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A Framework for Industry 4.0 Readiness and Maturity of Smart Manufacturing Enterprises: A Case Study

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Abstract: Recently, researchers have proposed various maturity models (MMs) for assessing Industry 4.0 (I4.0) adoption; however, few have proposed a readiness framework (F/W) integrated with technology forecasting (TF) to evaluate the growth of I4.0 adoption and consequently provide a roadmap for the implementation of I4.0 for smart manufacturing enterprises. The aims of this study were (1) to review the research related to existing I4.0 MMs and F/Ws; (2) to propose a modular MM with four dimensions, five levels, 60 second-level dimensions, and 246 sub-dimensions, and a generic F/W with four layers and seven hierarchy levels; and (3) to conduct a survey-based case study of an automobile parts manufacturing enterprise by applying the MM and F/W to assess the I4.0 adoption level and TF model to anticipate the growth of I4.0. MM and F/W integrated with TF provides insight into the current situation and growth of the enterprise regarding I4.0 adoption, by identifying the gap areas, and provide a foundation for I4.0 integration. Case study findings show that the enterprise's overall maturity score is 2.73 out of 5.00, and the forecasted year of full integration of I4.0 is between 2031 and 2034 depending upon the policy decisions.

Keywords: reference framework; industry 4.0; smart manufacturing; technology forecasting; maturity model; operator 4.0; factory 4.0; management 4.0; logistics 4.0

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1. Introduction

Industry has progressed through three major revolutions, each contributing momentous transformations in various facets of manufacturing and thus providing enormous benefits for humankind and societies [1,2] Four different industrial revolutions can be found in the literature, as presented in Figure 1.

The term Industry 4.0 (I4.0) comes from a project in the high-tech strategy of the German government aimed at stimulating the digitalization of manufacturing and supporting small and medium-sized enterprises (SMEs), helping them to exploit I4.0 strategies in terms of standardization and norms, security, legal frameworks, research, and workforce transformation [3]. The I4.0 abbreviation is generally used to refer to the Industry 4.0 term in academic research [4–7]. The concept of I4.0 is envisioned as the significance of the interconnectivity between the departments of an organization. I4.0 is more about intelligent manufacturing systems such as self-adapting processes and real-time communication, which go beyond traditional automation [8]. The I4.0 vision manages the value chain across the product lifecycle. It also involves ordering, development, production, and providing customized product demands. Real-time monitoring availability of all relevant information through the connection of all objects in the value chain allows precise predictions about the capacity to determine the optimal value flow. Based on the predictions, operations can be optimized according to various criteria such as cost, availability, and resource consumption [9].

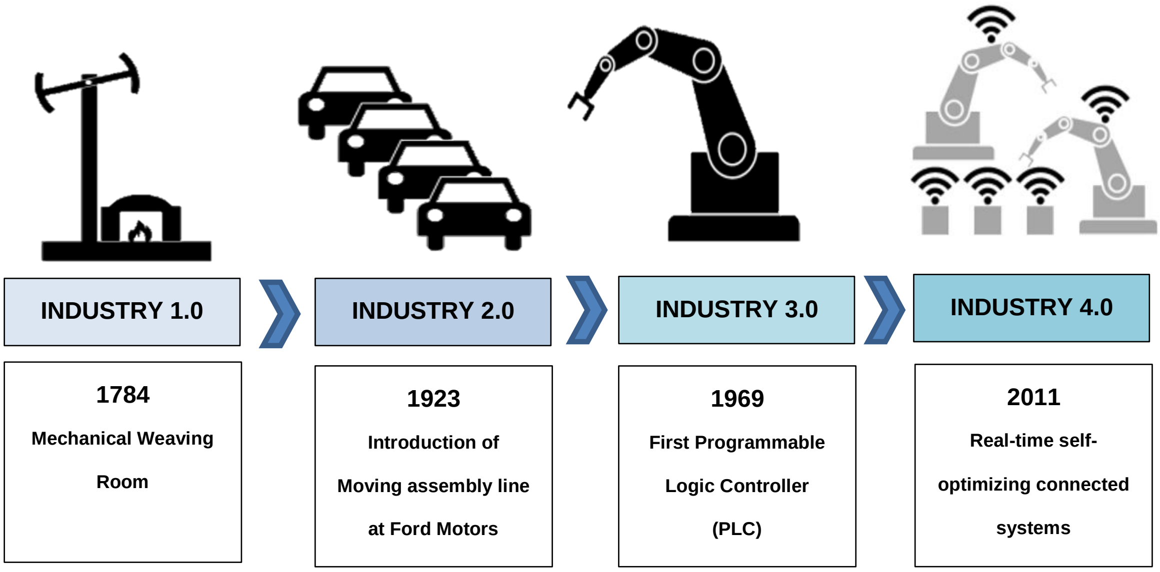

Figure 1. Industrial revolutions.

To further understand the technological requirements for manufacturing enterprises to become (I4.0) recognized, the nine I4.0 pillars [10], (1) autonomous robots, (2) simulation, (3) horizontal and vertical system integration, (4) industrial internet of things (IIoT), (5) cybersecurity, (6) additive manufacturing, (7) augmented reality, (8) big data analytics, and (9) cloud computing, are used to demonstrate how SMEs should incorporate emerging technologies to become automated, autonomous, and optimized [11]. Managerial capabilities of industrial processes play an essential role in the enterprise strategy of I4.0 in terms of monitoring, control, optimization, and autonomy [12]. Companies are overwhelmed and seem incapable of designing effective execution plans given recent changes in the technological transition to smart factories and the I4.0 revolution [13]. I4.0 advances where the internet and nine I4.0 pillars serve as a backbone to integrate physical objects, human actors, intelligent machines, production lines, and processes across organizational boundaries to form [14]. Each enterprise should determine the conditions and individual specifications, then pick the I4.0 principles that provide the greatest chances of fulfilling the objectives [15]. Therefore, there is a need to create effective models and instruments to determine the existing state or maturity of technological advances in manufacturing organizations, as well as to apply Industry 4.0 principles depending on their suitability for a specific enterprise [16].

Expertise, awareness, and readiness in the industry are lacking in terms of the growth and advances in technology [17]. Furthermore, TF has not been integrated with any framework, maturity model, or reference framework to assess and evaluate I4.0 adoption. Although Industry 4.0 vision is well-explained in the literature, there is less consideration paid to the integration of I4.0 and proposing a framework toward the I4.0 revolution for smart manufacturing enterprises. Therefore, research studies have not provided a bridge or link between academia and real-world businesses. None of the studied maturity models in the literature fully meet all the criteria of scope, purpose, completeness, clarity, and objectivity.

In this context, we aimed (1) to review the research related to existing I4.0 maturity modes (MMs) and frameworks (F/Ws); (2) to propose a modular MM with four dimensions, five levels, 60 second-level dimensions, and 246 subdimensions, and a generic F/W with four layers and seven hierarchy levels; (3) to conduct a case study by applying the proposed MM and F/W to assess and measure the I4.0 adoption of an automobile parts manufacturing enterprise; and (4) to apply the technology forecasting (TF) model to anticipate the growth in I4.0 for the enterprise. The proposed MM and F/W integrated with TF deliver insight into the current situation and the growth of a smart manufacturing enterprise toward I4.0 adoption, helping to explicitly identify the gap areas and to provide the foundation for policy decisions toward I4.0 integration to maximize the potential of I4.0. UNIDO [18] explained the policy interventions using three categories; (1) developing framework conditions through investments in infrastructure and suitable institutional and economic environments; (2) fostering specific I4.0 enabling factors through dedicated programs, facilities, and incentives mechanisms; and (3) enhancing vocational training and higher education programs around I4.0-related competencies in ways that anticipate the implications of I4.0 on skills, employability, and the functioning of education systems.

The remainder of this paper is structured as follows: Section 2 explains the existing maturity models (MMs) and frameworks (F/W) in the literature. Section 3 presents the research methodology; the proposed maturity model including dimensions, levels, and subdimensions; the proposed framework including layers, hierarchy levels, and life cycle value stream; and the selected technology forecasting growth models. Next, Section 4 presents the application of the proposed MM, F/W, and TF to a large automobile parts manufacturing enterprise as a case study. Section 5 presents the discussion of the results of the case study, and Section 6 provides the outcomes of the paper and describes future research guidelines.

2. Existing Maturity Models and Frameworks

2.1. Industry 4.0: Maturity Models

Presently, large enterprises in developed countries have already completed their transition to I4.0 or are in the transformation stage. Many researchers have highlighted the importance of I4.0 technologies in manufacturing systems [11,17,19–25]. To understand the awareness and readiness of a country to undertake industrial revolution, surveys and analyses are required. Therefore, the maturity model methodology can be used to observe the readiness of a country or organization for the I4.0 revolution. In general, maturity is described as a state of being complete, ideal, or ready [26]. The capabilities of technological and organizational studies can be increased over time by maturing the systems. Maturity models (MMs) are commonly used as a method to indicate the maturity of a process or an organization. Maturity may be measured discretely or continuously, qualitatively or quantitatively [27]. Readiness and maturity can be distinguished from each other: readiness assessment is required before engaging in the maturing process, whereas maturity assessment aims to capture the as-is state during the maturing process.

