highlighting the distinct challenges in developing countries such as limited ICT infrastructure, financial constraints, and a lack of skilled employees. Furthermore, a critical review of 16 existing I4.0 MMs identified common and divergent dimensions, leading to a refined set of core dimensions suited to the Cairo manufacturing context. A Delphi-based expert survey was employed to validate these dimensions and calibrate their relevance.

For tourism, the thesis proposes a conceptual Model of Management (MM) with six dimensions: Organizational strategy and leadership, Technology and infrastructure, People and culture, Smart Operations and processes, Customer and services experience, and Stakeholder engagement. These dimensions are articulated over five maturity levels (0-4) and operationalized through an illustrative example (using artificial data) to assist SMEs in utilizing the model.

The findings and conclusions in the second, third, and fourth chapters discuss the research objectives achieved in detail. This chapter aims to highlight the main research conclusions related to each research question.

- **<u>RQ1:</u> What are the main barriers and opportunities (in developed and developing countries) for adopting I4.0 in the manufacturing sector?**

Chapter 2 (the literature review) of this study provides a comprehensive analysis of the obstacles and opportunities encountered by SMEs in the adoption of I4.0. It offers a detailed classification of specific challenges faced in various regions, enabling tailored policy recommendations and support mechanisms. The study identifies several key barriers to SME adoption of I4.0:

a. Organizational Barriers: Limited financial resources, inadequate management support, resistance to change, and insufficient research and development (R&D) were significant challenges, particularly in developing countries.
b. Technical Barriers: Issues such as inadequate information and communication technology (ICT) infrastructure, a shortage of skilled employees, and complexities in maintaining advanced technologies were prevalent.
c. Technological Barriers: Many SMEs encounter difficulties in deploying advanced technologies due to a lack of knowledge and technical expertise.
d. Legal Barriers: Concerns regarding privacy, data security, and regulatory compliance were also identified.

In terms of opportunities, the study found several areas where Industry 4.0 technologies could benefit SMEs:

a. Operational Efficiency: Industry 4.0 technologies can enhance operational efficiency, reduce costs, and improve quality control.
b. Market Competitiveness: SMEs can become more competitive in both domestic and international markets through innovation and digital collaboration.
c. Supply Chain Integration: Improved vertical and horizontal integration (VI & HI) can lead to better demand forecasting and inventory management.

- **<u>RQ2:</u> What are the essential dimensions of I4.0 maturity that are consistently identified across existing theoretical models?**

The SLR presented an initial set of candidate dimensions that recur across published MMs. Furthermore, we identified several MMs with numerous dimensions and extensive sets of exemplary maturity items.

This creates significant confusion, particularly for SMEs or newcomers (e.g., a company) which need to identify the requirements, dimensions, exemplary maturity items, maturity levels, and other relevant factors.

To alleviate this confusion, we began identifying the common dimensions studied across all models, along with their definitions, exemplary maturity items, and adoption categories (large, multinational, or SME, developed, developing country, etc.,). Then, we utilized spreadsheet Excel files for this purpose. Additionally, we identified the divergent dimensions, including their exemplary maturity items, definitions, and adoption categories, using the same process outlined above. Based on this analysis, we found the following:

a. Common Scopes: These include organizational strategy, smart factory, smart operations, smart products, vertical integration, horizontal integration, and information systems. These dimensions are crucial for both large enterprises and SMEs.
b. Divergent Scopes: These are noted in specialized areas such as data analytics, IT infrastructure, performance metrics, and business process transformation, reflecting the varying focuses of different models.

This chapter presents a comprehensive analysis of existing MMS providing novel insights into their applicability for SMEs and addressing a gap in the literature by identifying a set of maturity dimensions along with their exemplary maturity items (a generic model) for SMEs in developing countries. Unlike other models that predominantly focus on larger or multinational enterprises, our model offers a unique perspective for SMEs in developing nations.

- **<u>RQ3:</u> Which of the existing theoretical dimensions are most relevant and essential for Cairo Manufacturing SMEs?**

To address the research question, we conducted a Delphi survey involving 19 industrial experts from various sectors, including Agriculture, Automotive, Electrical Equipment, Food & Beverages, Metals & Machinery, Petrochemicals, and Textile.

The Delphi survey was structured into two rounds. The first round (R1) aimed to identify the current ICT readiness, the primary IT systems employed, the training requirements for managers, employees, and the necessary stakeholders to facilitate the adoption of I4.0.

In round 2 (R2), which was conducted with the same group of experts, to identify the weight of the common dimensions along with their exemplary maturity items and finalize the core scopes that are essential/relevant (according to their weight) for Cairo Manufacturing SMEs.

As a result, this research study identified a set of ten common dimensions and 32 exemplary maturity items that were used to develop the customized MM for SMEs. This includes organizational strategy, smart factory, smart operations, products, employees, leadership, customers, culture, technology, and information systems.

- **<u>RQ4:</u> How can these validated dimensions be structured into a progressive, multi-level MM that provides a realistic & actionable pathway for SMEs towards I4.0 adoption?**

The proposed MM employs a five-level, (0-4) scale, encompassing Initial, Foundation, Progressing, Managed, and Maturity. Each level is accompanied by a specific scoring scale, delineating concrete capability thresholds for each dimension. The model has been operationalized, and we have determined the maturity level for each dimension and the overall maturity score for Cairo manufacturing SMEs based on R1 data.

The findings demonstrate the following key points:

a. Strategic deficits (Level 1.1-1.13) were evident in the organizational strategy (1.1), culture (1.3), and information systems (1.4) scores, indicating systemic gaps in vision, planning, and cross-functional integration. Notably, only two experts reported that their companies had an I4.0 strategy, while 16 highlighted organizational resistance as a significant barrier.

b. Operational Progress (Level 2.0-2.2) showed higher maturity levels in Smart factory (2.1), Smart products (2.0), and Customers (2.2). However, Small and Medium Enterprises (SMEs) were using ERP, producing customized products, and employing e-catalogues, which were isolated digital improvements rather than signs of cohesive transformation.

c. Leadership and workforce gaps: Despite many SMEs investing in technology, leadership capacity and workforce digital skills were lagging behind. A significant number of experts highlighted a lack of strategic training and digital competence among employees. (13 experts mentioned “lack of human knowledge”; 13 also reported “unskilled workforce”).

- **<u>RQ5:</u> What are the critical dimensions and capabilities that determine digital maturity in the Egyptian tourism sector?**

This chapter expands upon the theoretical contributions of this research study by proposing a conceptual framework for tourism SMEs as a crucial service sector in Egypt. While previous chapters have explored the theoretical and empirical impact of Industry 4.0 on manufacturing SMEs, this chapter further delves into the digitalization of tourism as a counterpart to the service sector. It posits that both sectors face unique yet interconnected challenges in adapting to digital transformation.

The chapter reviews tourism digitalization frameworks, identifying challenges like infrastructure and governance, while highlighting opportunities through ICT and data analytics.

The conceptual model encompasses dimensions related to diversity considerations, including organizational strategy & leadership, customer services & experience, technology & infrastructure, people & culture, and stakeholders' engagement.

By examining the two industries of manufacturing and tourism, the thesis offers a broader perspective on Egypt's digital economy. It demonstrates how distinct sector-specific management models can be aligned to enhance national competitiveness.

6.2 Main Contributions

This study significantly contributes to the literature on the adoption of I4.0 in SMEs by providing a comprehensive analysis of barriers, reviewing existing maturity models, and proposing a customized maturity model tailored to the specific needs and constraints of SMEs in developing regions.

These contributions are grounded in empirical data and theoretical insights, offering a comprehensive roadmap for SMEs in Cairo and potentially similar developing regions to achieve digital transformation and enhanced competitiveness.

The study emphasizes the collaborative efforts required for successful digital transformation. Key contributions include:

a. Tailored Maturity Model: A customized maturity model specific to the needs and constraints of SMEs in developing regions.

b. Comprehensive Dimensions: Identification and validation of the critical dimensions necessary for SMEs to adopt I4.0, bridging the gap in current literature focusing on larger enterprises.
c. Human Capital Focus: Novel insights into human resource management by emphasizing training and skill development for both managers and employees.
d. I4.0 Roadmap: A step-by-step implementation guide (Initial, Foundation, Progress, Managed, Maturity) that SMEs can follow to gradually adopt I4.0 technologies.
e. Skill Development Framework: Specific recommendations for training programs, facilitating workforce readiness and capability-building crucial for I4.0 adoption.

In summary, this study effectively addresses its research questions offering theoretical advancements and practical tools to facilitate the adoption of I4.0 technologies among SMEs in Cairo's manufacturing sector. The identification of current ICT levels, development of tailored maturity model skills mapping, and stakeholder engagement strategies collectively contribute to a deeper understanding and practical roadmap for digital transformation in SMEs within developing countries.

6.3 Research Limitations and Future Directions

- The study's geographical focus on Cairo's manufacturing SMEs may restrict the generalizability of its findings to other regions or countries, which may possess varying levels of technological infrastructure, policy frameworks, and market conditions influencing I4.0 adoption. The study primarily considered existing technologies within I4.0 up to the time of the research; therefore, emerging technologies or advancements not included may impact the relevance and applicability of the proposed maturity model.
- Future research should extend to other regions and sectors to provide a comprehensive understanding of global I4.0 adoption. Comparative studies across different countries or regions, as well as in sectors beyond manufacturing, such as services, agriculture, and healthcare, would assist in identifying unique challenges and opportunities in these fields.

- Longitudinal studies monitoring the progress and impact of I4.0 adoption over time could yield deeper insights into long-term benefits and challenges, enabling adjustments to the proposed maturity models to align with evolving technological developments.
- Besides, future studies should involve larger and more diverse sample sizes. Engaging experts from various industrial sectors and academic backgrounds could enhance the robustness and generalizability of the findings.
- In-depth case studies of SMEs that have successfully adopted I4.0 technologies could provide practical insights and best practices, illustrating strategies that effectively overcame barriers and leveraged opportunities.
- As emerging technologies such as advanced robotics and novel AI advancements influence the adoption of I4.0, future research should analyze their implications on existing systems and processes to ensure the relevance of maturity models. Incorporating a comprehensive analysis of cultural, social, and economic factors that influence technology adoption in various regions can provide a more holistic perspective, enabling the customization of maturity models to specific contexts.
- Furthermore, the role of government policies and regulations in promoting or hindering I4.0 adoption should be investigated. Analyzing policy frameworks, incentives, and support mechanisms can guide policymakers in creating an environment conducive to digital transformation. Exploring educational and training programs that develop the necessary skills for I4.0 adoption can provide actionable insights for SMEs. In addition to, collaborations with educational institutions to develop targeted curricula and training modules can enhance workforce readiness.
- Finally, developing practical tools and frameworks to support the implementation of proposed maturity models, like digital platforms that provide assessments, benchmarks, and guided pathways for SMEs, can facilitate smoother transitions to I4.0.
- By addressing these limitations and exploring these future directions, subsequent research can build upon this study's foundational work, offering comprehensive strategies and tools for effective I4.0 technology adoption across diverse contexts.

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APPENDIX A – SYSTEMATIC LITERATURE REVIEW STUDY QUALITY ITEMS

		Study quality items (Sideway)									
#	**Article**	**Well-defined research question**	**Study design appropriate**	**Representativeness of the sample**	**Participant selection of the sample**	**Response rate**	**Outcomes identified**	**Outcomes measured**	**Conclusions support by data**	**Generalizability of the results**	**Conflict of interest**
1	(P. Kumar et al., 2021)	Yes	Yes, Development of structural self-interaction matrix	Literature review	N/A	N/A	Yes	Yes	Yes	Yes	N/A
2	(Calış Duman & Akdemir, 2021)	Yes	Yes	Yes (interviews & survey)	Yes (business executives)	Yes	Yes	Yes	Yes	Yes	N/A
3	(Yüksel, 2020)	Yes	Yes	Yes (surveys)	No	Yes	Yes	Yes	Yes	Yes	N/A
4	(Rafael et al. 2020)	Yes	Yes, maturity-model	Yes (survey)	Yes, a case-study of a firm	Yes	Yes	Yes	Yes	Yes	N/A
5	(Dassisti et al., 2019b)	Yes	Yes (meta-model)	no	No	No	Yes	Yes	Yes	Yes	N/A
6	(R. Kumar, Singh, and Dwivedi 2020)	Yes	Yes, DEMATEL & Delphi methods	Yes (survey)	Yes (industrial experts & academics)	Yes	Yes	Yes	Yes	no	N/A
7	(Ghobakhloo and Ching 2019)	Yes	Yes, cross-sectional	Yes	Yes (SMEs Iran& Malaysia	Yes	Yes	Yes	No	Yes	N/A
8	(Yu and Schweisfurth 2020)	Yes	Yes (cross-sectional)	Yes (survey)	Yes (German SMEs	Yes	Yes	Yes	Yes	No	N/A
9	(Onu and Mbohwa 2021)	Yes	Yes (exploratory)	No	No	No	No	No	No	No	N/A
10	(Bazaz et al. 2021)	Yes	Yes (quantitative, support structure matrix)	Yes (survey)	Yes (operators)	Yes	Yes	Yes	No	No	N/A

11	(Torn and Vaneker 2019)	Yes	Yes (a review)	No	No	No	No	No	No	No	N/A
12	(Blixt and Simon 2021)	Yes	Yes (SLR)	No	Yes (literature survey) (IoT& AI)	No	Yes	Yes	No	No	N/A
13	(Ghobakhloo & Fathi, 2020)	Yes	Yes (review)	Yes (long-term case study)	Yes (small enterprise, supplier to automobile manufacturing)	Only one case	Yes	Yes	Yes	Yes	N/A
14	(Buer et al., 2020)	Yes	Yes (review)	Yes (survey)	Yes (Norwegian manufacturing co.)	Yes	Yes	Yes	No	Yes	N/A
15	(Sánchez-Rodríguez et al., 2019)	Yes	Yes (empirical)	Yes (survey)	Yes (managers)	Yes	Yes	Yes	no	Yes	N/A
16	(Revolution, 2020)	No	Yes (a review)	No	No	No	No	No	No	No	N/A
17	(Mangla et al., 2020)	Yes	Yes (empirical)	Yes (survey)	Yes (SMEs engineers &managers)	Yes	Yes	Yes	No	Yes	N/A
18	(Raut et al., 2018)	Yes	Yes (review)	Yes (interpretive structural modeling based on experts' opinions)	No	No	Yes	Yes	No	Yes	N/A
19	(Kumar et al., 2020)	Yes	Yes (review)	Yes (principal component analysis, fuzzy AHP, K-means)	No	No	Yes	Yes	Yes	no	N/A
20	(Cunha et al., 2020)	Yes	Yes (exploratory& descriptive)	Yes (survey)	Yes (industry professionals)	Yes	Yes	Yes	No	Yes	N/A
21	(Kaushik & Singh, 2019)	Yes	Yes (a review)	Yes (survey) AHP-Topsis approach	Yes (managers, academicians, entrepreneurs)	Yes	Yes	Yes	No	Yes	N/A
22	(Ul Haq & Franceschini, 2019)	Yes	Yes (review)	Yes (historical survey database)	Yes (Italian SMEs)	No	Yes	Yes	Yes	Yes	N/A

23	(Jaiswal et al., 2020)	Yes	Yes (review)	Yes (interviews) (grey-DEMATEL approach)	Yes (based on expert's views)	Yes	Yes	Yes	No	Yes	N/A
24	(Kandil & Abd El Aziz, 2018)	Yes	Yes (review)	Yes (interviews)	Yes (decision makers)	Only one case study	Yes	Yes	No	No	N/A
25	(Al-Sayed & Yang, 2018)	Yes	Yes (review)	Yes (interviews & survey)	Yes (experts, academics, managers)	Yes	Yes	Yes	No	Yes	N/A
26	(Maroufkhani et al., 2020)	Yes	Yes (review)	Yes (survey) structural equation modeling	Yes (Iranian SMEs)	Yes	Yes	Yes	Yes	Yes	N/A
27	(Rahman et al., 2017)	Yes	Yes (review)	Yes (Historical Published survey & a case study)	Yes (Bangladesh SMEs)	Yes	Yes	Yes	No	Yes	N/A
28	(Nimawat & Gidwani, 2020)	Yes	Yes (review)	AHP&ANP rankings were based on the review	No	No	Yes	Yes	No	N/A	N/A
29	(Asiaei & Nor, 2019)	Yes	Yes (review)	TOE framework & structural equation modeling	yes (Malaysian SMEs)	Yes	Yes	Yes	Yes	Yes	N/A
30	(Indrawati et al., 2020)	Yes	Yes (review)	Yes (survey &focus group)	Yes (Indonesian SMEs)	Yes	Yes	Yes	No	Yes	N/A
31	(Ghadge et al., 2020)	Yes	Yes (critical review)	No	Yes (Turkish SMEs)	No	No	No	Yes	N/A	N/A
32	(Chen, 2020)	Yes	Yes (review)	Yes (interviews, qualitative exploration multiple case studies)	Yes (Taiwan SMEs)	Yes	Yes	Yes	Yes	yes	N/A
33	(Shin, 2017)	Yes	Yes (review)	Yes (interviews & a case study)	Yes (Korean SMEs)	Yes	Yes	Yes	Yes	Yes	N/A
34	(Garzoni et al., 2020)	Yes	Yes (review)	Yes (case study	Yes (SMEs in south Italy)	Yes	Yes	Yes	Yes	No	N/A
35	(Pirola et al., 2019)	Yes	Yes	Yes (multiple case studies)	Yes (Italian SMES)	Yes	Yes	Yes	Yes	Yes	N/A
36	(AL-Shboul, 2019)	Yes	Yes (review)	Yes (survey)	Yes (developing economies)	Yes	Yes	Yes	Yes	Yes	N/A

37	(Dutta et al., 2020)	Yes	Yes (literature survey)	Yes (maturity survey)	Yes (Indian SMEs)	Yes	Yes	Yes	No	Yes	N/A
38	(D. Kumar et al., 2017)	Yes	Yes (review)	Yes (survey)	Yes (Indian SMEs)	Yes	Yes	Yes	No	No	N/A
39	(Pinto et al., 2019)	Yes	Yes (review)	Yes (a model)	Automotive industry	No	Yes	Yes	Yes	No	N/A
40	(Pirola et al., 2019a)	Yes	Yes (review)	Yes (empirical)	Yes (multiple case studies)	Yes	Yes	Yes	No	yes	N/A
41	(Indrawati et al., 2020)	Yes	Yes (review)	Yes (mixed approach, focus group & interviews	Yes (SMEs operated in the last 5 years in Indonesia	Yes	Yes	Yes	Yes	Yes	N/A
42	(Horváth & Szabó, 2019)	Yes	Yes (review)	Yes (interviews)	Yes (CEO, digital officers)	Yes	Yes	Yes	Yes	Yes	N/A
43	(Majumdar et al., 2021)	Yes	Yes (review)	Yes (survey)	Yes (industry experts)	Yes	Yes	Yes	No	No	N/A
44	(Turkyilmaz et al., 2021)	Yes	Yes (review)	Yes (SWOT analysis from literature)	No	Yes	Yes	No	No	No	N/A
45	(Matarazzo et al., 2021)	Yes	Yes (review)	Yes (multiple case studies in Italy)	Yes	Yes	Yes	Yes	No	Yes	N/A
46	(Jimeno-Morenilla et al., 2021)	Yes	Yes (systematic review)	Yes (manufacturing sector	No	No	Yes	No	No	No	N/A
47	(Moeuf et al., 2020)	Yes	Yes (review)	Yes (experts)	Yes (Delphi method)	Yes	Yes	Yes	No	Yes	N/A
48	(S. Kamble et al., 2020)	Yes	Yes (review)	Yes (managers)	Yes (DEMATEL)	Yes	Yes	Yes	Yes	Yes	N/A
49	(Maldonado-Guzmán et al., 2017)	Yes	Yes (review)	SMEs (Mexico)	Yes (structural equation modeling)	Yes	Yes	Yes	No	Yes	N/A

50	(Ramírez-Durán et al., 2021)	Yes	Yes (review)	No	No	No	No	No	No	No	N/A
51	(Benitez et al., 2020)	Yes	Yes (review)	Yes (stakeholders	Yes (conceptual framework based on surveys &interviews)	Yes	Yes	Yes	No	No	N/A
52	(Bag et al., 2020)	Yes	Yes (review)	Yes (south Africa, researchers, operation managers)	Yes (structural equation modeling, survey	Yes	Yes	Yes	Yes	No	N/A
53	(Aboelmaged, 2018)	Yes	Yes (review)	Yes (survey) owners, managers	Yes (PLS-SEM model)	Yes	Yes	Yes	Yes	Yes	N/A
54	(Mittal, Khan, et al., 2018)	Yes	Yes (critical review)	No	No	No	Yes	Yes	No	No	N/A

APPENDIX B - SIMILAR MATURITY MODELS SCOPES & EXEMPLARY ITEMS

#	Dimensions	Exemplary Maturity Item
2	Smart Factory	• Automated production environment • Equipment infrastructure • IT systems • VI (ERP, MES, Digitized machines) • Traceability (final products, raw materials) • Energy Management (Energy consumption, Energy monitoring) • Automation (automated identification, industrial robots, M2M communication) • Virtualization (AI for maintenance, AI for production) • Flexibilization (Flexible line, additive manufacturing)
3	Smart Operation	• Information Sharing • Cloud usage • IT security • Decentralization of processes • Modeling & simulation • Interdepartmental collaboration • Data Analytics • Information sharing
4	Smart Product	• New data driven services (e.g., self-reporting, identification, localization) • Online presence • Integrated customer management • Customized products • Digitization of products/services systems • Product integration • Defined roadmap for smart products. • Data processing • R&D • Passive smart products • Active smart products • Autonomous smart products
5	Employees	• Digital skills • ICT competences of employees

		• Openness of employees to new technology • Autonomy of employees
6	Leadership	• Management of digital competences & methods • Existence of central coordination for I4.0 strategy • Leadership & strategy
7	Customers	• Utilization of customer data • Digitization of sales/services • Customers digital media competences
8	Culture	• Knowledge sharing • Open innovation & cross-company collaboration • ICT value inside the company • Democratic leadership • Open communication
9	Governance	• Labor regulations for I4.0 • Suitability of technology standards • Protection of Intellectual property • Organizational level (strategy, structure, management, resources allocation, digital awareness, integrated departments
10	Technology	• Existence of modern ICT (IoT, CPS, BDA, cloud-computing, adaptive robotics, AI, embedded sys, additive manufacturing, sensors & actuators, RFID) • Utilization of mobile devices • ICT integration (VI&HI) • Cyber-security • IoT utilization
11	Data-driven / Governance	• BDA • Data collection and usage
12	Information Systems	• Data analysis • Contextualized data delivery • Resilient IT infrastructure • HI&VI • Data governance • IT security • Cloud computing • IoT • IT resources

APPENDIX C - DIFFERENT MATURITY MODELS SCOPES & EXEMPLARY ITEMS

#	Scope	Exemplary Maturity Item
1	Data Collection	• Availability of data-driven • Share of revenue • Share of data used
2	Digital Business models & customer access	• Digital solutions • Applications
3	Data Analytics	• Basic analytical capabilities • Predictive analytics
4	IT-infrastructure	• IT-architecture
5	Organization, Employees & Digital culture	• Collaboration
6	Cross-sectional technology criteria	• Assessing used technology across different I4.0 fields
7	Digitization Awareness	• Defined product roadmap. • Portfolio for digital products • Framework for smart products
8	Smart services	• Defined roadmap for smart services
9	Services systems	• Roadmap for services systems • Strategic ecosystems • Digital enterprise
10	Production process	• Product development • Product planning • Process control • Facility management • Logistics management
11	Performance	• Performance assessment
12	Resources	• Digital competences • Automated data acquisition • Decentralized processing of data
13	Connectivity	• Data sharing • IT security • Data structuring
14	Value creation	• Data usage for orders • Forecasting

15	Competences	• Digital competences • Training • Learning
16	Smart working	• Production monitoring • Remote operation • Augmented & virtual reality
17	Supply chain collaboration	• Digital platforms with other companies • Digital platforms with suppliers • Digital platforms with distributors
18	Process transformation	• Planning • Acquisition • Sales & distribution • Production
19	Maturity	• Infrastructure for IoT • Analytical skills • Absorptive capacity
20	Performance	• Benefits of I4.0 adoption • Impact of efficiency
21	Business process	• N/M

APPENDIX D - DELPHI-SURVEY: FIRST ROUND

Delphi-Survey (First Round).

Small and Medium Enterprises (SMEs) Industry 4.0 Adoption in Manufacturing Industries.

Description

Thank you in advance for your share in this academic research, it is very appreciated!

Kindly note that this Delphi-Questionnaire is **only** for academic research (PhD Level).

The researcher: **is a PhD candidate at the University of Minho, Braga, Portugal. Currently working as, a Teaching Assistant at the Arab Academy for Science, Technology and Maritime Transport, College of International Transport and Logistics, Alexandria, Egypt.**

Email: Hussein_magdy@aast.edu

This Delphi-Survey targets SMEs Experts in the Manufacturing sectors, to evaluate the Egyptian SMEs innovation level, identify and access the current Information and Communication Technologies (ICT) level of the Egyptian SMEs in manufacturing industries. Also, to investigate the barriers of adopting innovative ICT. Finally, to determine the main reasons that might draw a roadmap for SMEs to adopt Industry 4.0.

I, the undersigned Hussein Magdy (Academic Researcher), would like to declare that all the collected data will be highly confidential and used for the purpose of Academic Research ONLY.

Hussein Magdy Elhusseiny.

Academic Researcher.

Section 1: General Information

Industry Sector(s):

- Automotive
- Metals and Machinery
- Electrical equipment's
- Food and Beverages
- Textile
- Agriculture
- Petrochemicals

Section 2: Cairo Manufacturing SMEs ICT level

The purpose of this section is to assess the usage of ICT in Cairo manufacturing SMEs (Elbeltagi et al., 2016; Frank et al., 2019; H. Zaied, 2012; Müller & Voigt, 2018; Nick et al., 2019).

- **Please, determine the degree of adoption to each dimension of technology according to your experience and knowledge in the field**.