Gökalp et al. [28] analyzed seven MMs according to scope, objective, completeness, and clarity. Existing MMs in terms of origin, institution, approach, and structure have been analyzed in this study. To assess Turkey's readiness, Akdil et al. [29] introduced a novel maturity model focused on three dimensions: services, strategy and organization, and smart business processes and smart products, and four levels: level 0 = absence, level 1 = life, level 2 = survival, and level 3 = maturity. They also conducted a survey of companies to understand their current state of technology for I4.0, in which human resources, smart marketing, and smart finance were recognized as key contributors to increasing companies' perspectives on I4.0. The operator role in the context of I4.0 was defined by [30]. Temur et al. [31] reviewed I4.0 readiness level evaluation methodologies and applied the IMPULS MM to three different Turkish manufacturers in terms of operational and socioeconomic perspectives from various industrial sectors. They concluded that manufacturers have failed to create road maps as well as new workforce planning strategies in the I4.0 revolution.

Bauer and Horváth [32] stated that I4.0 technologies significantly influence Germany's gross domestic product (GDP), providing an expected increase of 23% (EUR 78.77 billion) in the years between 2013 and 2025. In this context, smart manufacturing enterprises should try to reshape their operations in line with the I4.0 technologies to prevent losing competitiveness. I4.0 technologies are in their early phases of growth. Therefore, it is critical to define a strong structure and a clear methodology as application guidelines toward the I4.0 revolution [28]. The method to provide comprehensive guidance and introduce a road map is organizational approaches such as frameworks or MMs. The MM is a tool that provides an assessment of the current effectiveness of the system. In other words, MMs are used to define the level of a system's effectiveness within the context of I4.0 technologies. Accordingly, as the degree of the system's maturity increases, better progress is occurring in various characteristics that contribute to the enterprise's maturation. MM levels and dimensions are used to define the degree of a system's maturity.

Existing MMs in terms of origin, institution, approach, and structure have been analyzed in Table 1; all maturity models under study have some common features and a common goal, yet they have some uniqueness in their approaches according to the definition and number of levels and dimensions. An exclusive MM for the assessment of the adoption of I4.0 is urgently needed because of its unique social and cultural challenges and constraints. The proposed MM can be conducted internationally for all sizes of enterprises [14]. Furthermore, the incorporation of TF anticipated novelty.

Table 1. Current maturity models (MMs) in the sense of I4.0.

Maturity Model	Origin	Institution/Source	Assessment Approach	Levels/Dimensions/Items
The Connected Enterprise Maturity Model [33]	USA	Rockwell Automation	A five-stage approach to identifying I4.0; technology assessment has four dimensions and five5 levels	Five levels and four dimensions, no details about items
IMPULS [1]—Industry4.0 Readiness [34]	DE	Manufacturing enterprises	IMPULS MM is developed by a German aircraft manufacturer that specialized in beginner and flight training hang gliders	Six levels, six dimensions, eighteen items
RAMI4.0 [35]	DE	Society for measurement, automation, and technology	The Reference Architecture Model Industry (RAMI 4.0) MM has a three-dimensional structure that shows how to approach I4.0	Six levels, seven dimensions, no details about items
Digital Maturity and Transformation [36]	CH	Manufacturing enterprises	Contains nine dimensions: Product innovation, Information Technology (IT), process digitalization, culture and expertise, customer experience, product innovation, strategy, organization, collaboration, transformation management	Nine dimensions, no details about levels and items
I4.0 Reifegradmodell [37]	DE	FH—Oberösterreich	Assessment of maturity; no details for items and development of this maturity model is not finished yet	Ten levels, three dimensions, thirteen items
Empowerment and Implementation Strategies for I4.0 [38]	DE	Stator assembly for an electrical drive with 30 single teeth and a housing	Assessment of I4.0 MM is used to quickly check and realize a part of a process model	No details about levels, dimensions, or items
MM for Industrial Internet [39]	FI	Heavy-equipment manufacturing industries	Provides systematic design guidelines for industrial internet maturity model for mass production manufacturing industries	No details about levels, dimensions, or items
A Categorical Framework of Manufacturing for I4.0 [40]	U.K.	Manufacturing enterprises	The five levels contain four dimensions: factory, business, products, and customers	Five levels, four dimensions, no details about items

Table 1. *Cont.*

Maturity Model	Origin	Institution/Source	Assessment Approach	Levels/Dimensions/Items
I4.0/Digital Operations Self-Assessment [41]	DE	PricewaterhouseCoopers	Online self-assessment with seven dimensions split into three stages of digital maturity; three of the six maturity dimensions require the use of a consultancy instrument.	Three levels, six dimensions, no details about items
SIMMI 4.0 [42]	DE	-	System Integration Maturity Model Industry 4.0 (SIMMI 4.0) has no exploratory case study has been conducted	Five levels, four dimensions, no details about items
A Maturity Model for Assessing I4.0 Readiness [14]	DE	Manufacturing enterprises	Readiness and maturity model specifically used to evaluate readiness and maturity of manufacturing enterprises	Five levels, nine dimensions, sixty-two items
ACATECH I4.0 Maturity Index [43]	DE	ACATECH, National Academy of Science and Engineering	Value-based development stages presented in the model	Six dimensions, no details about levels or items
SPICE-based I4.0 MM [28]	TR	No exploratory case study	Software Process Improvement Capability Determination (SPACE)-based I4.0 MM evaluates system maturity in light of I4.0	Six levels, nine dimensions, no details about items
DREAMY [44]	I	Manufacturing enterprises	Digital Readiness Assessment MM (DREAMY) used to help manufacturing enterprises to create a roadmap for I4.0 integration	Five levels, six dimensions, no details about items
The University of Warwick (WMG) MM [45]	U.K.	Crimson & Co., Pinsent Masons	Online self-assessment provided for this model to evaluate maturity of the company	Four levels, six dimensions, fifty-three items
Maturity and Readiness Model for I4.0 [29]	TR	Retail company operating in Turkey	Measures companies' maturity and business levels	Four levels, three dimensions, thirteen items
MM for assessing the implementation of I4.0 [46]	IN	Auto-component manufacturing	Implemented to real-world companies to validate the model	Five levels/seven dimensions, thirty-six items

[1] IMPULS: German aircraft manufacturer.

We aimed to locate current MMs in the literature to determine the sufficiency of the models in terms of the evaluation of an organization's maturity for the adoption of I4.0 technologies and to identify the MMs' strengths and weaknesses. We found 16 different MMs in the literature, and each of them was reviewed as follows:

Connected Enterprise MM [33]: Connected Enterprise MM was assessed on five maturity levels; however, the MM dimensions of the model were not mentioned, so no information is available regarding MM dimensions or MM items.

IMPULS [34]: The maturity level is influenced by the maturity stage of competitor companies. In other words, the maturity stage of the market is evaluated if other businesses in the same market were involved in the survey; otherwise, they are disregarded.

RAMI 4.0 [35]: The RAMI model has six levels: business, functional, information, communication, integration, and assets; and seven dimensions: product, field device, control device, station, work centers, enterprise, and connected world. This model is used to evaluate the maturity of the system and take actions to complete I4.0 integration. However, there is no information provided regarding items, and the structure does not include the operator role in the I4.0 technologies.

Digital Maturity and Transformation MM [36]: The assessment contains nine dimensions, but there is no information about levels and items. The structure of the model is not presented in their research.

I4.0 Reifegradmodell MM [37]: There are three dimensions and ten levels indicated in this assessment of maturity. There are no details provided for items or development of this maturity model, and it is not yet finished.

Empowerment and Implementation Strategies for I4.0 MM [38]: The maturity evaluation of a company is a limited portion of the analysis of the I4.0 revolution. No full explanations are available in terms of the maturity model's composition or its dimensions and items.

A Categorical Framework of Manufacturing for I4.0 [40]: This is a framework proposed to identify the need for the fourth industrial revolution including five levels: connection, conversion, cyber, cognition, and configuration. Dimensions are defined as: factory, business, products, and customers. However, there are no details about the items or dimensions.

I4.0/Digital Operations Self-Assessment [41]: This is an online self-assessment tool-based MM for I4.0 readiness, with attention specifically paid to digital readiness for I4.0. The model has six dimensions, as presented in Table 1. Dimensions and items are neither presented in their study nor shared with the users.

SIMMI 4.0 [42]: Software and technological aspects of maturity are considered to evaluate the maturity of the business. The organizational (such as company vision and employees) and environmental (such as market structure and competitors) aspects are not considered in the MM.

An MM for Assessing I4.0 Readiness and MM [14]: This MM proposes nine dimensions for the assessment; the dimensions are leadership, culture, technology, strategy, customer, products, people, operations, and governance. The assessment method is based on the Likert-scale rating methodology. The advantage of this model is that is it easy to use for maturity level assessment but only proposes an average ranking without any additional details.

ACATECH I4.0 Maturity Index [43]: Value-based development stages are presented in this model, and the dimensions are identified as computerization, connectivity, visibility, transparency, predictive capacity, and adaptability. However, there are no details about items or levels.

SPICE-based MM [28]: SPICE-based I4.0 MM was proposed to evaluate a system's maturity in terms of I4.0. This model has six levels: incomplete, performed, managed, established, predictable, and optimizing, and has nine dimensions: process performance, performance management, work–product management, process deployment, process definition, process control, process measurement, process innovation, and continuous optimization. No details are available for the items, and the scope of the dimensions does not include data protection or culture impacts for I4.0 integration.

A Maturity Model for Assessing the Digital Readiness [44]: The DREAMY model is used to help manufacturing enterprises to create a road map for I4.0 integration. MM has five levels: initial, managed, defined, integrated and interoperable, and digital-oriented, and five dimensions: process, monitoring, control, technology, and organization. The items are defined in their model. However, the operator role in the context of I4.0 is not included in this model, as no related items were found in the structure of the model. It does not provide an action plan to overcome weaknesses in full I4.0 integration.

WMG MM [45]: The WMG model provides a practical method to assess companies' readiness and adoption for the cyber–physical age. Dimensions of the model are defined as supply chain, products and services, manufacturing and operations, business model, strategy and organization, and legal considerations. The levels are beginner, intermediate, experienced, and expert. In this study, 53 responses from 22 different countries were evaluated [45].

Maturity and Readiness Model for I4.0 [47]: Mettler's architecture was used to construct this MM [48]. In the context of the industrial internet, the analysis establishes a concept guideline for maturity modeling. This model cannot be evaluated as a complete assessment, since the research is not yet completed.

Our literature review can be summarized as showing an increase in the number of publications related to I4.0 in the past couple of years [28]. Due to a lack of study on the use of maturity models in the sense of I4.0, a research void was identified. Sixteen maturity models were analyzed, and we concluded that none of them fully cover all the criteria of scope, fitness for purpose, completeness, clarity, and objectivity. Thus, no previous study has considered all the criteria available, so this research is unique, as we considered all the criteria. The MMs are presented in Table 2 based on specific criteria.

Table 2. Summary of MMs. N-A, P-A, L-A, and F-A represent not achieved, partially achieved, largely achieved, and fully achieved, respectively.

Maturity Models	**Reference**	**Fitness of Purpose**	**Completeness**	**Dimension Granularity**	**Measurement Attribute**	**Complete Method**	**Objectivity**
The Connected Enterprise	[33]	N-A	P-A	N-A	N-A	N-A	N-A
IMPULS	[34]	P-A	P-A	P-A	L-A	F-A	L-A
RAMI 4.0	[35]	L-A	P-A	L-A	N-A	F-A	L-A
Digital Maturity	[36]	P-A	L-A	P-A	P-A	P-A	P-A
I4.0 Reifegradmodell	[37]	P-A	P-A	P-A	L-A	F-A	L-A
I4.0 Empowerment and Implementation Strategies	[38]	N-A	N-A	N-A	N-A	N-A	N-A
MM for Industrial Network	[39]	N-A	N-A	N-A	N-A	N-A	N-A
A categorical Framework of Manufacturing for I4.0	[40]	N-A	N-A	N-A	N-A	N-A	N-A
I4.0/Digital operations Self-Assessment	[41]	P-A	P-A	P-A	P-A	N-A	P-A
SIMMI 4.0	[42]	P-A	P-A	P-A	P-A	L-A	P-A
An MM for Assessing I4.0 Readiness and Maturity	[14]	P-A	P-A	P-A	P-A	P-A	P-A
ACATECH I4.0 Maturity Index	[43]	P-A	P-A	N-A	N-A	N-A	P-A
SPICE-based MM	[28]	P-A	L-A	L-A	P-A	F-A	L-A
DREAMY MM	[44]	P-A	P-A	P-A	P-A	N-A	P-A
WMG MM	[45]	P-A	P-A	L-A	P-A	F-A	L-A
Maturity and readiness model for I4.0	[29]	P-A	N-A	N-A	N-A	N-A	N-A

2.2. Industry 4.0: Standards and Frameworks

I4.0 fundamentally refers to the integration of virtual environments with real operations, so engineering, logistics, and IT must work together smoothly [49]. However, an efficient, effective, and rapid transformation and adaption of I4.0 is not possible without the standardization of products and processes across the globe [50]. There is a need to develop a common model of reference whose implementation would allow interaction among all interested parties and interconnection of the most diverse technology in use. This can be accomplished by using a structured architecture that frames and integrates the principles, axioms, interactions, and specifications as a direction of mutual contact between all entities [51]. In terms of a reference architecture, a framework describes how a collection of structures and relationships allows a set of predetermined specifications to be met and can provide recommendations in the form of best practices [51]. Existing F/W models in terms of architecture, I4.0 technology, layers, levels, and life cycle value stream have been analyzed in this study.

The RAMI 4.0 model originated in Germany and meets the DIN SPEC 91345 standard, developed as an initial compilation of the vital technological elements of I4.0. It is seen as a requirement for implementing the I4.0 definition, as well as a paradigm that needs global acceptance [50]. The RAMI 4.0 model was developed by BITCOM (Germany's Digital Association), VDMA (Germany's Engineering Industry Association), and ZWEI (Germany's Electrical Industry). It is based on the globally established Smart Grid Architecture Model (SGAM), which was launched in 2014, but with two additional bottom layers to address unique I4.0 aspects [52]. SGAM was originally envisaged and established for coordination in green energy source networks. The RAMI 4.0 model is a slight upgrade of the SGAM [53]. The three-dimensional RAMI 4.0 maturity model aims to identify existing standards, identify gaps, and eliminate loopholes in the existing standards.

New standards are being created by standardization organizations. Based on standards, architecture models are created to provide guidelines and standards for institutions toward the Industry 4.0 revolution. The CEN-CENELEC-ETSI Smart Grid Coordination Group [54] established an architecture model used for network communication in the scope of I4.0 applications.

Integrated Information Infrastructure Reference Model (I3RM) was proposed for digital manufacturing platforms [55]. This model was created by combining different reference models to support the architecture of digital manufacturing platforms in practical use cases. Computer Integrated Manufacturing Open System Architecture (CIMOSA) is an architecture based on an event-driven approach to model company processes in a virtual world [56]. International Society of Automation (ISA) 95 is an architecture paradigm that recognizes the need for industrial transition and offers guidelines focused on its own hierarchical structures of production processes to simplify the convergence of business functions and control systems [38].

The National Institute of Standards and Technology (NIST) [57] helps the smart manufacturing vision cope with the challenges of the I4.0 revolution that manufacturers have been experiencing in terms of quality, efficiency, and customized production. The architecture model was proposed for small- and medium-sized enterprises to integrate I4.0 and its standards to gain benefit from conformance testing, public documentation, and reference software implementations. Intelligent Manufacturing System Architecture (IMSA) [58] was developed to foster standardization by guiding the upgrade of Chinese manufacturing toward the I4.0 revolution. The smart manufacturing concept includes the implementation of machinery, new materials, new information technology, novel equipment, and numerical control tools as crucial characteristics to aid in the growth of China's economy. IMSA is a guideline for constructing standards for manufacturing processes.

Industrial Internet Reference Architecture (IIRA) [47] was issued for the first time in 2015 by the Industrial Internet Consortium (IIC). The Industrial Internet of Things (IIoT)-based reference model is used to design smart systems in accordance with the ISO 42010 standard by employing a standard lexicon and a standardized framework [55]. Existing F/W models are listed in Table 3.

Based on the analyzed framework models literature, two major concerns are emphasized: the first is a lack of instructions for defining the areas that need to be tackled to implement I4.0, and the second is a lack of knowledge about how to practically implement I4.0 after the areas have been defined. These two concerns lead to disruption between academia and industry. To provide a generic framework that is applicable to real-world industries, the following questions should be answered by the framework: where should we start implementing I4.0? How can a roadmap toward industrial revolution be created? Therefore, a generic framework model is required for practical uses; a generic framework should be in line with modular maturity model dimensions and items.

Table 3. Existing architecture models that guide the digital transformation of companies according to standards.

Architecture	I4.0 Technology	Architecture Layers	Architecture Levels	Life-Cycle Value Stream
CIMOS [56]	IT Human–Machine Integration	Organization Resource Information Function	Generic Partial Particular	Requirement Definition Model Design Specification Model Implementation Description Model
RAMI 4.0 [35]	Smart Mobility Smart Devices Smart Grid	Business Functional Information Communication Integration Asset	Product Field Device Control Device Station Work Centers Enterprise Connected World	Development Production
NIST [57]	Cloud Computing Interoperability Cybersecurity Internet of Things (IoT)	Privacy Security Cloud Services Management Service Orchestration Service Deployment	Application Middleware Operating System	Cloud Carrier Cloud Broker Cloud Provider Cloud Auditor Cloud Consumer
The National Institute of Standards and Technology Architecture [59]	Smart Manufacturing Cloud Computing	Cloud Transformation Model Ecosystem Manufacturing System	Product Production Business	-
IMSA [58]	Connectivity Cybersecurity	New Business Patterns Information Fusion Interconnection System Integration Resource Elements	Equipment Control Workshop Enterprise Cooperation	Design Manufacture Logistics Sale Service
IIRA [47]	Cloud computing Containerization Infrastructure-as-a-Service (IaaS) Platform-as-a-Service (PaaS)	Business Usage Functional Implementation	Manufacturing Transportation Energy Healthcare Retail Smart Factory	Disposal Evaluation Operation Deployment Test/Validation Build Development Prototyping/Design Requirement Conceptualization
IBM Industry 4.0 Reference Architecture [60]	Cybersecurity Cloud Computing	Equipment/Device Platform (Hybrid Cloud) Enterprise IT	Data Security Knowledge Devices Service Quality Network Configuration	Edge Plant Enterprise
SGAM [54]	Smart Grid	Business Function Information Communication Component	Market Enterprise Operation Station Field Process	Customer Premises Distributed Electrical Resources Distribution Transmission Generation

2.3. Technology Forecasting Applications

Modern technological inventions increase the demand for TF tools. The prime motivations for Technological Forecasting summarized by [61] are listed:

1. Guidance of resource allocation

2. Identification of market opportunities or threats
3. Guidance of staff, facilities, or capital planning
4. Development of strategies or policies
5. Assistance with R&D management
6. Evaluation of new products
7. Maximize gain or minimize loss due to internal or external elements of the organization

TF can be used for both quantitative or qualitative studies. These studies offer an auxiliary role to managers, and they are required to choose the use of quantitative or qualitative methods. In general, the life cycle of a product or a service displays a bell-shaped curve, and this curve consists of five parts: innovators, tornado, main street, decline, and obsolescence. Similarly, the technology adoption life cycle is divided into five parts: innovators, early majority, late majority, and laggards [62]. Hence, the growth of adopters in new products or services can look like a sigmoid curve. Some TF approaches can be a tool to fit and forecast a trend, e.g., Fisher-Pry and Gompertz. However, many existing models are adapted, or new models are developed in the literature [63]. These approaches can fit data sets reasonably well in some specific products or services, such as the rate of mobile phone adoption, and represent the trend of a new product or a service.