#	Technologies for smart manufacturing	Not Applicable	Application is under discussion	Application is under development	Application is NOT fully Adopted	Fully Adopted
1	SMEs use a well-structured system that enables different departments to be connected.					
2	SMEs use software like Enterprise Recourse Planning (ERP) for providing production status					
3	SMEs use electronic advertising					
4	SMEs use IT for customer services					
5	SMEs use IT for tracing order fulfillment and delivery					
6	SMEs offer online/electronic payment services for customers					
7	SMEs purchase materials from suppliers via electronic payment					

8	SMEs use the internet to search for customers					
9	SMEs use internet to search for suppliers					
10	SMEs use the internet to communicate with customers					
11	SMEs use the internet to collect information about customers					
12	SMEs use internet to collect information about competitors					
13	SMEs use IT to advertise products/ services					
14	SMEs use IT only for receiving/managing customer orders					
15	SMEs use the internet only in offering after-sales services for customers					
16	SMEs use electronic catalogues to sell products/ services to customers					
17	SMEs use electronic catalogues in offering after-sales services to customers					
18	SMEs use IT for accessing suppliers' products/ services database					
19	SMEs use IT in Placing/ managing orders with suppliers					
20	Suppliers can access SMEs inventory via Information system (IS)					
21	SMEs use electronic catalogues to buy raw materials from suppliers					

22	SMEs use software in product designs e.g., Computer Aided Design (CAD)					
23	SMEs use cloud computing for data storage and backup					
24	SMEs IT for monitoring machine and production process					
25	SMEs produce customized products					
26	SMEs uses 3D printing					
27	SMEs use cloud computing for collecting product usage data					
28	SMEs use digitized machines (e.g., sensors)					

Section 3: Production Digitization level and Information Transfer:

1. Which is the digitization level of Cairo SMEs production plant? (Pirola et al., 2019a)

- Purely physical production system (the production system does not communicate with the IT system, and no information can be collected about the production process
- Low-digitized production system (the production system is connected to the IT system, but it is possible to collect only some information about the production process (machine status)

- Well-digitized production system (the production system is connected to the IT system and information on the production process (machine status, management parameters, processing parameters) are collected and analytically analyzed)

2. Does Cairo SMEs collect data from the production system? (Pirola et al., 2019)
    - No, SMEs do not collect data from the production system, and do not know which data to collect
    - No, SMEs do not collect data from the production system, however, some companies know which data to collect
    - Yes, but not in continuous (e.g., only at the end of turn)
    - Yes, in continuous (real-time)
    - Yes, in continuous and data can be viewed remotely (real-time)

3. In which operating units are the Egyptian SMEs planning investments/developing projects for digitization? (Pirola et al., 2019)
Indicate the object of the investment.

	No investment	Investments under discussion	Investments planned but not in execution	Ongoing investments	Investment concluded
Sales & marketing					
R&D					
Purchasing					
Production					
Quality management					
Internal maintenance					
Logistics					
After-sales-services					
HR					
Cybersecurity					
IT infrastructure					
Other: --------					

4. **Which data on machinery/processes are collected? How are they collected?** (Pirola et al., 2019)

	Not applicable	Not collected	Yes, with PAPER support	Yes, but NOT in continuous	Yes, in continuous and connected with the company IS
Warehouse data					
Performance in line assembly machines					
Availability of production machines					
Waste/production defects					
Faults/ malfunctions of machinery					
Causes of machinery malfunctions/ assembly					
Energy consumption					
Other: --------					

5. Which IT systems are used in Cairo SMEs, and which are integrated with the main information system? (Pirola et al., 2019)

IT	Main information system	Not used	Used but NOT integrated	Used and integrated
Enterprise Resource Planning (ERP)				
Manufacturing Execution System (MES)				
Product Data Management (PDM)				
Product lifecycle Management (PLM)				
Customer Relationship Management (CRM)				
Computer Aided Design (CAD)				
Document Management				
Workflow Management				

E-commerce				
Warehouse Management System (WMS)				
Other: ---------				

Section 4: Supply Chain (SC) Collaboration:

- **What is the degree of integration with customers and suppliers?** (Pirola et al., 2019)

	All customers	**Main customers**	**All suppliers**	**Main suppliers**	**Distributors**	**Wholesalers**
No integration						
Electronic Data Interchange (EDI) (e.g., sharing information between SC partners)						
Fully integrated information system (IS)						
Other: ------						

Section 5:

<u>Industry 4.0 Knowledge and Awareness:</u>

10. Do you know what industry 4.0 is?
- Yes
- No

11. Do you know what IoT (internet of things) is?
- Yes
- No

12. Do you know what CPS is (cyber physical system)?
- Yes
- No

13. Do you know what big data analytics is?
- Yes
- No

14. Do you know what Additive manufacturing is?
- Yes
- No

15. Do you know what cloud computing technologies are?
- Yes

- No

16. Has an industry 4.0 been defined as the mentioned sector?

- Yes
- No

17. If an industry 4.0 strategy has been introduced in the Egyptian SMEs, which support tools/ analysis are used? (Pirola et al., 2019)

- A strategy has not been defined but we would like to define it
- The strategy is under definition.
- A strategy has been defined, but not an action plan
- A well-defined strategy exists, with an action plan
- Other: ----------

18. Is there a roadmap for planning the activities for the introduction of industry 4.0 solutions for Egyptian SMEs? (Pirola et al., 2019)

- A roadmap does not exist
- A roadmap does not exist, but we are going to define it
- A roadmap is under definition
- A roadmap exists and we are starting with the implementation phase
- A roadmap exists and it is fully implemented

Section 6: Main drivers for I4.0 adoption

- **To what extent do you agree/disagree on the following factors to adopt industry 4.0?**
  - (Elbeltagi et al., 2016; Horváth & Szabó, 2019).

#	Driving force	Strongly Agree	Agree	Moderate	Disagree	Strongly disagree
1	Digital technologies reduce inventory cots					
2	Digital technologies reduce operational costs					
3	Digital technologies reduce marketing costs					
4	Digital technologies reduce documentation process					
5	Using Digital technologies reduces human work					
6	Digital technologies improve the company's competitive advantages (e.g., new products/services, customized products, better customer services, etc.					
7	Digital technologies allow customers to customize their products					
8	Digital technologies increase the company's market share					
9	Digital technologies increase the company's business efficiency					

10	Digital technologies improve the company's information quality					
11	Digital technologies improve company's quality of following up with customer claims and complaints					
12	Digital technologies improve company's quality in reduction of transaction errors					

Section 7: The Main Stakeholders required to facilitate I4.0 Adoption:

1) According to your knowledge, please select at least (4) barriers from the following list

(Birkel et al., 2019; Dalmarco et al., 2019; H. Zaied, 2012; Horváth & Szabó, 2019a; Müller, Kiel, et al., 2018a; Oztemel & Gursev, 2020a; Pirola et al., 2019a).

#	**Barrier**
1	Lack of human knowledge
2	Lack of efficiency in value chain and product/services quality
3	Lack of cyber security
4	Decision making deficiencies
5	Unskilled employees and managers
6	Inadequate organizational structure
7	Financial constraints
8	Demobilization (loss of jobs)
9	Limited use of IT by SMEs
10	Organization resistance to change
11	Absence of legal and regulatory systems
12	Governmental regulations

2) Whose stakeholders are crucial to the success of industry 4.0 technologies adoption?

Please, select at least "3" from the following list:

- Government
- Universities

- Banks
- Financial organizations
- International community support funds
- Technology Support companies
- Technology Supply companies
- Egyptian chamber of commerce
- Supply chain members, e.g., suppliers
- Supply chain members, e.g., customers
- Consulting companies
- Third party partner, e.g., product and manufacturing design partner, freight consolidation, transportation, digital services providers, etc.

Section 8: Training and skills required for Managers and Employees for I4.0 adoption:

- *As an expert in your field, please support the research with the necessary training skills needed in human power for I4.0 adoption.*

1. What types of training programs do you recommend for improving managers' skills?

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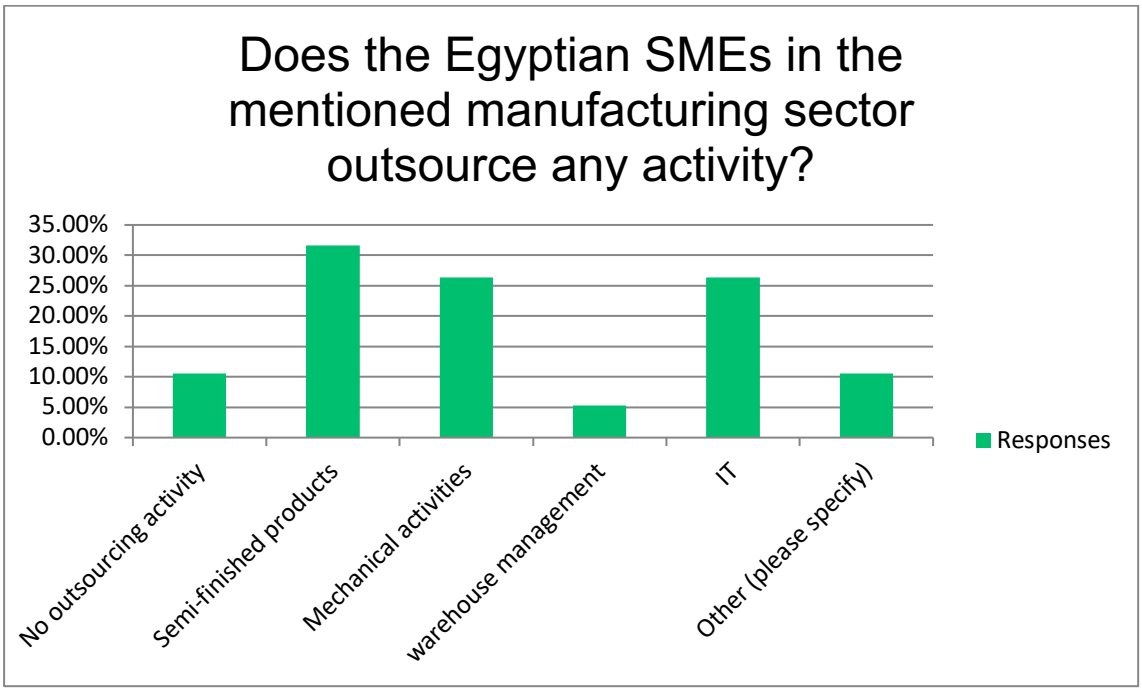
2. What types of training programs do you recommend for improving employee's skills?

APPENDIX E - DELPHI-SURVEY: FIRST ROUND EXPERTS RESPONSES

Section 1

According to experts the following:

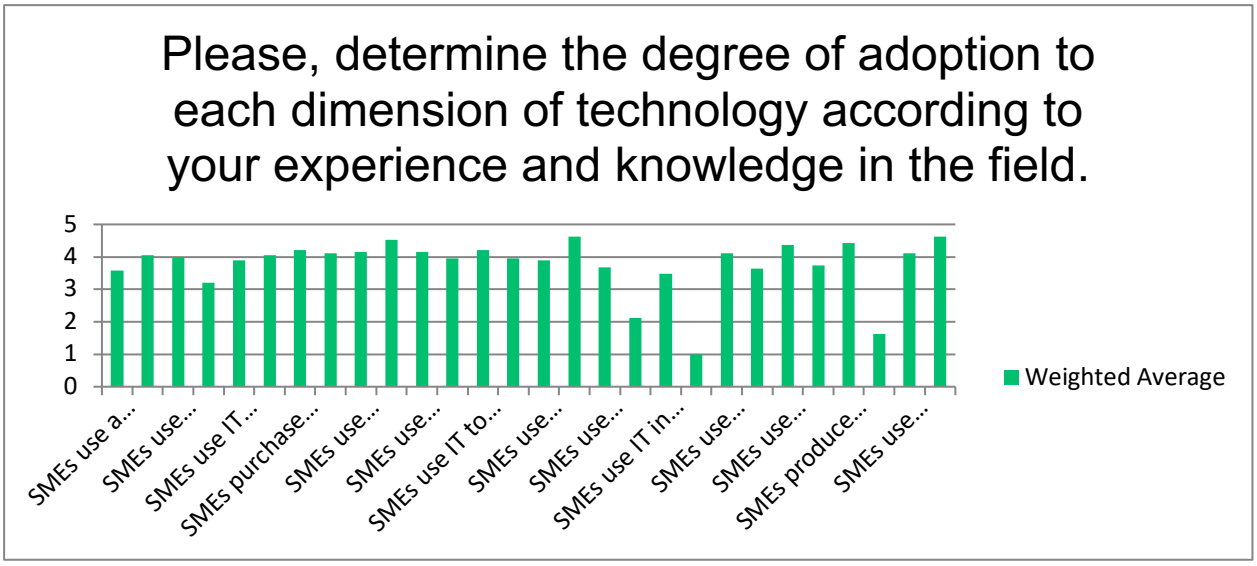
- Most of SMEs customers are international and national (73.68%), national (5.26%), and foreign market (5.26%).
- Types of supplies are international and national (73.68%), national (15.79%), and international (10.53%).
- the annual capital turnover is from 10 to 50 million EGP (36.84%), and more than 50 million (42.11%) EGP. However, from 1-5% (57,89%) is invested in R&D.
- The manufacturing process of SMEs in the manufacturing sector is (63.16%) Automated assembly/production lines, (26.32%) manufacturing production process, (10.53%) manual assembly lines.
- The approach SMEs with respect to customer's orders is (84.21%) MTO, (47.37%) MTS, 15.79% (ETO)
- The outsourcing activity is (31.58%) semi-finished goods, (26.32%) mechanical activities, (10.53%) other third party like transport and packaging, and (5.26) for warehousing.



Section 2

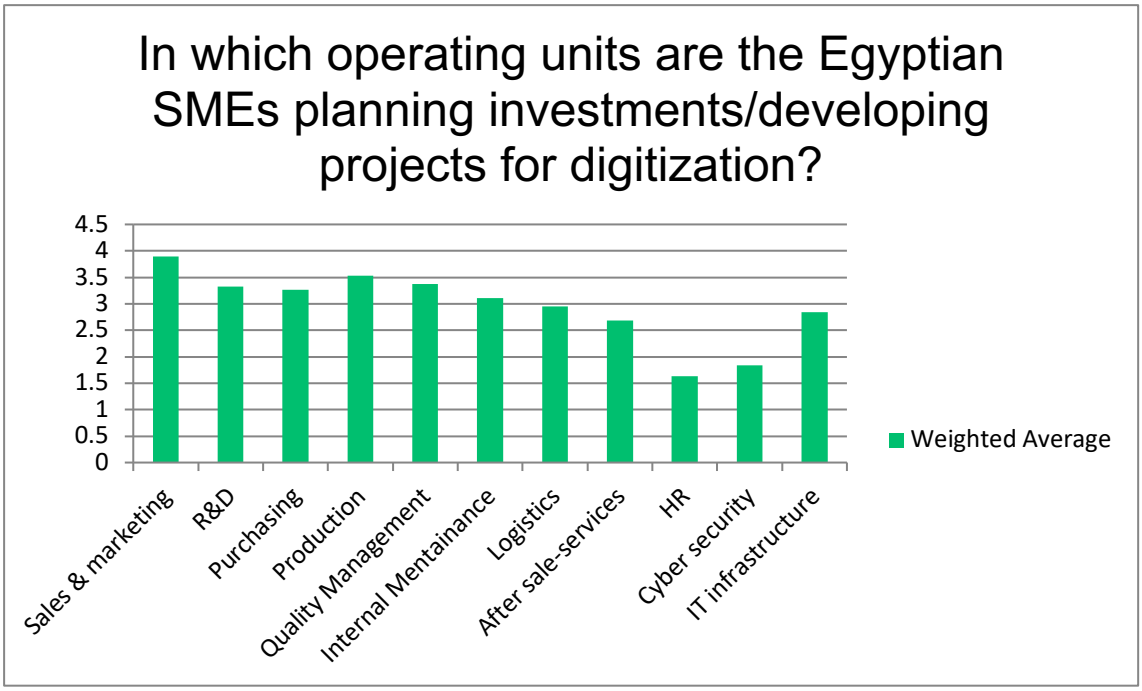
The ICT level of SMEs appears on the usage of the:

- Electronic catalogues to sell products/services to customers (e.g., social media, websites) 84.21% fully adopted.
- Digitized machines for production/assembly 74% fully adopted
- Internet to communicate with customers 63% fully adapted
- Production of customized products 57% fully adopted
- Cloud computing (e.g., Google drives) for data storage and backup 63%
- Electronic payments with suppliers (e.g., mobile applications, bank transfer, L/C) 57%, and 68% with customers.
- IT for advertising (e.g., social media, websites) 68%
- Internet to search for suppliers (usually used by foreign suppliers) 52%, to collect information about competitors (usually by local surveys) 47%, to search for customers (42%)
- ERP systems (100%) of the sector use full modules, mainly used modules: (accounting, purchasing, warehousing in food and textile sectors)
- IT for receiving/managing orders 63%, and 52% for tracing orders fulfillment and delivery
- Aftersales services 47% (mainly in the automotive assembly sector)
- Monitoring machine and production process 30%
- Software for designs 47% (textile, food sectors)
- The integration between departments via a structured system 26%
- IT for customer services 31%
- 3D printing 15% (handmade industries on a very small scale)
- Neither enterprises nor suppliers have access to their databases 0%

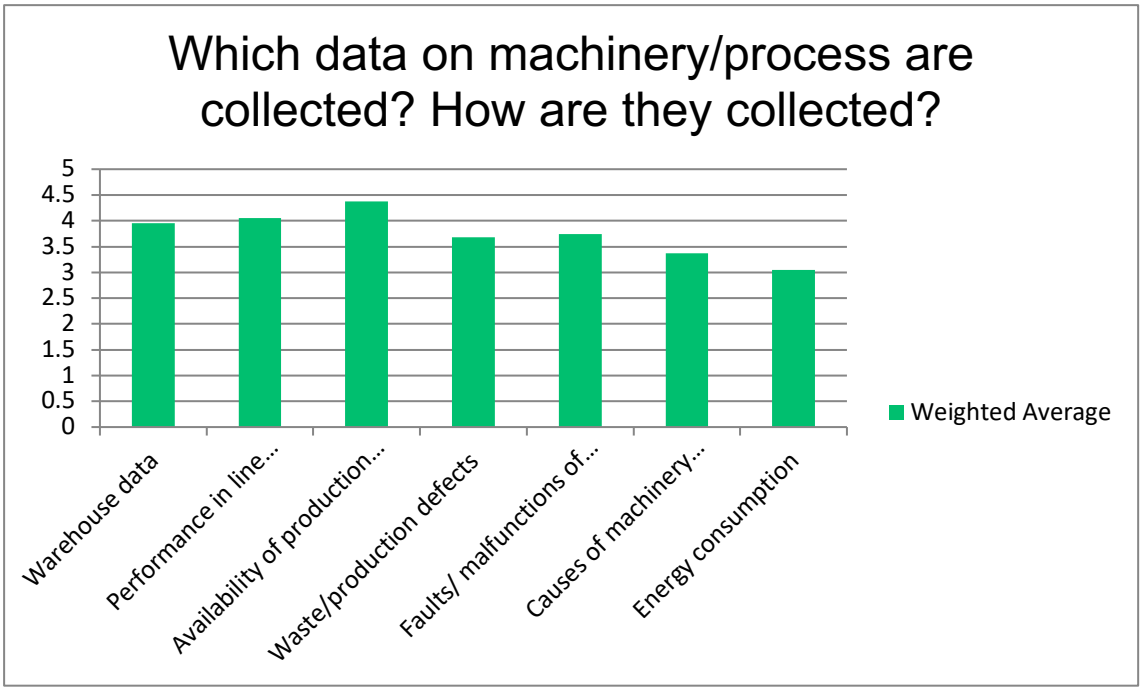


Section 3

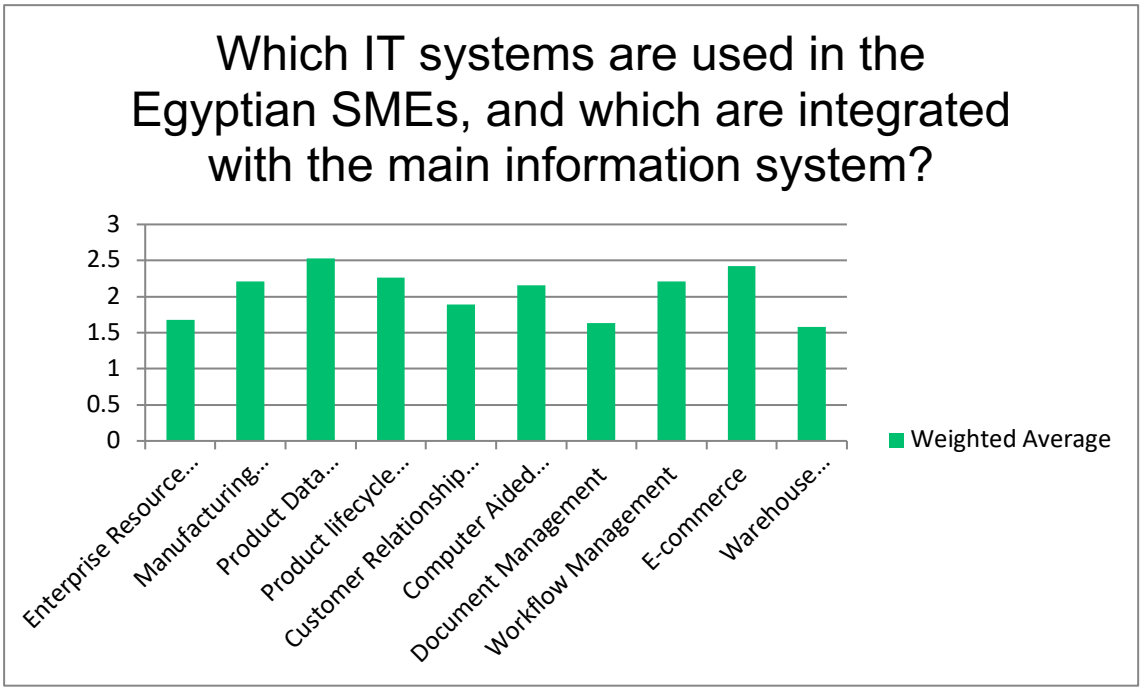
1. The digitization level of SMEs is Low-digitized production system (the production system is connected to the IT system, but it is possible to collect only some information about the production process (machine status) (94.74%)
2. The data collected from the production system is continuous and data can be viewed remotely (real-time) (42%), but not in continuous (e.g., only at the end of turn) (36%), continuous (real-time) (21.05%).
3. In terms of investments projects for digitization, Egyptian SMEs ongoing investments are mainly in the following operating units:
   a) Sales & Marketing, production, quality management (73%).
   b) Research and development (R&D) (68%).
   c) Purchasing (63%)
   d) Internal maintenance (63%)
   e) Logistics (57%) *"transportation is the main outsourced logistical activity"*
   f) IT infrastructure (42.11%)
   g) After sale-services (42%) *"mainly in automotive sector"*
   h) Cyber security (10%) *"it was observed the lack of investments in cyber-security and HR projects throughout all conducted sectors"*
   i) HR (15.79%)



4. In terms of data on how data on machinery is collected:
   a) Availability of production machines (57%) is continuously collected via Information Systems (IS)
   b) Performance of machines in assembly lines (52%) are continuously collected via Information Systems (IS)
   c) Warehouse data (52%) are continuously collected via Information Systems (IS)
   d) Faults/malfunctions of machinery (42%) are continuously collected via Information Systems (IS)
   e) Waste/production defects (31%) are continuously collected via Information Systems (IS)
   f) Causes of machinery malfunctions (36%) are continuously collected via Information Systems (IS)
   g) Energy consumption (31%) is continuously collected via Information Systems (IS).

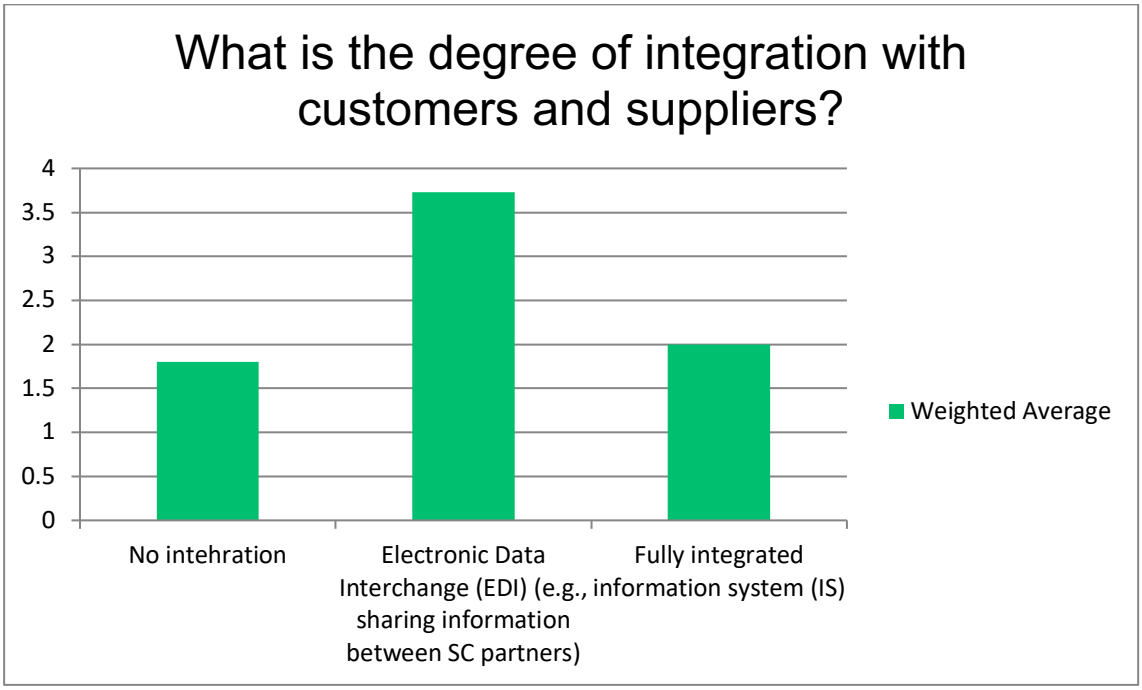


5. In terms of Main IT systems used:
   a) ERP is used by (68 %)
   b) Warehouse Management system (WMS) (68%)
   c) Document management (Microsoft office apps) (63%)
   d) CRM (32%)
   e) Product lifecycle management (PLM) (21%)
   f) CAD (21%)
   g) E-commerce (16%)
   h) Manufacturing Execution system (MES) (10%)
   i) Product Data Management (PDM) (10%)
   j) Workflow management (0%)



Section 4: supply chain (SC) collaboration

- Electronic Data Interchange (EDI) between SC partners are as follows:
  a) 20% with main customers
  b) 40% with main suppliers
  c) 33.33% with distributors