Frank et al. [64] applied the modified logistic model to forecast wireless communications, and Vanston [65] implemented the Fisher-Pry and Gompertz models to forecast the use of residual broadbands. TF often utilizes the "S" curve to direct the phases at which technologies grow from initial adoption to development and then maturity [66]. To understanding technological trends and have insights on the adoption of I4.0 technologies, TF models are utilized to generate forecasts that help in developing a better understanding of how technologies develop in markets. This, in turn, assists decision-makers and company managers to understand the potential of certain technologies for their businesses. According to [66], TF can be classified into five families: monitoring, expert opinion, trend extrapolation, modeling, and scenarios. Table 4 elaborates the advantages, limitations, and usages of each approach. A suitable technology growth forecasting model should be adopted to predict the growth of I4.0 technologies.

Table 4. Comparison of technological forecasting methods.

	Strengths	Weaknesses	Uses
Monitoring	Providing large useful information.	Information overload happened without selections.	To provide useful information for structuring a forecast.
Expert Opinion	Tapping high-quality models internalized by experts	Identifying experts is difficult and some extraneous factors will affect experts.	To forecast when experts in this field exist and where data are lacking.
Trend Analysis	A substantial and data-based forecast of quantifiable parameters.	It requires good and enough effective data and it did not explicitly address the causal mechanisms.	To project quantifiable parameters, and analyze adoption and substitutions of technologies.
Modeling	Simplifying the future behavior of complex systems. Building process provides good insight into complex system behavior.	Models that are not heavily data-based may be misleading.	To reduce the complex systems to manageable representations.
Scenarios	It can portrait the possible futures explicitly and incorporate qualitative and quantitative information produced by others.	It may be more fantasy than forecast, unless a firm basis in reality is maintained by the forecasters.	To integrate quantitative and qualitative information and to integrate forecasts from various sources. To provide a forecast when data are too weak to use other methods.

3. Research Methodology

Various strategies can be implemented in research including surveys, case studies, experiments, grounded theory, action research, archival research, narrative inquiry, and ethnography, each having its own characteristics, application context, and practicability according to the research objectives [67]. Our overall research methodology included literature surveys, primary data acquisition through questionnaires, and data analysis. A quantitative survey-based inductive approach was adopted. As this research was initiated to explore the adoption of I4.0 for smart manufacturing enterprises, the nature of this research was both exploratory and explanatory. The research approach is visualized in Figure 2.

Figure 2. Inductive approach processes.

A quantitative research strategy involves the collection of data through surveys, questionnaires, and experiments; these collected data are followed by mathematical, statistical, and numerical analyses, which aim to generalize the given results across diverse participants to address the specific phenomena [68]. In quantitative research, data are normally collected through survey questionnaires, which are commonly known and easy to understand. In addition, using surveys can be helpful for the researcher, as they provide the opportunity to access several sources of information at minimum cost [69]. Questionnaires can generate a large amount of data in a short time, which make them appropriate to use with managers who may not be able to participate in other research methods. The main disadvantage of questionnaires is the low response rate, which may lead to difficulties in assessing whether the obtained sample size is representative of the phenomenon under study [70]. For instance, Coatney and Poliak [21] studied the outcomes of an exploratory review of the current research related to I4.0 in manufacturing systems using a survey. Horick [19] conducted a survey-based study to evaluate and analyze I4.0 production networks.

In this research, the case study approach was adopted to test the proposed MM and F/W with TF for a large automobile parts manufacturing enterprise. A similar approach to test the MMs was adopted by [14,71–73]. Our research methods are explained as a plan in Figure 3. The study started with a review of the literature based on Industry 4.0 MMs and F/Ws. The findings from the literature led to the development of a new maturity model to fill the research gap, which was explained in the Introduction. To find inputs to evaluate the proposed maturity model, a survey was developed based on a quantitative study. From the respondents, the required data were collected via the survey.

The questionnaire was designed based on the proposed maturity model and framework. The participants comprised experts from various fields and management levels working for an automotive parts manufacturing enterprise. The questionnaire was designed in the Survey Monkey platform as an online survey. Ethical approval was obtained from the Eastern Mediterranean University (EMU) Ethics Committee, and their valuable suggestions and comments were considered before disseminating the survey. The participants were informed about the scope of the research, and their identities were kept anonymous. Data analysis was performed to determine the level of awareness and maturity in the fourth industrial revolution. Based on the collected data, the Gompertz growth model and a logistic growth model were applied to forecast the technological expectations in the coming years.

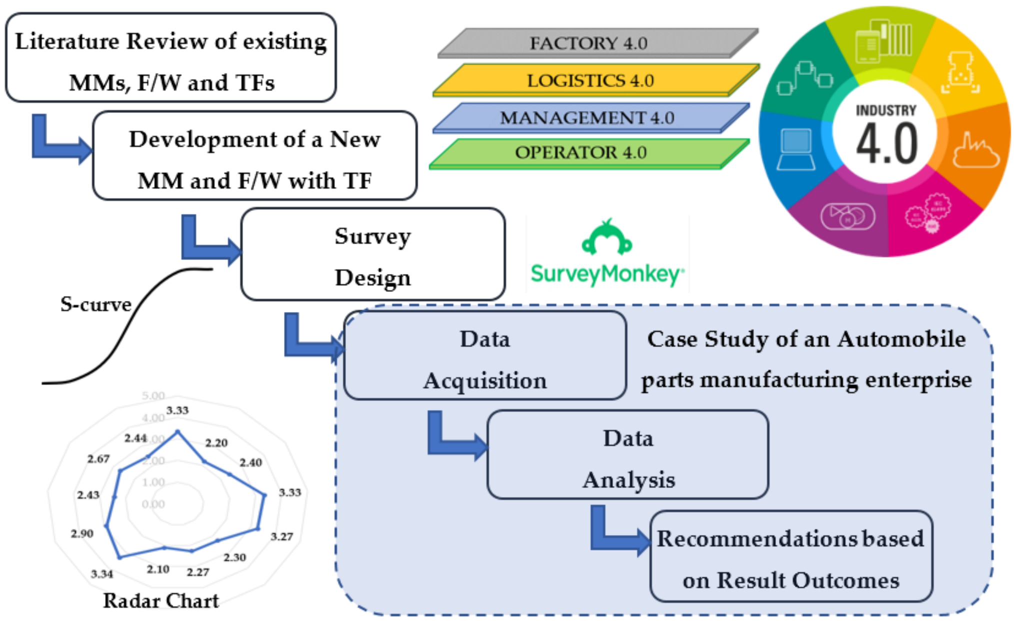

Figure 3. Research methodology.

3.1. Proposed Maturity Model

Based on the literature, the next step was to explore the literature to identify an appropriate maturity model. However, the existing maturity models include little information on mechanism, structure, and evaluation technique creation. The operator role in I4.0 is insufficiently mentioned in existing MMs, because the design of a readiness maturity model requires the evaluation of the readiness and maturity of an enterprise. A novel I4.0 MM was constructed, placing heavy emphasis on operational dimensions, seeking to expand current models and resources. The concept of the proposed MM was designed to evaluate I4.0 maturity for real-world manufacturing enterprises, and this generic maturity model can be adapted to any size of enterprises. The model details, structure, and assessment procedure ensure transparency for the enterprises applying the proposed model.

Subdimensions delineate the thematic focus of the assessment model and cover a wide range of subject matter inquiries about the introduction of I4.0 technologies [74]. Each dimension of an MM is subdivided into more detailed aspects with a scoring scheme, and each aspect is measured and aggregated on a dimensional level [75]. The proposed maturity model was subjected to the MM assessment flow diagram presented in Figure 4, which consists of four levels of Industry 4.0 readiness. They have explicit statements of what needs to be achieved to reach that particular level of readiness for each sub-dimension [45]. The proposed MM considers four core dimensions, 32 second-level dimensions, and 55 subdimensions. The core dimensions are listed in Table 5.

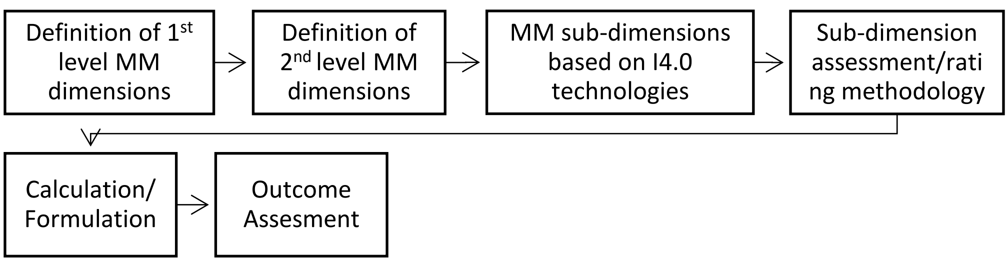

Figure 4. MM assessment flow diagram.