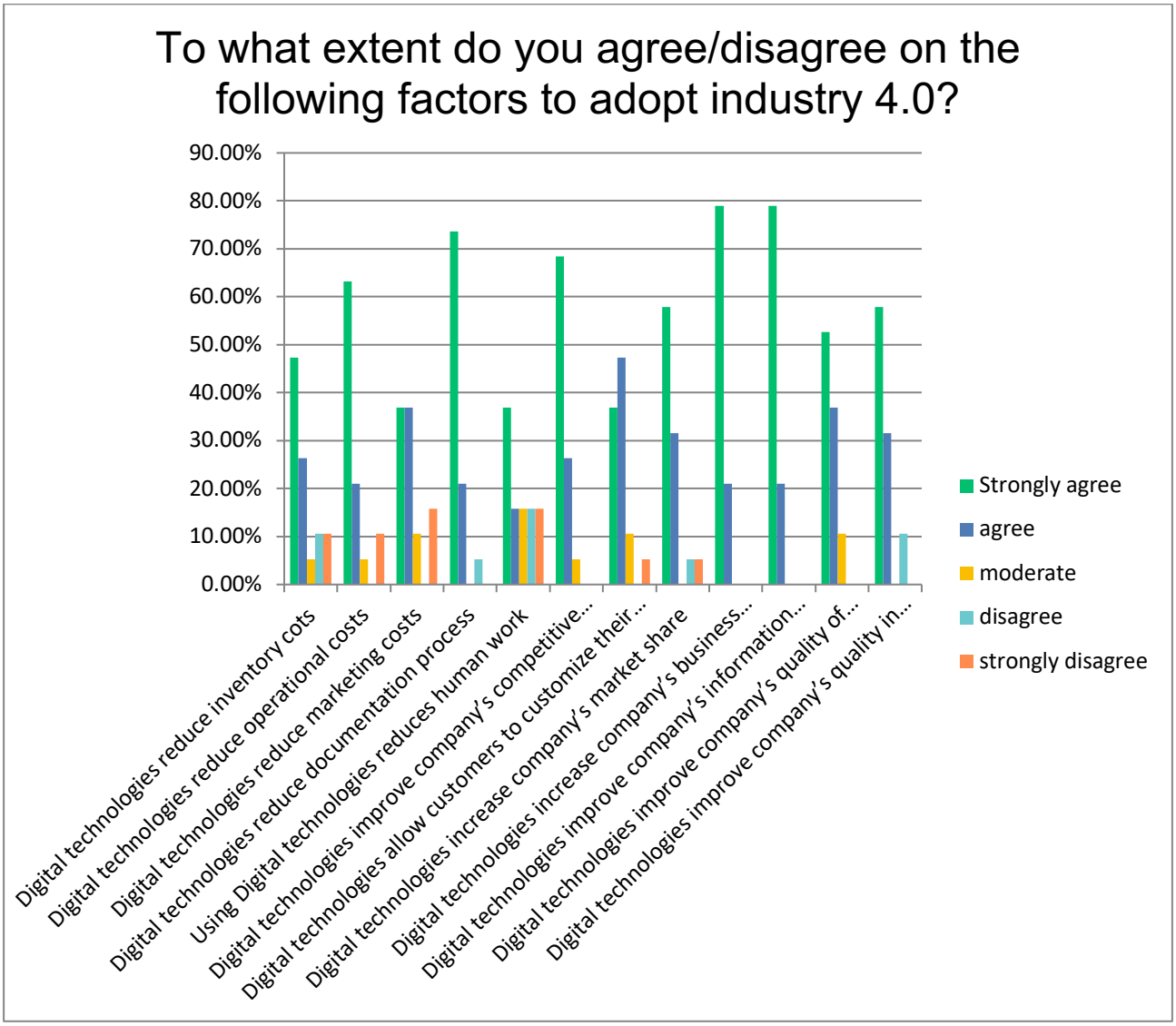
Section 5: Expert's knowledge about the fourth-generation industry:

Term	***Yes***	***No***
Industry 4.0	15.7%	84.2%
IoT	42.1%	57.8%
CPS	15.7%	84.2%
BDA	26.3%	73.6%
Additive manufacturing	26.3%	73.6%
Cloud-computing	94.7%	5.2%
Industry 4.0 introduction to the manufacturing sector	10 % (Textile sector)	90%
Is there a roadmap for planning the activities for the introduction of industry 4.0 solutions for Egyptian SMEs?	----	100%
If an industry 4.0 strategy has been introduced in the Egyptian SMEs, which support tools/ analysis are used?	A) A strategy has not been defined but we would like to define it (90 %) B) The strategy is under definition (10 %)	

Section 6: Main drivers for I4.0 adoption

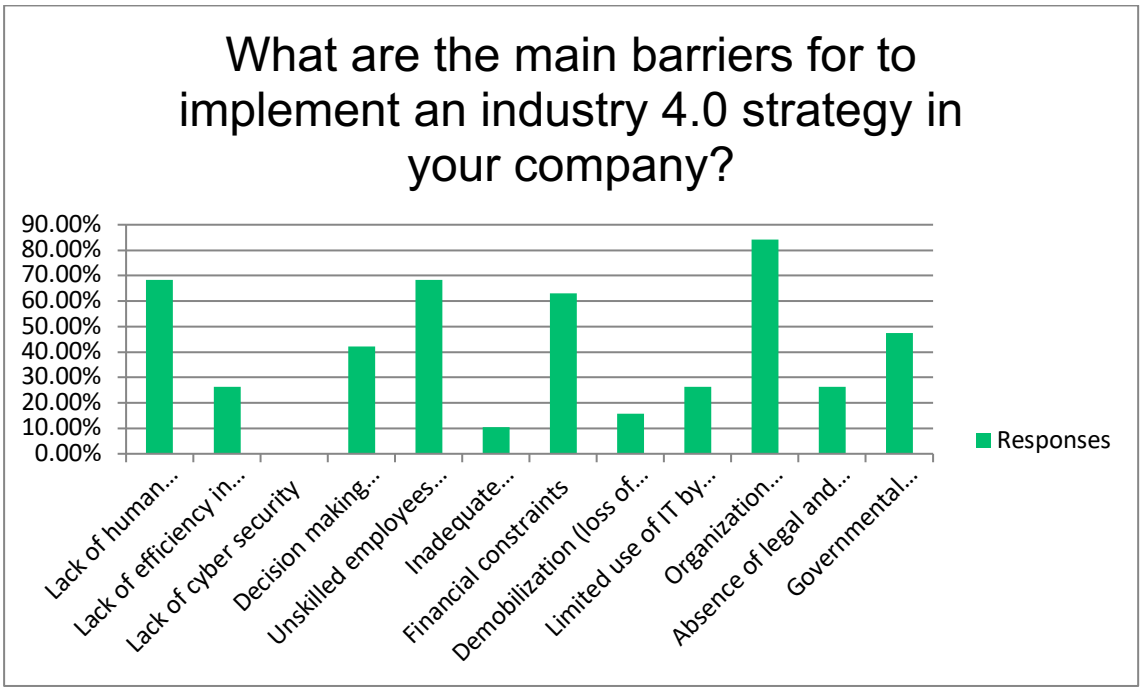
#	**Driving force**	**Strongly Agree**	**Agree**	**Moderate**	**Disagree**	**Strongly disagree**
1	Digital technologies reduce inventory cots	47%	26%	5%	11%	11%
2	Digital technologies reduce operational costs	63%	21%	5%	0	11%
3	Digital technologies reduce marketing costs	37%	37%	11%	0	16%
4	Digital technologies reduce documentation process	74%	21%	0	5%	0

5	Using Digital technologies reduces human work	37%	16%	16%	16%	16%
6	Digital technologies improve the company's competitive advantage (e.g., new products/services, customized products, better customer services, etc.	68%	26%	5%	0	11%
7	Digital technologies allow customers to customize their products	37%	47%	11%	0	5%
8	Digital technologies increase the company's market share	58%	32%	0	5%	5%
9	Digital technologies increase the company's business efficiency	79%	21%	0	0	0
10	Digital technologies improve the company's information quality	79%	21%	0	0	0
11	Digital technologies improve company's quality of following up with customer claims and complaints	53%	36%	11%	0	0
12	Digital technologies improve company's quality in reduction of transaction errors	58%	32%	0	11%	0


To what extent do you agree/disagree on the following factors to adopt industry 4.0?
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Digital technologies reduce inventory cots
Digital technologies reduce operational costs
Digital technologies reduce marketing costs
Digital technologies reduce documentation process
Digital technologies reduces human work
Using Digital technologies improve company's competitive...
Digital technologies allow customers to customize their ...
Digital technologies increase company's market share
Digital technologies increase company's business...
Digital technologies improve company's information...
Digital technologies improve company's quality of...
Digital technologies improve company's quality in...
Strongly agree
agree
moderate
disagree
strongly disagree

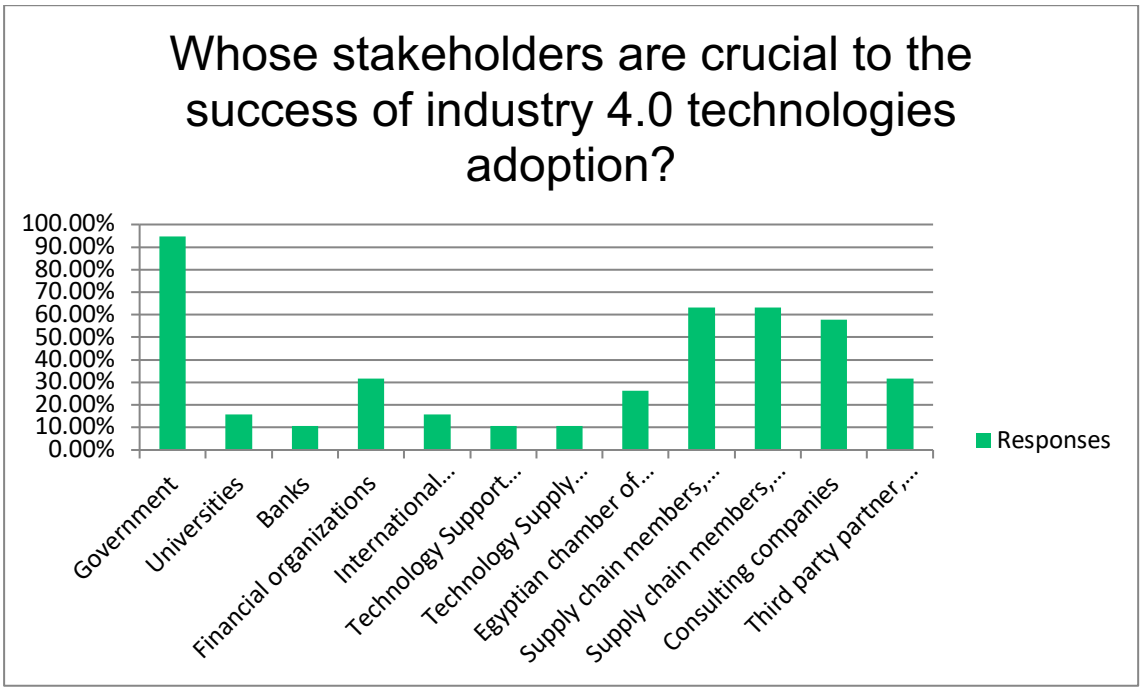
Section 7: Main barriers to adopt I4.0 in the Egyptian SMEs

- What are the main barriers to implementing an industry 4.0 strategy in your company?



1. Organization resistance to change (84%)
2. Lack of human knowledge (68%)
3. Unskilled employees and managers (68%)
4. Financial constraints (63%)
5. Governmental regulations (47%)
6. Decision making deficiencies (42%)
7. Lack of efficiency in value chain product/services quality (26%)
8. Limited use of IT by SMEs (26%)
9. Absence of legal and regulatory systems (26%)
10. Demobilization (16%)
11. Inadequate organizational structure (11%)

- Whose stakeholders are crucial to the success of industry 4.0 technologies adoption?



1. Government (95%)
2. Supply chain members (suppliers) (63%)
3. Supply chain members (customers) (63%)
4. Consulting companies (58%)
5. Financial organizations (32%)
6. Third party partner (product and manufacturing design partner, freight consolidation, transportation, digital services providers) (32%)
7. Egyptian chamber of commerce (26%)
8. Universities (16%)
9. International community support funds (16%)
10. Banks (11%)
11. Technology support companies (11%)
12. Technology supply companies (11%)

Section 8: Training and Skills:

1. What types of training programs do you recommend for improving managers skills?

Skills/courses/Academic degree	word counts
Strategic planning skills	11
Negotiation skills	9
MBA	7
Marketing skills	6
Project Management skills/courses	5
six-sigma diploma/courses	4

2. What types of training programs do you recommend for improving employee's skills?

skills	word count
communication skills	12
computer skills	11
safety & security skills	9
technical skills	8
education	3
technical trainings workshops	3

APPENDIX F- CAIRO SMES MANUFACTURING SECTOR MM DELPHI FIRST ROUND RESULTS

MMs Characteristics	Dimensions	Exemplary Maturity Items	Questionnaire-related Questions.	Scale	Values collected according to the questionnaire scale
MM1: IMPULS-Industries 4.0 Readiness	D1 Organizational Strategy	Strategic planning I4.0 corporate strategy	**(Section 5)** "Has an I4.0 strategy been defined?"	Binary (yes/no)	Only (2 Experts) 10% of experts see an Industry 4.0 introduction/strategy implemented
			(section 5) "Is there a roadmap?"	Scale #5items {not exist, fully implemented}	No roadmap exists for planning I4.0 activities (100%).
			(Section 3.3) terms of investments projects for digitization, Egyptian SMEs ongoing investments are mainly in the following operating units:	Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted}	j) Sales & Marketing, production, quality management (14 Experts) (74%). k) Research and development (R&D) (13 Experts) (68%). l) Purchasing (12 Experts) (63%) m) Internal maintenance (12 Experts) (63%) Logistics (11 Experts) (58%) "transportation is the main outsourced logistical activity" n) IT infrastructure (8 Experts) (42%) o) After sale-services (8 Experts) (42%) "mainly in automotive sector" p) Cyber security (2 Experts) (10%) "it was observed

					the lack of investments in cyber-security and HR projects throughout all conducted sectors” q) HR (3 Experts) (16%)
			Section 7: Organizational resistance to change and inadequate organizational structure	2 questions: Binary (yes/no)	"Organization resistance to change” (16 Experts) (84%) and "Inadequate organizational structure"
	D2 Smart Factory	Automated production environment Equipment infrastructure IT systems	(Q24 & 28) Use of digitized machines for production/assembly	2 Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted}	(13 Experts) 70%
			(Q24 &28) IT for monitoring machines; Use of digitized machines (e.g., sensors)	2 questions: Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted}	monitoring machine and production process is adopted by (6 Experts) 30%
			(Q1 & 2) Structured systems across departments; ERP for production status	2 questions: Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted}	
			Section 3.1: what is the degree of digitization level of SMEs for production system?	Nominal #3items {physical, Low-digitized, Well-digitized}	indicates a Low-digitized production system (the production system is connected to the IT system, but it is possible to collect only some information about the production process (machine status) (18 Experts) (95%).
			Section 3.4: In terms of data on how data on machinery are collected	Scale #5items {NA, not collected, yes_paper, yes_not continuous, yes_continuous}	h) Availability of production machines (11 Experts) (57%) is continuously collected via Information Systems (IS) i) Performance of machines in assembly lines (10

					Experts) (52%) are continuously collected via Information Systems (IS) j) Warehouse data (10 Experts) (52%) are continuously collected via Information Systems (IS) k) Faults/malfunctions of machinery (8 Experts) (42%) are continuously collected via Information Systems (IS) l) Waste/production defects (6 Experts) (31%) are continuously collected via Information Systems (IS) m) Causes of machinery malfunctions (7 Experts) (36%) are continuously collected via Information Systems (IS) n) Energy consumption (6 Experts) (31%) is continuously collected via Information Systems (IS).
	D3 Smart Operation	Information sharing Cloud usage IT security	(section 4) Electronic Data Interchange (EDI) between SC partners	Nominal # 3 items	Electronic Data Interchange (EDI) between SC partners are as follows: d) (4 Experts) 20% with main customers e) (8 Experts) 40% with main suppliers

					f) (6 Experts) 33% with distributors
			(Q23 &27) Cloud for storage/backup; Cloud for product usage data	Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted}	(18 Experts) 95%
			(Sec.7) general IT Integration and investments priorities) Indirectly via system reliability, integration, security awareness	Scale #5items {No Investments, application under discussion, Investments planned but not executed, Ongoing Investments, Investments concluded}	• Sales & Marketing, production, quality management (14 Experts) (74%). • Research and development (R&D) (13 Experts) (69%). • Purchasing (12 Experts) (63%) • Internal maintenance (12 Experts) (63%) Logistics (11 Experts) (58%) “transportation is the main outsourced logistical activity” • IT infrastructure (8 Experts) (42%) • After sale-services (8 Experts) (42%) “mainly in automotive sector” • Cyber security (2 Experts) (10%) “it was observed the lack of investments in cyber-security and HR projects throughout all conducted sectors” • HR (4 Experts) (16%) • lists "Lack of cyber security" as a main barrier (13 Experts) (68%), and Section 3.3 indicates

					low investment in cyber security (2 Experts) (10%). *"It was observed the lack of investments in cyber-security and HR projects throughout all conducted sectors"*
	D4 Smart product	Automated identification Efficient production management New data driven services	(section 2) Use of CAD software in design	Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted}	software for designs (CAD) is (9 Experts) 47%/ (PLM) (4 Experts) 21% adopted
			(section 2) IT for receiving and managing orders	Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted}	(10 Experts) 52%
			(Q27) Cloud use for collecting product usage data	Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted}	(18 Experts) 95%
	D5 Data Collection	Availability of data-driven Share of revenue share of data used	(section 3.4) IT used for process monitoring; production data collection	Scale #5items {NA, not collected, yes paper, yes not continuous, yes continuous}	• Availability of production machines (11 Experts) (57%) is continuously collected via Information Systems (IS) • Performance of machines in assembly lines (10 Experts) (52%) are continuously collected via Information Systems (IS) • Warehouse data (10 Experts) (52%) are continuously collected via Information Systems (IS) • Faults/malfunctions of machinery (8 Experts)

					(42%) are continuously collected via Information Systems (IS) • Waste/production defects (6 Experts) (31%) are continuously collected via Information Systems (IS) • Causes of machinery malfunctions (7 Experts) (36%) are continuously collected via Information Systems (IS) • Energy consumption (6 Experts) (31%) is continuously collected via Information Systems (IS).
			NOT COVERED	NOT COVERED	NOT COVERED
			(section 3.2) Cloud-based product usage partially reflects utilization/data viewing capabilities	Scale #5items { No, SMEs do not collect data from the production system, and do not know which data to collect, No, SMEs do not collect data from the production system, however, some companies know which data to collect, Yes, but not in continuous (e.g., only at the end of turn), Yes, in continuous (real-time), Yes, in continuous and data can be viewed remotely (real-time)}	remotely (real-time) by (8 Experts) 42%, not continuous by (7 Experts) 36%, continuous (real-time) by (4 Experts) 21%.
	D6 Employees	Digital skills	(sec.8) What types of training programs do you recommend for improving employee skills?	Open Ended question	(communication skills (12-word count), computer skills (11), safety & security skills

					(9), technical skills (8), education (3), technical trainings/workshops (3)), addressing digital skills improvement.
MM2: Industry 4.0/Digital operations self-assessment	D1 Digital Business Models & Customer Access	Digital solutions Applications	(Section. 2) Electronic catalogues usage for products/services	Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted}	(16 Experts) 84%
			(section.2) internet usage in communication	Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted}	(12 Experts) 63%
			(section.2) CRM usage	Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted}	(6 Experts) 31%
			(sec. 2) IT usage for advertising	Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted}	(13 Experts) 68%
	D2 Digitization of products & Services	Online presence Integrated customer management	(sec. 2) Electronic catalogues usage for products/services	Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted}	(16 Experts) 84%
			(sec. 2) IT systems usage for customer services	Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted}	(6 Experts) 31%
	D3 Digitization & integration of vertical &horizontal value-chains	Fully automated process Integrated process	Section 3.1: what is the degree of digitization level of SMEs for production system?	Nominal #3items {physical, Low-digitized, Well-digitized}	indicates a Low-digitized production system (the production system is connected to the IT system, but it is possible to collect only some information about the production process (machine status) (18 Experts) (95%).
			Section 2: interdepartmental integration between departments via a structured system	Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted}	(5 Experts) 26%

			Section 4: Electronic Data Interchange (EDI) between SC partners	Nominal # 3 items	Electronic Data Interchange (EDI) between SC partners are as follows: a) (4 Experts) 20% with main customers b) (8 Experts) 40% with main suppliers c) (6 Experts) 33% with distributors
			Section 3.5: Main IT systems used	Nominal # 10 items	• ERP is used by (13 Experts) (68 %) • Warehouse Management system (WMS) (13 Experts) (68%) • Document management (Microsoft office apps) (12 Experts) (63%) • CRM (6 Experts) (32%)
MM3: Industry 4.0 Maturity Model	D1 Strategy	Implementing I4.0 roadmap Realizing available resources for digitization and smart automation Adopting business models	Section 5, Q9: "Is there a defined I4.0 strategy/vision?"	Scale #5items {A roadmap does not exist, A roadmap does not exist, but we are going to define it, A roadmap is under definition, A roadmap exists, and we are starting with the implementation phase, A roadmap exists and it is fully implemented}	10% (mainly textile sector)
			(Section 3.3) terms of investments projects for digitization, Egyptian SMEs ongoing investments are mainly in the following operating units:	Scale #5items {No Investments, application under discussion, Investments planned but not executed, Ongoing Investments, Investments concluded}	• Sales & Marketing, production, quality management (14 Experts) (74%). • Research and development (R&D) (13 Experts) (69%). • Purchasing (12 Experts) (63%) • Internal maintenance (12 Experts) (63%) Logistics (11

					Experts) (58%) “transportation is the main outsourced logistical activity” • IT infrastructure (8 Experts) (42%) • After sale-services (8 Experts) (42%) “mainly in automotive sector” • Cyber security (2 Experts) (10%) “it was observed the lack of investments in cyber-security and HR projects throughout all conducted sectors” • HR (4 Experts) (16%)
			Section 7: Organizational resistance to change and inadequate organizational structure	Mentioned before	"Organization resistance to change" (16 Experts) (84%) and "Inadequate organizational structure" (2 Experts) (10%) were found as main barriers to implementing an I4.0 strategy.
	D2 Leadership	Willingness of leaders to embrace I4.0 Management of digital competences and methods Existence of central coordination for I4.0 strategy	Section 5, Q9: “Is there a defined I4.0 strategy/vision?”	Scale #5items {A roadmap does not exist, A roadmap does not exist, but we are going to define it, A roadmap is under definition, A roadmap exists, and we are starting with the implementation phase, A roadmap exists and it is fully implemented}	(2 Experts) 10% (mainly textile sector)

	D3 Customers	Utilization of customer data Digitization of sales/services Customers digital media competences	• SMEs use the internet to search for customers • SMEs use the internet to search for suppliers • SMEs use the internet to communicate with customers • SMEs use the internet to collect information about customers • SMEs use the internet to collect information about competitors	Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted}	• (8 Experts) 42% • (10 Experts) 52% (usually used for foreign suppliers) • (12 Experts) 63% • (9 Experts) 47% • (9 Experts) 47%
	D4 Products	Individualization of products (customized products) Digitization of products (products/service systems) Product integration into other systems (smart products)	• SMEs produce customized products • Digitized Machines • Design software	Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted}	• (11 Experts) 57% • (14 Experts) 73% • (9 Experts) 47%
	D5 Operations	Decentralization of processes Modeling & Simulation Interdisciplinary & interdepartmental collaboration	Section 3.3 lists investments in production, purchasing, internal maintenance, and logistics Section 3.1: production digitization level (Decentralization of processes Modeling & Simulation are NOT covered)	Scale #5items {No Investments, application under discussion, Investments planned but not executed, Ongoing Investments, Investments concluded}	(14 Experts) 73%, (12 Experts) 63%, (12 Experts) 63%, (11 Experts) 57%
				Nominal #3items {physical, Low-digitized, Well-digitized}	Low-digitized level (18 Experts) 95%
	D6 Culture	Knowledge sharing Open innovation & cross-company collaboration ICT Value inside the company	Section 2: integration between departments via a structured system Section 4: EDI integration with SC partners	• Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted} • Nominal # 3 items	(5 Experts) 26% (mentioned before)

	D7 People	ICT competences of employees Openness of employees in new technology Autonomy of employees	(sec.8) What types of training programs do you recommend for improving employee skills? Openness of employees in new technology and Autonomy of employees are NOT COVERED	Open Ended question	recommended training programs for employees (communication skills (12), computer skills (11), safety & security skills (9), technical skills (8), education (3), technical trainings/workshops (3)).
	D8 Governance	Labor regulations for I4.0 Suitability of technological standards Protection of intellectual property	NOT COVERED	NOT COVERED	NOT COVERED
	D9 Technology	Existence of modern ICT Utilization of mobile devices Utilization of machine-to-machine (M2M) communication	Section 3.5 Main IT systems (ICT infrastructure) Section 2: adopted technologies	• Nominal # 10 items • Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted}	• ERP is used by (13 Experts) (68%), Warehouse Management system (WMS) (13 Experts) (68%), Document management (Microsoft office apps) (12 Experts) (63%), CRM (6 Experts) (32%) Product lifecycle management (PLM) (4 Experts) (21%), CAD (4 Experts) (21%), E-commerce (3 Experts) (16%), Manufacturing Execution system (MES) (2 Experts) (10%), Product Data Management (PDM) (2 Experts) (10%). • Technology adoption percentages (Cloud (12 Experts) 63%, digitized machines (14 Experts) 73%, monitoring (7 Experts) 36%).