Table 5. Proposed MM dimensions and their scope.

No	MM Dimension	Description
1	Factory 4.0	A concept that refers to a modern factory paradigm that has arisen as a result of the fourth industrial revolution. Mechanization, industrialization, and automation are the predecessors of the first three major developmental processes that are known as revolutions.
2	Logistics 4.0	Use of digital technologies in the supply chain is referred to as Logistics 4.0. The different facets of end-to-end logistics and supply chain management are discussed by Logistics 4.0.
3	Operator 4.0	The primary enabling factor of the resultant Operator 4.0 paradigm focuses on advanced sensors and actuator systems, as well as connectivity solutions.
4	Management 4.0	Applies to I4.0 management paradigms such as the ageing population, resource-effective and clean urban manufacturing, mass customization, growing demand heterogeneity, shorter product life cycle, competitive supply chain, unpredictable economies, and cost-containment pressure.

Factory 4.0 is referred to as the smart factory; this term makes it possible to collect and process data accumulating in the value creation processes in an efficient and future-oriented manner and also enables the product-related forwarding and provision of data for several processes' steps in production [76]. Logistics 4.0 is expressed as a concept to overcome new challenges that have occurred in the logistics sector as a result of the rise of industry 4.0, and these challenges require high technological modifications such as supply chain transparency and integrity control that guarantees the delivery of the products to the right location in right time [77]. Operator 4.0 is a term for an intelligent, skilled operator who performs cooperative work with robots and also aided work by machines in terms of human cyber–physical systems, advanced machine to machine interaction systems, and adaptive automation systems towards achieving human automation symbiosis work systems [78]. Management 4.0 includes the structural characteristics and the internal/external dynamics of the organization and the identification phase of the objectives to be achieved to determine a roadmap to integrate innovative strategies that take into account a company's potential for competitiveness in the market [79].

Table 6 provides a thorough breakdown of the related subdimensions of the corresponding maturity thresholds for each dimension. The MM was created to illustrate the company's long-term priorities and the differences in present and long-term goals. The assessment was developed to be completed as a group as well as individually. It acts as a foundation for furthering the discussion to ensure that companies are taking advantage of the possibilities provided by the I4.0 era.

Table 6. Proposed maturity model dimensions and subdimensions.

1st-Level Dimensions	2nd-Level Dimensions	Subdimensions/I4.0 Concept
Factory 4.0	Technology integration	Agile manufacturing system
		Automated manufacturing and assembly
		Continuous and uninterrupted material flow models
		Plug-in produce
	Autonomous workplace	Self-adapting manufacturing systems
		Autonomous robotics
	Data-driven services	Integrated and digital real-time monitoring systems
		Remote monitoring of products
	Robotics and automation	Smart assistance systems
	Digital modeling	Digital twin
		Computer-aided manufacturing (CAM)
		Additive manufacturing (3D printing)
		Augmented reality
	Big Data	Big data analytics
		Traceability (MES) integration

Table 6. *Cont.*

1st-Level Dimensions	2nd-Level Dimensions	Subdimensions/I4.0 Concept
		Cloud computing
	Machine Learning	Artificial intelligence
	IT-supported business	Industrial internet of things (IIoT)
	Smart Products	Identification and tracking technology
		Customized products
		Digital product-service systems
	Product Design and Development	Product lifecycle management
		Digital and connected workstations
	Communication and Connectivity	Internet of things
		Cyber–physical systems
	Operations	Self-adapting manufacturing systems
Logistics 4.0	Transparency	Automated Material Replenishment (E-Kanban)
	Customers	End-to-end visibility
	Inventory control	Wireless communication
	Supply chain	Vertical and horizontal system integration
		Sustainable supply chain design
		Collaboration network models
	Real-time tracking	Smart sensors
	Warehouse and Storage	Automated storage systems
	Automated scheduling	Smart assistance systems
Operator 4.0	Collaboration	Cultural transformation
	Human resources 4.0	Training 4.0
	Governance	Operator role
	Operator ergonomics	Automated material handling systems
		Collaborative robots
Management 4.0	Leadership and organization	Decentralization
		Predictive maintenance
	Scheduling and maintenance	Tele-maintenance
		Object self-service
	Investments	Real-time process control systems
	Finance	Material requirements planning (MRP)
		Manufacturing resource planning
		Servitization and sharing economy
	Data security	Cybersecurity
	Intellectual property	Copyrights and patents
	Business models 4.0	Digital lock-in
		Freemium
	Standards 4.0	CPS standards
	Innovation strategy	Open innovation
		Strategy 4.0

3.1.1. Factory 4.0

A smart factory is an intelligent, interconnected factory. Completion of I4.0 integration in traditional production allows for distributed and fully automated operations, auto-guided systems through production, and real-time monitoring product operations. These technologies are required in the smart factory environment. Production, supply chain, and logistics are extensively organized without requiring human assistance. The use of cyber–physical systems (CPSs) provides interconnection between virtual environments and physical environments in which I4.0 technologies are effectively used to provide or gather clean data for digital modeling. As such, real-time cross-enterprise collaboration between IT, production, and operators can be provided. Consequently, the accumulated large amounts of data can be used for decision-making models.

3.1.2. Logistics 4.0

Barreto et al. Barreto et al. [80] described Logistics 4.0 using five characteristics: (1) real-time big data analytics (BDA), for instance, optimized routing; (2) autonomous robots with tracking; (3) decision-making or decision support systems; (4) real-time information exchange; and (5) the use of complex systems supported by CPSs. Winkelhaus and Grosse [81] described Logistics 4.0 as the replacement of existing hardware-oriented logistics with software-oriented logistics. To standardize the definition of Logistics 4.0, three aspects are used:

- Change in the production paradigm to mass customization in logistics [82];
- Replacement of existing logistics operations with the new digital technologies, e.g., CPS, IoT, etc.;
- Consideration of human factors and product customization toward changing environments, e.g., employees, customers, and stakeholders.

3.1.3. Operator 4.0

Interactions between operators and machines are crucial in the digital transformation. To provide an intelligent workforce that substantially impacts the nature of work, workers are required to be integrated into I4.0 technologies [83]. Integration can be easier depending on the operator's skills, education level, cultural background, physical ergonomics, and cognitive ergonomics [30]. Otherwise, integration may be challenging. Therefore, the Operator 4.0 concept was created to understand the operator role and related technologies based on human–cyber–physical systems (H-CPSs) to simplify cooperation between machines and humans [83,84].

3.1.4. Management 4.0

The Management 4.0 concept covers the high investment cost and risks associated with the I4.0 technologies (e.g., predictive maintenance, digital twins, etc.). The necessity of new business models including I4.0 technologies was considered [83]. To successfully implement I4.0, investments in new technologies are required. With new technologies, investment costs and service costs can pose challenges. It is conceivable that the client may fail to share the investment costs [83]. These packages can be risky for the organization but also provide the possibility of taking complete advantage of technical competence when designing the system based on the optimal performance of the operation and maintenance [85]. Data processing is used in services and represents a technology-driven market growth approach [86]. Willingness to invest in I4.0 is another critical point for I4.0 integration. Therefore, top management's perspective, technology integration challenges, and benefits need to be considered periodically in strategy meetings.

3.2. Assessment Evaluation

The assessment was designed around five readiness levels as explained in Table 7 using explicit statements about what needs to be done to achieve each subdimension's degree of preparation.

Table 7. Levels and their descriptions.

Levels	Experience	Description
Level 0	Outsider	Companies have not done anything to deal with I4.0.
Level 1	Beginner	Companies have I4.0-based plans and pilot applications
Level 2	Intermediate	Companies have already taken the first step in I4.0 integration
Level 3	Experienced	Companies use I4.0 technologies in particular areas, but I.40 is not yet extended to the whole company
Level 4	Top Performer	Leading companies that are already well on the way to I4.0 integration

After thoroughly exploring the literature, we identified existing MMs and F/Ws that are already intended to be applied in industry. In this study, I4.0-success-related indicators were systematically identified. The completion of the systematic representation of the theoretical evaluation model allowed us to delineate the estimation process. In particular, the evaluation method can be divided into five components: target score, importance of the company, the gap to the target, level of the maturity model, and the weighted gap.

The enterprise's I4.0 score is a quantitative rating given by the enterprise's delegate. The respondent attempts to estimate the degree of Industry 4.0 regarding a specific definition. The company score in 2 years is a quantitative rating that represents the I4.0 standard in comparison with a definition that the enterprise delegate indicated would be suitable for their own sector. The importance score is a subjective value that encapsulates the degree of significance of the discussed Industry 4.0 definition. The company's gap to the target describes the known shortcomings that must be resolved to reach a competitive position. A subtraction can be used to calculate the size of the distance, as illustrated in Equation (1) [73].

$$\text{Company's gap to target} = \text{Company I4.0 score in 2 years} - \text{Company's I4.0 score} \quad (1)$$

The final procedural step of the maturity model evaluation method is the weighted gap. Equation (2) is used to calculate the weighted gap [73].

$$\text{Weighted gap} = \frac{\text{Company's gap to target} \times \text{Importance of the company}}{\text{Level of the maturity model}} \quad (2)$$

The maturity level of each dimension is then calculated by taking the weighted average of all maturity items within its relevant dimension. For each object, the weighting factor equals the average significance ranking from all respondents. The maturity level is determined by applying Equation (3) [14], where M stands for maturity, D represents dimension, I is item, G is the weighting factor, and n is the number of maturity items in the equation.

$$M_D = \frac{\sum_{i=0}^{n} M_{Dli} \times g_{Dli}}{\sum_{i=1}^{n} g_{Dli}} \quad (3)$$

3.3. *Proposed Framework*

3.3.1. Framework Layers

Our research approach involved investigating the awareness, knowledge, and maturity level of the industry. The proposed maturity model should align with the proposed framework to provide reliable investigation into Industry 4.0. In this regard, the framework's layers were developed from maturity model dimensions. The framework layers are presented in Figure 5.