MM4: SIMMI 4.0 (System Integration Maturity Model for I4.0)	D1 Vertical Integration	Focuses on the components of the lowest level of an enterprise.	structured systems across departments. ERP use for production info	Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted}	(5 Experts) 26%, (13 Experts) 68%
	D2 Horizontal Integration	Information flow across the enterprise and even beyond the enterprise borders (SC)	Section 2: integration between departments via a structured system Section 4: EDI integration with SC partners	• Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted} • Nominal # 3 items	(5 Experts) 26% (mentioned before)
	D3 Digital Product Development	supporting the product development continuously along the entire SC using advanced systems/technologies	SMEs IT for monitoring machine and production process SMEs use digitized machines (e.g., sensors) Software for designs R&D investments supporting the product development continuously along the entire SC using advanced systems/technologies is NOT COVERED	• Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted} • Scale #5items {No Investments, application under discussion, Investments planned but not executed, Ongoing Investments, Investments concluded}	(6 Experts) 30% (13 Experts) 70% (9 Experts) 47% (13 Experts) 68%
	D4 Cross-Sectional Technology Criteria	Assessing the extent to which technologies are used across all different fields of I4.0 based requirements (e.g., cloud computing, BDA, IT security, IoT)	NOT COVERED	NOT COVERED	NOT COVERED
MM5: Maturity Model in SMEs towards Industry 4.0	D1 Strategy	Not Defined in the model	Not Defined in the model		Not Defined in the model
	D2 Leadership	Not Defined in the model	Not Defined in the model		Not Defined in the model
	D3 Customers	Not Defined in the model	Not Defined in the model		Not Defined in the model

	D4 Products	Not Defined in the model	Not Defined in the model		Not Defined in the model
	D5 Operations	Data analytics Information sharing	Which data on machinery/processes are collected? How are they collected?		
			(section 3.4) IT used for process monitoring, production data collection	Mentioned Before	• Availability of production machines (11 Experts) (57%) is continuously collected via Information Systems (IS) • Performance of machines in assembly lines (10 Experts) (52%) are continuously collected via Information Systems (IS) • Warehouse data (10 Experts) (52%) are continuously collected via Information Systems (IS) • Faults/malfunctions of machinery (8 Experts) (42%) are continuously collected via Information Systems (IS) • Waste/production defects (6 Experts) (31%) are continuously collected via Information Systems (IS) • Causes of machinery malfunctions (7 Experts) (36%) are continuously collected via Information Systems (IS)

					• Energy consumption (6 Experts) (31%) is continuously collected via Information Systems (IS).
	D6 Culture	Not Defined in the model	Not Defined in the model		Not Defined in the model
	D7 People	Not Defined in the model	Not Defined in the model		Not Defined in the model
	D8 Governance	Not Defined	Not Defined in the model		Not Defined in the model
	D9 Technology	New technologies ICT integration Cyber-security Data governance IoT utilization Cloud – computing M2M communication	Which IT systems are used in the Egyptian SMEs, and which are integrated with the main information system? Data governance and specific IoT/M2M utilization are NOT COVERED	Mentioned before	Mentioned before
MM6: Maturity Model for Digital Transformation	D1 Digitization Awareness	defined product roadmap portfolio for digital products framework for smart products	Is there a roadmap for planning the activities for the introduction of industry 4.0 solutions for Egyptian SMEs? portfolio for digital products and framework for smart products is not mentioned	Mention before	NO (0%)
				Not explicitly covered	Not explicitly covered
	D2 Smart Products	defined roadmap for smart products data processing R&D	*"Customized product production"* assesses flexibility and personalization	Mention before	(11 Experts) 57%
			R&D investments	Mention before	(13 Experts) 68%
			Cloud usage	Mention before	(12 Experts) 63%
	D3 Smart Services	defined roadmap for smart services	• ERP usage • Managing and receiving orders • Orders fulfillment/delivery • Integration between departments	Mention before	• (13 Experts) 68% • (12 Experts) 63% • (10 Experts) 52% • (5 Experts) 26%

	D4 Services Systems	roadmap for services systems strategic ecosystem digital enterprise	Not explicitly covered	Not explicitly covered	Not explicitly covered
	D5 Data-driven	Big Data Analytics (BDA)	Not available	Not available	Not available
MM7: Guideline Industrie 4.0	D1 Integration of Sensors	Communication Data storage/exchange Monitoring	(section 3.4) IT used for process monitoring; production data collection	Mention before	• Availability of production machines (11 Experts) (57%) is continuously collected via Information Systems (IS) • Performance of machines in assembly lines (10 Experts) (52%) are continuously collected via Information Systems (IS) • Warehouse data (10 Experts) (52%) are continuously collected via Information Systems (IS) • Faults/malfunctions of machinery (8 Experts) (42%) are continuously collected via Information Systems (IS) • Waste/production defects (6 Experts) (31%) are continuously collected via Information Systems (IS) • Causes of machinery malfunctions (7 Experts) (36%) are continuously

					collected via Information Systems (IS) • Energy consumption (6 Experts) (31%) is continuously collected via Information Systems (IS).
	D2 No use of Sensors	No interfaces No functionality No monitoring			
	D3 Sensor Readings	Product bus interface Passive data storage Recording of operating condition	SMEs IT for monitoring machine and production process	Mention before	(13 Experts) 70%
			SMEs use digitized machines (e.g., sensors)	Mention before	monitoring machine and production process is adopted by 30%
			Product bus interface and Passive data storage are Not explicitly covered	Not explicitly covered	Not explicitly covered
	D4 Data Evaluation & Analysis	Ethernet interfaces Data storage Autonomous information exchange	Cloud usage to collect product data	Mention before	(12 Experts) 63%
			(section 3.4) IT used for process monitoring; production data collection	Mention before	Mention before
			(section 3.2) data driven capabilities (real-time)	Mention before	(8 Experts) 42%
	D5 Product Independency	Access to the internet Data and information exchange IT integrated infrastructure	Section 2: IT usage for monitoring machine & production process	Mention before	(7 Experts) 36%
			Which IT systems are used in the Egyptian SMEs, and which are integrated with the main information system?	Mention before	Mentioned before
			Section 4: EDI integration with SC partners	Mention before	Mentioned before
	D6 Data Processing in the Production	M2M communication ICT infrastructure Man-machine interfaces & efficiency with small batches	Section 3.5 Main IT systems (ICT infrastructure)	Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted}	• ERP is used by (13 Experts) (68%), Warehouse Management system (WMS) (13 Experts) (68%), Document management (Microsoft office apps) (12 Experts) (63%), CRM (6

					Experts) (32%) Product lifecycle management (PLM) (4 Experts) (21%), CAD (4 Experts) (21%), E-commerce (3 Experts) (16%), Manufacturing Execution system (MES) (2 Experts) (10%), Product Data Management (PDM) (2 Experts) (10%). • Technology adoption percentages (Cloud (12 Experts) 63%, digitized machines (14 Experts) 73%, monitoring (7 Experts) 36%).
	D7 No Processing of Data	No communication No networking of production No information exchange			
	D8 Storage of Documented Data	Information exchange Central data services in production Flexible production systems	(section 3.4) IT used for process monitoring; production data collection	Mention before	Mention before
			Section 2: integration between departments Section 4: EDI integration with SC partners	Mention before	(5 Experts) 26% Mentioned before
			Central data services in production and Flexible production systems are Not explicitly covered		Not explicitly covered
	D9 Analysing Data	Industrial ethernet Uniform data formats Data exchange Production monitoring control	Section 2: SMEs use cloud computing for collecting product usage data	Mention before	(12 Experts) 63%
			Section 2: IT usage for monitoring machines and production process	Mention before	(7 Experts) 36%
			Section 4: EDI integration with SC partners	Mention before	Mentioned before
			Industrial ethernet and Uniform data formats are Not explicitly mentioned		Not explicitly covered

	D10 Evaluation	Evaluation Machines have access to internet. Order tracking Mobile user interface	Section 2: IT usage for monitoring machines and production process	Mention before	(7 Experts) 36%
			SMEs use software like Enterprise Recourse Planning (ERP) for providing production status	Mention before	(13 Experts) 68%
			IT for tracking order fulfillment/delivery	Mention before	(10 Experts) 52%
			Machines have access to internet Not explicitly mentioned		Not explicitly mentioned
	D11 Application	Automatic process planning M2M software Suppliers/customers are fully integrated. Augmented and assisted reality	SMEs use software like Enterprise Recourse Planning (ERP) for providing production status	Mention before	(13 Experts) 68%
			SMEs use IT for accessing suppliers' products/ services database	Mention before	(10 Experts) 52%
			SMEs use IT for tracing order fulfillment and delivery	Mention before	(13 Experts) 68%
			Electronic payment M2M software, AR (are not available)	Scale #5items {NA, application under discussion, under development, not fully adopted, fully adopted}	(13 Experts) 68% M2M software, AR (are not available)
MM8: Smart Assessment Model	D1 Production Process	Product development Product planning Process control Quality control Facility management Logistics management	Investments including production	Mention before	(14 Experts) 74%
			(section 3.4) IT used for process monitoring; production data collection	Mention before	Mention before
			Logistics investments	Mention before	(11 Experts) 57%
	D2 System & Automation	Information system Facility automation	Section 3.5 Main IT systems (ICT infrastructure)	Mention before	Mentioned before
			Section 4: EDI integration with SC partners	Mention before	Mentioned before
	D3 Performance	Performance assessment	(section 3.4) IT used for process monitoring; production data collection	Mention before	Mention before
	D4 Leadership	Leadership & strategy	Section 8 – *"What training is needed for employees?"*	Open Ended question	(Strategic planning (11), Negotiation skills (9), MBA (7), Marketing skills (6), Project Management skills/courses (5), Six-sigma diploma/courses (4)), which aim to improve leadership skills and strategy focus.

MM9: Actech Industrie 4.0 Maturity Index	D1 Resources	Digital competencies Automated data acquisition Decentralized processing of data	(section 3.4) IT used for process monitoring, production data collection Decentralized processing of data is Not explicitly mentioned	Mention before	Mention before Not explicitly mentioned
	D2 Information Systems	Data analysis Contextualized data delivery Resilient IT infrastructure Application of user interface HI & VI Data governance IT security	SMEs use software like Enterprise Recourse Planning (ERP) for providing production status	Mention before	Mention before
			SMEs IT for monitoring machine and production process	Mention before	Mention before
			SMEs use digitized machines (e.g., sensors)	Mention before	Mention before
			Section 3.5 Main IT systems (ICT infrastructure)	Mention before	Mentioned before
	D3 Organizational Structure	Flexible communication Agile management Customer benefits Cooperation within the network	SMEs use a well-structured system that enables different departments to be connected.	Mention before	(5 Experts) 26%
			Flexible communication, Agile management, and Customer benefits are Not explicitly mentioned		Not explicitly mentioned
	D4 Culture	Democratic leadership Open communication Data-base learning & decision making Continuous professional development Openness to innovation	Not explicitly covered	Not explicitly covered	Not explicitly covered
MM10: Methodology for modelling and assessing human activities within	D1 Abstraction	Physical: the activity affects the physical process generally Cyber/digital: the activity affects digitalized information.	(section 3.4) IT used for process monitoring, production data collection	Mention before	Mention before
			Holistic: the activity affects concepts or ideas is Not explicitly mentioned	Not explicitly mentioned	Not explicitly mentioned
			Not explicitly covered	Not explicitly covered	Not explicitly covered

cyber-physical systems (CPS)		Holistic: the activity affects concepts or ideas			
	D2 Decision Making	Detect (situation awareness) Determine (analysis and decision making) Develop (task execution)/ other added activities	Not explicitly covered	Not explicitly covered	Not explicitly covered
	D3 Innovations	Routine-based (based on practice) Rules & methods (based on shared sets of knowledge) Creative (develop new solutions)	Section 3.3. R&D	Mention before	(13 Experts) 68%
			Rules & methods (based on shared sets of knowledge)	Not explicitly covered	Not explicitly mentioned
			Creative (develop new solutions)	Not explicitly covered	Not explicitly mentioned
	D4 Social Interaction	No or poor social interaction. Negotiation Social cohesion	No or poor social interaction.	Not explicitly covered	Not explicitly mentioned
			Negotiation	Not explicitly covered	Not explicitly mentioned
			Social cohesion	Not explicitly covered	Not explicitly mentioned
	D5 Human Component	Work activities that require workers to have specific abilities, skills, and knowledge	(sec.8) What types of training programs do you recommend for improving employee skills?	Mention before	recommended training programs for employees (communication skills (12), computer skills (11), safety & security skills (9), technical skills (8), education (3), technical trainings/workshops (3)).
	D6 CPS Component	Decision support Intelligent dashboard visualization Workplace learning Worker augmentation Workplace adaptation	Decision support	Not explicitly covered	Not explicitly covered
			Intelligent dashboard visualization	Not explicitly covered	Not explicitly covered
			Workplace learning	Not explicitly covered	Not explicitly covered
			Worker augmentation	Not explicitly covered	Not explicitly covered
			Workplace adaptation	Not explicitly covered	Not explicitly covered

MM12: 360 Digital Maturity Assessment (360 DMA)	D1 Technology	Business intelligence tool (MES, ERP) Cloud computing	Section 3.5 Main IT systems (ICT infrastructure)	Mentioned before	Mentioned before
	D2 Connectivity	Data sharing capabilities IT security Standard data structuring/ transmission architectures	SMEs use a well-structured system that enables different departments to be connected.	Mention before	(5 Experts) 26%
			Section 4: Electronic Data Interchange (EDI) between SC partners	Mention before	Electronic Data Interchange (EDI) between SC partners are as follows: • (4 Experts) 20% with main customers • (8 Experts) 40% with main suppliers • (6 Experts) 33% with distributors
			Standard data structuring/ transmission architectures	Not explicitly covered	Not explicitly covered
	D3 Value Creation	Data usage for orders Forecasting	Section 2: SMEs use cloud computing for collecting product usage data	Mention before	(12 Experts) 63%
			Tracking order fulfillment/delivery Forecasting	Mention before	(10 Experts) 52% Not explicitly covered
	D4 Competences	Digital competences Training Learning	(sec.8) What types of training programs do you recommend for improving employee skills?	Mention before	recommended training programs for employees (communication skills (12), computer skills (11), safety & security skills (9), technical skills (8), education (3), technical training/workshops (3)).
	D5 Governance	Organizational level (e.g., strategy, organizational structure, management, resource allocation,	SMEs use a well-structured system that enables different departments to be connected.	Mention before	(5 Experts) 26%

		digital awareness, integrated departments			
MM14: Development of an assessment model for industry 4.0: industry 4.0 maturity model	D1 IT	Cloud computing IT infrastructure Cyber-security IoT IT resources	Section 3.5: Main IT systems used	Mention before	• ERP is used by (13 Experts) (68 %) • Warehouse Management system (WMS) (13 Experts) (68%) • Document management (Microsoft office apps) (12 Experts) (63%) • CRM (6 Experts) (32%) • PLM (5 Experts) (21%) • CAD (5 Experts) (21 %) • E-commerce (3 Experts) (16%) • MES (2 Experts) (10%) • PDM (2 Experts) (10%) • Cyber-security (2 Experts) (10%) • IoT (Not used)
	D2 Data Governance	Data collection BDA	(section 3.4) IT used for process monitoring, production data collection	Mention before	Mention before
			BDA	Not available	Not available
	D3 Information Flow	Integrated/ automated information flow	Section 4: Electronic Data Interchange (EDI) between SC partners	Mention before	Electronic Data Interchange (EDI) between SC partners are as follows: a) (4 Experts) 20% with main customers b) (8 Experts) 40% with main suppliers c) (6 Experts) 33% with distributors