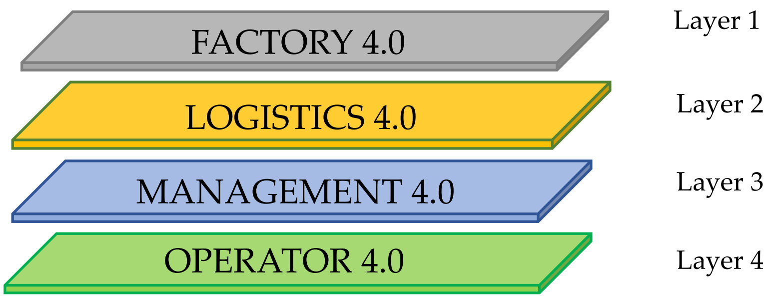

Figure 5. Framework layers.

3.3.2. Life Cycle Value Stream

A business model maximizes consumer and shareowner trust by leveraging customer-focused value sources, transparent transparency, and streamlined support systems. It provides a framework for increasing the value-to-non-value ratio in the total life cycle of consumer deliverable goods, processes, or services, as well as ensuring that the value stream matches or exceeds customer needs. The life cycle value stream of the designed framework was grouped into five flows, as shown in Figure 6:

8. Flow 1: Initial requirements to obtain a new product for the organization.
9. Flow 2: The theoretical strategy and capability development of the new product for the organization.
10. Flow 3: Continuation of the existing business in parallel to the new product.
11. Flow 4: The development of product processes in manufacturing.
12. Flow5: Providing goods and services after obtaining a new product.
13. Continuous Improvement: Monitoring and continuously improving the product.

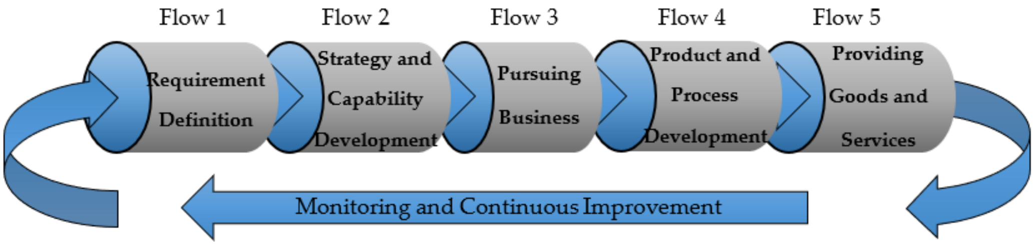

Figure 6. Framework life cycle value stream.

3.3.3. Hierarchy Levels

As a generalization, the framework hierarchy is divided into seven parts associated with specific levels. Broadly, hierarchy levels were designed in a horizontal view of how I4.0 adoption is started and accomplished in an organization [52]. F/Ws can be structured hierarchically into multiple layers referring to different levels of granularity of maturation [87]. The hierarchy levels of the proposed F/W are presented in Figure 7. In the proposed hierarchy level, I4.0 adoption starts with a specific part, the product, and proceeds to the general level, which is the smart plant. A smart plant expresses the I4.0 adoption in the whole enterprise including suppliers, production, logistics, and customers. Maturity level of the company highlights the company's hierarchy level in the proposed F/W.

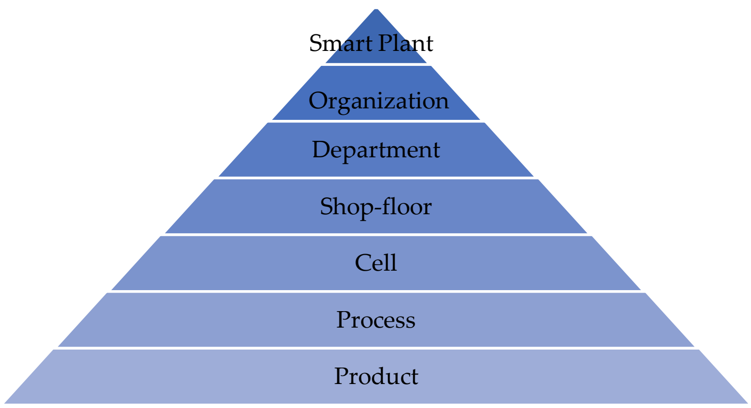

Figure 7. Framework hierarchy levels.

The framework structure is a method used to visualize the maturity level of the layers as well as to provide the organization's overall maturity level. The framework also provides a roadmap for organizations that includes specific requirements to fully adopt I.40. The framework structure template is presented in Figure 8.

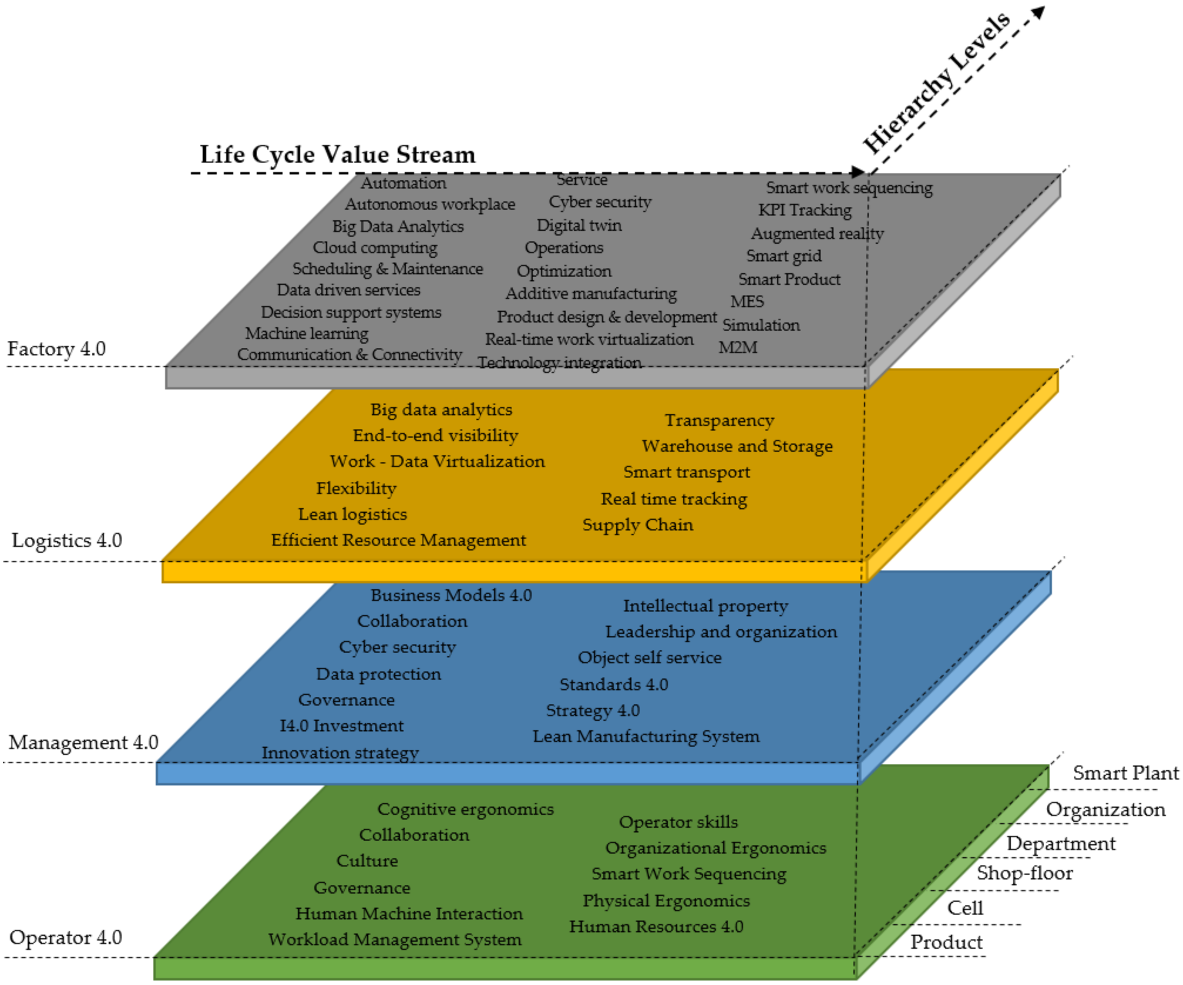

Figure 8. Framework structure.

3.4. Survey Design

Building upon the requirements of the MM, a questionnaire was developed to explore specific aspects [45]: (1) structural attributes of the companies, (2) general questions regarding Industry 4.0 technologies, and (3) degree to which companies satisfy the dimensions of Industry 4.0.

In the first part of the questionnaire, respondents are asked to provide information about the structure of their companies. This information is used primarily to ensure the survey is representative and to enable projections. The second part of the questionnaire contains general questions about industry 4.0, e.g., to what extent the company is involved in I4.0 and an assessment by the respondents about I4.0 technology integration to the company. At the heart of the survey was the definition of the indicators used to describe the four dimensions in detail and measure the extent to which indicators were present. A total of 107 questions were formulated for this purpose.

3.5. Technology Forecasting

TF has been emerging for several years, and it is still developing, since many new technological developments increase the demands of forecasting tools. Modern technology forecasters use various methods to predict a technology's future performance, including methods based on complex mathematics such as time-series analysis, stochastic methods, and simulation [61]. These methods often rely on the assumption that past behavior will continue. These forecasts complement techniques based on expert opinion and panels by providing extrapolative results that are quantified and reproducible [61]. As the results are obtained from complimentary techniques based on expert opinion, technological forecasting insights can provide value, although the predictions are inaccurate [88]. Although forecasters attempt to make accurate forecasts, insights gained from the technological forecasting process can provide value whether the predictions are accurate or inaccurate [88]. Although the forecasts may not always be accurate, the insight they help to generate can be valuable and have a significant impact on their organizations. This particular area of research is significant in its ability to help organizations avoid costly mistakes.

Various TF studies have been performed to examine a broad variety of developments, including Radio Frequency Identification (RFID), programming languages, optical storage, fuel cells, food protection, 3D television, operating systems, and so on. The growth pattern is used to investigate the innovation process and the features of the market [89]. The S curve provides an understanding of how technology evolves without historical data over time, but it is important to follow the disruptive technology's advancement as it travels down the S curve of sustaining technology [90].

In this study, trend analysis based on expert opinion was used to conduct TF to provide an overall perspective to organizations aiming toward readiness for the industrial revolution and to anticipate the direction and rate of I4.0 integration. The S-curve evaluation is shown in Figure 9.

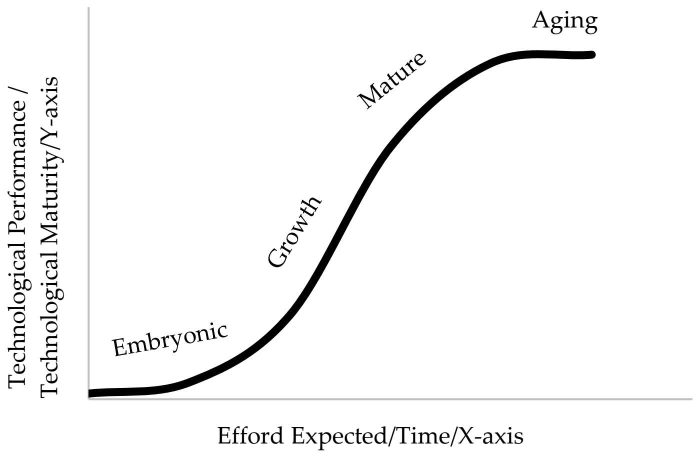

Figure 9. Technology growth S curve. Adapted from [90].

The growth curve of technology is based on a hypothesis that describes how technology advances and spreads. It represents the status of improvements in evolving technology standards as cumulative types over time. Simply stated, the principle uses time-series data to predict the rate of transition, assuming that the increase or spread in a particular technology fits a statistical formula [91]. The technology growth curve shows the trend in the technological transition and can forecast changes in technology efficiency [92]. Several models, such as the Bass diffusion model (BASS), Pearl, Gompertz, and Fisher–Pray models, can be used to produce a growth curve. The appearance or lack of symmetry is a noticeable contrast between the exceptional Pearl model and the Gompertz model. The difference originates in the pace of development and the inflection point [91]. In the literature, the most commonly used growth curves for technology forecasting are logistic (Pearl) and Gompertz functions [90]. Therefore, the Gompertz growth curve and logistic (pearl) curve were applied here to perform technology forecasting. The Gompertz growth equation and logistic growth curve are given in Equations (4) and (5), respectively [90,91,93], where a is the asymptote or carrying capacity, b is the displacement on the X-axis, and c is the growth rate.

$$\text{Gompertz Growth Model}: \ Y(t) = a.e^{\left(-b.e^{-k.t}\right)} \tag{4}$$

$$\text{Logistic Growth Curve}: \ Y(t) = \frac{a}{1 + b.e^{(-ct)}} \tag{5}$$

Multigenerational technology innovation happens as many emerging inventions begin to evolve in a single technology field and eventually expand around the globe. The technology integration growth is expected to increase dramatically at a specific point, then settle. After reaching a specific point, technology requires longer to be adopted after reaching a specific maturity level [94]. Relatively, the Gompertz growth model is asymmetrical to the inflection point ($Y = a/e$). The point of inflection occurs at $t = \frac{ln(b)}{e}$. The curve grows steadily until it reaches the inflection point, then the rate of growth decreases [91]. Therefore, the Gompertz growth model was applied to predict the time required for the adoption of Industry 4.0 and its technologies. As some researchers found a connection between the trend in biological development and the growth in a technology's performance capability, the logistic growth model was also used in this research to provide comprehensive consequences [90,95]. The logistic growth model (Pearl) is symmetrical to the inflation point $Y = (a/2)$; the inflection point occurs at $t = \frac{lnb}{c}$ [94].

4. Case Study

A case study was designed to validate the proposed MM and F/W integrated with TF in a real-time scenario. Therefore, a case study was conducted based on a large automobile parts manufacturing enterprise that employs more than 1500 people in Turkey. The objective of the case study was to evaluate I4.0 adoption and the maturity of the enterprise based on the proposed MM with respect to proposed F/W. Respondents from different departments were required to evaluate the I4.0 maturity of the enterprise in four different dimensions: (1) Factory 4.0, (2) Management 4.0, (3) Logistics 4.0, and, (4) Operator 4.0. A total of 30 people working at the enterprise participated in the online survey to help assessing the I4.0 technology adoption of the enterprise. The survey results were obtained from SurveyMonkey, and data calculations and analyses were performed in Microsoft Excel. The I4.0 technology integration of the company was evaluated, and the findings from the case study were reported to the company. The report included the current I4.0 maturity level of the company based on the proposed MM framework and the growth curve of the company toward complete I4.0 technology integration.

The work experience and expertise of the participants are presented in Figures 10 and 11. The respondents mainly had 11–20 years of experience. The study mostly considered the expertise of process development engineers in the company.

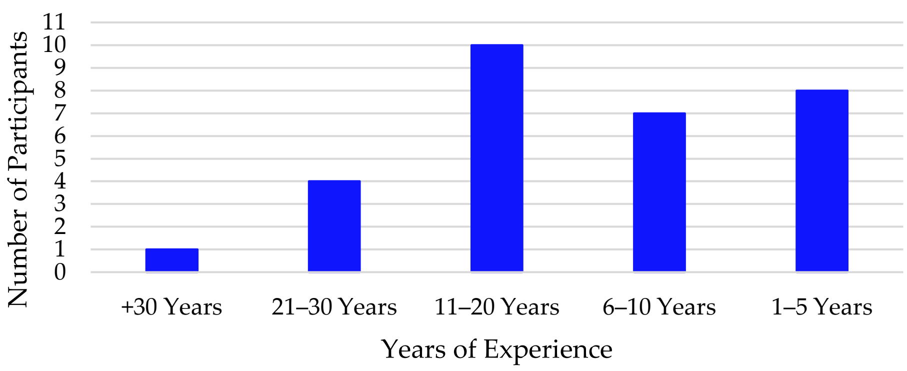

Figure 10. Work experience of participants.

Based on the survey results, the enterprise's maturity level was obtained, as shown in Figures 12 and 13. Company's overall maturity level was scored 2.73 out of 5.00. In other words, the company has 54.52% completed its I4.0 technology revolution. Each dimension was also evaluated: Factory 4.0 maturity level = 2.75/5.00, Logistics 4.0 maturity level = 2.74/5.00, Management 4.0 maturity level = 2.69/5.00, and Operator 4.0 maturity level = 2.73/5.00.

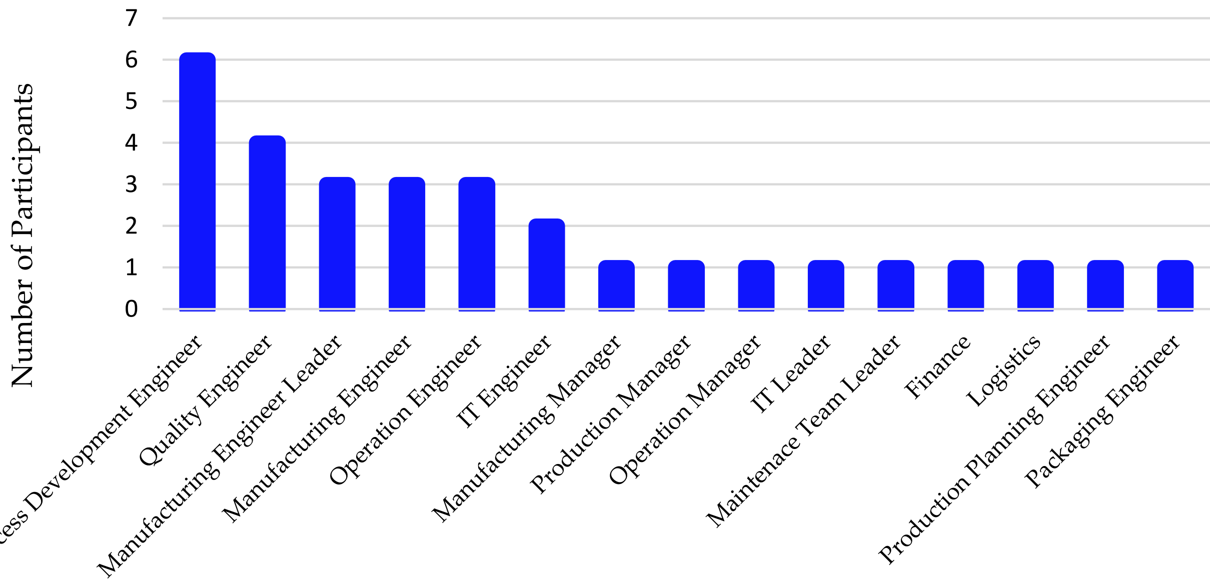

Figure 11. Expertise of the participants.