	D4 Process Transformation	Planning Acquisition Sales & marketing Production	Section 3.3: investments areas: production	Mention before	(14 Experts) 74%
			Sales & marketing	Mention before	(14 Experts) 74%
			Planning	Not explicitly covered	Not explicitly covered
			Acquisition	Not explicitly covered	Not explicitly covered
	D5 Organizational Structure/ strategy	Enterprise architecture in terms of structure & strategy Knowledge / IT skills IT investments	SMEs use a well-structured system that enables different departments to be connected.	Mention before	(5 Experts) 26%
			IT investments	Mention before	• Sales & Marketing, production, quality management (14 Experts) (74%). • Research and development (R&D) (13 Experts) (69%). • Purchasing (12 Experts) (63%) • Internal maintenance (12 Experts) (63%) Logistics (11 Experts) (58%) "transportation is the main outsourced logistical activity" • IT infrastructure (8 Experts) (42%) • After sale-services (8 Experts) (42%) "mainly in automotive sector" • Cyber security (2 Experts) (10%) "it was observed the lack of investments in cyber-security and HR projects throughout all conducted sectors" • HR (4 Experts) (16%)
MM15: Towards a	D1 Strategy	Investments IoT roadmap	Section 3.3 lists of investments areas	Mention before	Mentioned before
			IoT roadmap	Mention before	0%

framework for assessing the maturity of manufacturing companies in industry 4.0 adoption		Enhancements of the product through IoT, development of new products Cyber security Choice of platform & standards HI & VI IoT in organization	Enhancements of the product through IoT, development of new products	Mention before	0%
			Cyber security	Mention before	Mentioned before
			Choice of platform & standards	Not explicitly covered	Not explicitly covered
			HI & VI	Mention before	Mentioned before
	D2 Maturity	Equipment infrastructure IT systems Security systems Technology adoption Ability to analyze big data. Awareness of the importance of analyzing big data Reasons to use big data. Self-evaluation system Real-time change abilities based on analytics. Effective use of big data Employee training system Knowledge management system Awareness of skills required for IoT	Equipment infrastructure	Mention before	Mentioned before
			IT systems	Mention before	Mentioned before
			Security systems	Mention before	1 expert
			Technology adoption	Mention before	Mentioned before
			Ability to analyze big data.		Traditional tools
			Awareness of the importance of analyzing big data	Binary (yes/no)	5 experts
			Reasons to use big data.	Not explicitly covered	Not explicitly covered
			Self-evaluation system	Not explicitly mentioned	Not explicitly covered
			Real-time change abilities based on analytics.	Not explicitly mentioned	Not explicitly covered
			Effective use of big data	Not explicitly mentioned	Not explicitly covered
			Employee training system	Mentioned before	Mentioned before
			Knowledge management system	Binary (yes/no)	• I4.0 (9 E) • IoT (10 E) • CPS (5 E) • BDA (5 E) • Additive manufacturing (5 E) • Cloud technologies (18 E)
			Awareness of skills required for IoT	Binary (yes/no)	(11 E)

	D3 Performance	Economic benefits Order fulfillment rate Cost, lead-time, energy consumption and defect reduction Reduction in time for decision making. Impact of inventory requirements	To what extent do you agree/disagree on the following factors to adopt industry 4.0? NOTE: Number of experts here reflects to "Strongly Agree"	Scale #5items {from strongly agree to strongly disagree}	• Digital technologies increase company's business efficiency (15 E) • Digital technologies improve company's information quality (15 E) • Digital technologies reduce documentation process (14 E) • Digital technologies improve company's competitive advantage (e.g., new products/services, customized products, better customer services, etc. (13 E) • Digital technologies reduce operational costs (12 E) • Digital technologies increase company's market share (11 E) • Digital technologies improve company's quality of following up with customer claims and complaints (10 E) • Digital technologies reduce inventory cots (9 E) • Digital technologies allow customers to customize their products (7 E) • Digital technologies reduce marketing costs (7 E)
			Tracking order fulfillment/delivery	Mentioned before	(10 Experts) 52%

MM16: Maturity and readiness model for Industry 4.0 strategy	D1 Smart Products & services	Smart products & services	Section 2: production of customized products	Mentioned before	(11 Experts) 57%
	D2 Smart business process	Smart production & operations (production, logistics, procurement) Smart marketing & sales operations (an after-sales service, sales, promotion) Supportive systems (HR, IT, Smart finance)	Smart production & operations (production, logistics, procurement)	Mentioned before	Mentioned before
			Smart marketing & sales operations (an after-sales service, sales, promotion)	Mentioned before	Mentioned before
			Supportive systems (HR, IT, Smart finance)	Mentioned before	Mentioned before
	D3 Strategy and organization	Business models Strategic partnerships technology investments organizational structure & leadership	Business models	Not explicitly mentioned	Not explicitly mentioned
			Strategic partnerships	Not explicitly mentioned	Not explicitly mentioned
			technology investments	Mentioned before	Mentioned before
			organizational structure & leadership	Mentioned before	Mentioned before

APPENDIX G - DELPHI-SURVEY: SECOND ROUND

1. **Sector**

- ◯ Automotive
- ◯ Electrical Equipment's
- ◯ Food & Beverage
- ◯ Textile
- ◯ Petrochemichals
- ◯ Agriculture
- ◯ Metals and Machinery

2. **Organizational strategy**

Encompasses the strategic planning and control of I4.0 business strategy, specifically focusing on IT investments, the implementation of I4.0 roadmap, cyber security, and the utilization of existing resources for digitalization, as well as HI and VI

	Strongly agree	Neither agree nor disagree	Strongly disagree	Disagree	Agree
Organisational level (strategy, structure, management, resources allocation, digital awareness, integrated departments)	◯	◯	◯	◯	◯
IT Knowledge	◯	◯	◯	◯	◯
Technology strategy (e.g., cyber security)	◯	◯	◯	◯	◯
Networking & Integration	◯	◯	◯	◯	◯

Realizing available resources for digitization	◯	◯	◯	◯	◯
Roadmap for I4.0	◯	◯	◯	◯	◯
Implementing I4.0 roadmap	◯	◯	◯	◯	◯

3. **Smart factory** *

Is designed to create a highly automated and efficient production environment. This includes advanced equipment infrastructure, IT systems such as ERP and MES, digitized machines, traceability of final products and raw materials, energy management to monitor and control energy consumption, automation through automated identification and industrial robots, M2M communication, virtualization using AI for maintenance and production, and flexibilization with a flexible production

	Strongly agree	Neither agree nor disagree	Strongly disagree	Disagree	Agree
Automated production environment	◯	◯	◯	◯	◯
Equipment infrastructure	◯	◯	◯	◯	◯
IT systems	◯	◯	◯	◯	◯
VI (ERP, MES, Digitized machines)	◯	◯	◯	◯	◯
Energy Management (Energy consumption, Energy monitoring)	◯	◯	◯	◯	◯
Automation (automated identification, industrial robots, M2M communication)	◯	◯	◯	◯	◯
Virtualization (AI for maintenance, AI for production)	◯	◯	◯	◯	◯
Flexibilization (Flexible line, additive manufacturing)	◯	◯	◯	◯	◯

4. **Smart Operation** *

Focuses on achieving seamless integration between virtual and physical aspects, such as sharing information, utilizing cloud technology, ensuring IT security, decentralizing processes, employing modelling and simulation techniques, promoting interdepartmental communication, and utilizing data analytics

	Strongly agree	Neither agree nor disagree	Strongly disagree	Disagree	Agree
Information Sharing	○	○	○	○	○
Cloud usage	○	○	○	○	○
IT security	○	○	○	○	○
Decentralization of processes	○	○	○	○	○
Modeling & simulation	○	○	○	○	○
Interdepartmental collaboration	○	○	○	○	○
Data Analytics	○	○	○	○	○

5. **Smart Products** *

Are designed to streamline and optimize production management using advanced technology, such as ICT features. These functions include self-reporting, identification, localization, online presence, integrated customer management, customized products, and data processing

	Strongly agree	Neither agree nor disagree	Strongly disagree	Disagree	Agree
New data driven services (e.g., self-reporting, identification, localization)	◯	◯	◯	◯	◯
Online presence	◯	◯	◯	◯	◯
Integrated customer management	◯	◯	◯	◯	◯
Customized products	◯	◯	◯	◯	◯
Digitization of products/services systems	◯	◯	◯	◯	◯
Product integration	◯	◯	◯	◯	◯
Define roadmap for smart products.	◯	◯	◯	◯	◯
Data processing	◯	◯	◯	◯	◯
R&D	◯	◯	◯	◯	◯

6. **Employees** *

Play a crucial role in achieving digital transformation by enhancing their awareness, technical abilities, and participating in relevant training. This includes developing digital skills, improving ICT competencies, and fostering openness to new technologies

	Strongly agree	Neither agree nor disagree	Strongly disagree	Disagree	Agree
Digital skills	◯	◯	◯	◯	◯
ICT competences of employees	◯	◯	◯	◯	◯
Openness of employees to new technology	◯	◯	◯	◯	◯

7. **Leadership Management** *

Focuses on enhancing management strategies, such as managing digital competences and processes, establishing central coordination for I4.0 strategy, and integrating leadership and strategy

	Strongly agree	Neither agree nor disagree	Strongly disagree	Disagree	Agree
Management of digital competences & methods	◯	◯	◯	◯	◯
Existence of central coordination for I4.0 strategy	◯	◯	◯	◯	◯
Leadership & strategy	◯	◯	◯	◯	◯

8. **Customers** *

The objective is to enhance the utilization of client data, digitize sales and services, and improve customers' digital media competencies

	Strongly agree	Neither agree nor disagree	Strongly disagree	Disagree	Agree
Utilization of customer data	◯	◯	◯	◯	◯
Digitization of sales/services	◯	◯	◯	◯	◯
Customers digital media competences	◯	◯	◯	◯	◯

9. **Culture** *

Refers to a mindset that is receptive to change, embraces new ideas, encourages working together, and promotes the exchange of knowledge

	Strongly agree	Neither agree nor disagree	Strongly disagree	Disagree	Agree
Knowledge sharing	◯	◯	◯	◯	◯
Open innovation	◯	◯	◯	◯	◯
Supply chain Collaboration	◯	◯	◯	◯	◯
ICT value inside the company	◯	◯	◯	◯	◯
Democratic leadership	◯	◯	◯	◯	◯

10. **Technology** *

Refers to the existence of advanced technologies like IoT, CPS, Cloud-computing, etc.,

	Strongly agree	Neither agree nor disagree	Strongly disagree	Disagree	Agree
Existence of modern ICT (IoT, CPS, BDA, cloud-computing, adaptive robotics, AI, embedded sys, additive manufacturing, sensors & actuators, RFID)	◯	◯	◯	◯	◯
Utilization of mobile devices	◯	◯	◯	◯	◯
ICT integration (VI&HI)	◯	◯	◯	◯	◯
Cyber-security	◯	◯	◯	◯	◯

11. **Data governance** *

Refers to the existence of BDA, data collection and usage

	Strongly agree	Neither agree nor disagree	Strongly disagree	Disagree	Agree
BDA	◯	◯	◯	◯	◯
Data collection and usage	◯	◯	◯	◯	◯

12. **Information systems** *

Refers to the existence of IS that allows data analysis, cloud-usage, etc

	Strongly agree	Neither agree nor disagree	Strongly disagree	Disagree	Agree
Data analysis	◯	◯	◯	◯	◯
Contextualized data delivery	◯	◯	◯	◯	◯
Resilient IT infrastructure	◯	◯	◯	◯	◯
IT security	◯	◯	◯	◯	◯

APPENDIX H - DELPHI-SURVEY: SECOND ROUND MEAN SCORE RESULTS

#	Dimension	Exemplary Maturity Items	Mean Average
1	Organizational strategy	• Organizational level (strategy, structure, management, resources allocation, digital awareness, integrated departments) • IT Knowledge • Realizing available resources for digitization	• 4.47 • 4.42 • 4
2	Smart factory	• Automated Production Environment • Equipment Infrastructure • IT systems • VI (ERP, MES, Digitized machines) • Traceability (final products, raw materials) • Energy Management (Energy consumption, Energy monitoring)	• 4 • 4.26 • 4.36 • 4.78 • 4.05 • 4
3	Smart operations	• Cloud usage • IT security • Interdepartmental Collaboration • Data Analytics	• 4.26 • 4.05 • 4 • 4
4	Smart products	• New data driven services (e.g., self-reporting, identification, localization) • Online presence • Integrated customer management • Customized products • Digitization of products/services systems • Data processing • R&D	• 4.21 • 4.47 • 4.10 • 4.05 • 4.05 • 4 • 4.15
5	Employees	• Digital skills	• 4
6	Leadership Management	• Management of digital competences	• 4.05
7	Customers	• Utilization of customer data • Digitization of sales/services • Customers digital media competences	• 4.05 • 4.15 • 4.15
8	Culture	• Open to innovation • Supply chain Collaboration	• 4.10 • 4.05
9	Technology	• Utilization of mobile devices • ICT integration (VI&HI)	• 4.5 • 4.05
10	Information systems	• Data analysis • Resilient IT infrastructure • Protection of intellectual property	• 4 • 4 • 4