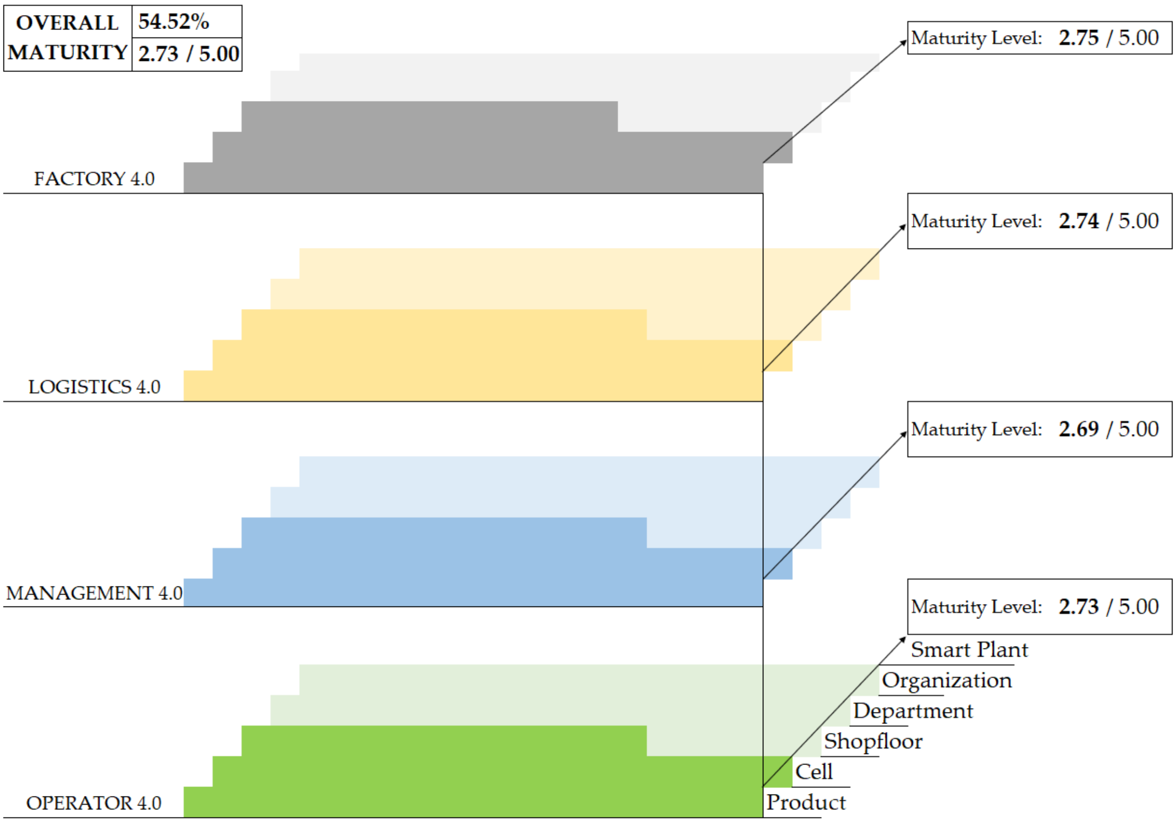

Figure 12. Enterprise's maturity level evaluation.

Each dimension has numerous subdimensions used to help identify the required technologies that were not considered by the enterprise in its I4.0 revolution. Factory 4.0 has 25 different subdimensions, as presented in Figure 14; Logistics 4.0 has 11 different subdimensions, as shown in Figure 15; Management 4.0 has 13 different subdimensions, as illustrated in Figure 16; and Operator 4.0 has 11 different subdimensions (Figure 17).

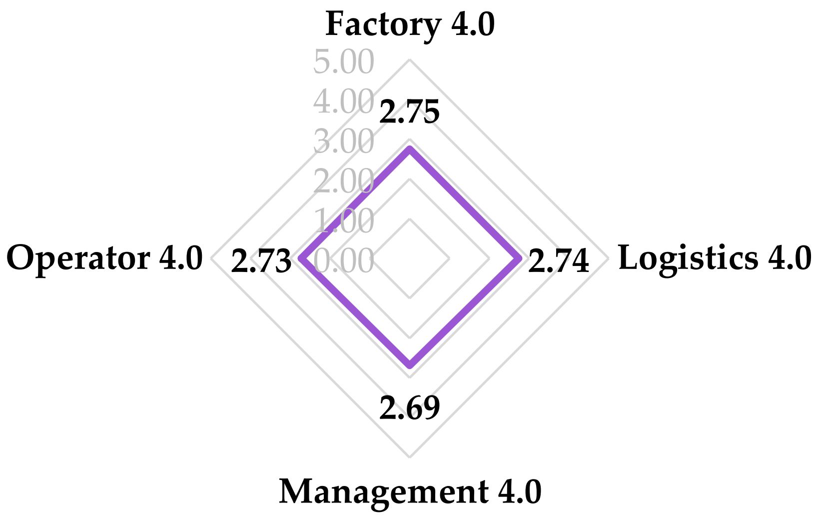

Figure 13. Overall enterprise maturity level of dimensions.

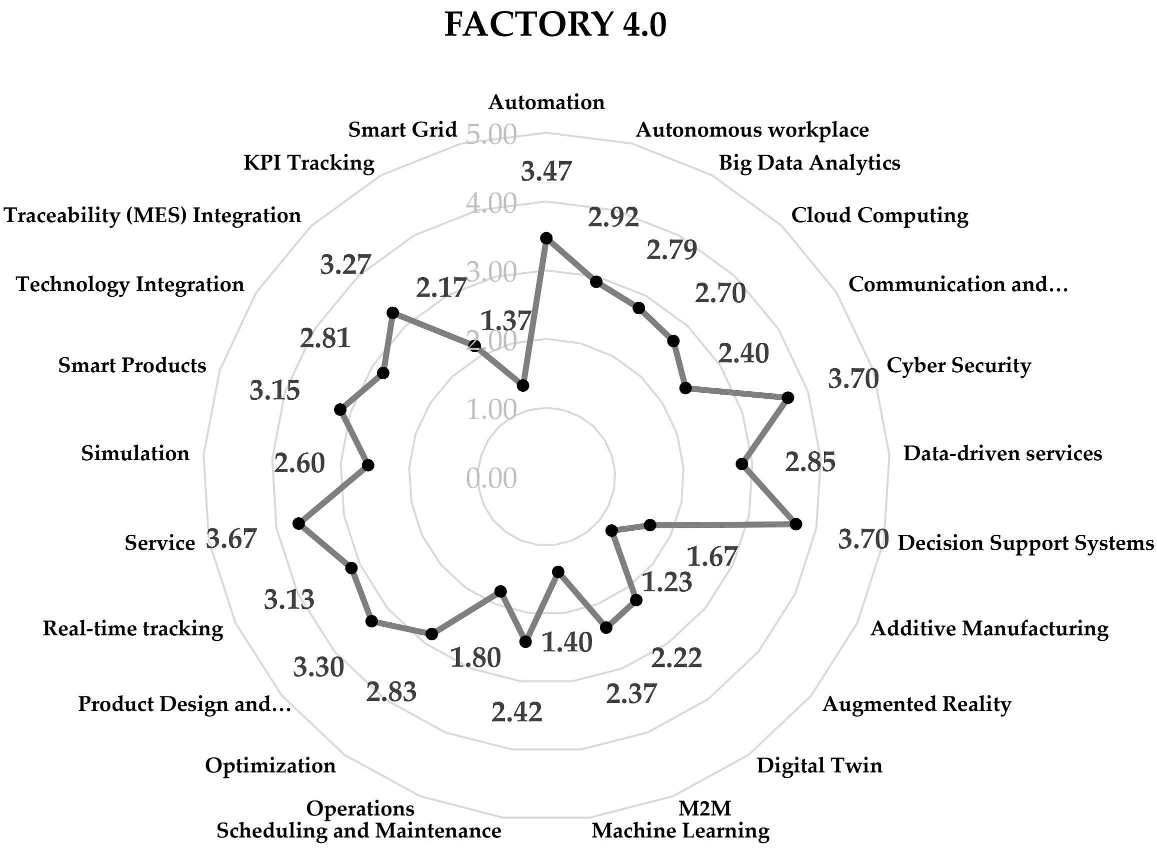

Figure 14. Maturity level of Factory 4.0 subdimensions.

The maturity model evaluation showed that the enterprise needs to pay more attention to the use of renewable energy sources, predictive/preventative maintenance, application of machine learning, application of augmented reality, and additive manufacturing technologies, which scored lower in the Factory 4.0 dimension. In the Logistics 4.0 dimension, warehouse and storage, real-time tracking, supply chain, and smart transport scored lower. In the Management 4.0 dimension, innovation strategy, Business 4.0, Strategy 4.0, and I4.0 investment scored lower. In the Operator 4.0 dimension, operator skills, Human Resources 4.0, governance, and culture scored lower. Overall, company's maturity score was higher in the Factory 4.0 dimension and lower in the Management 4.0 dimension.

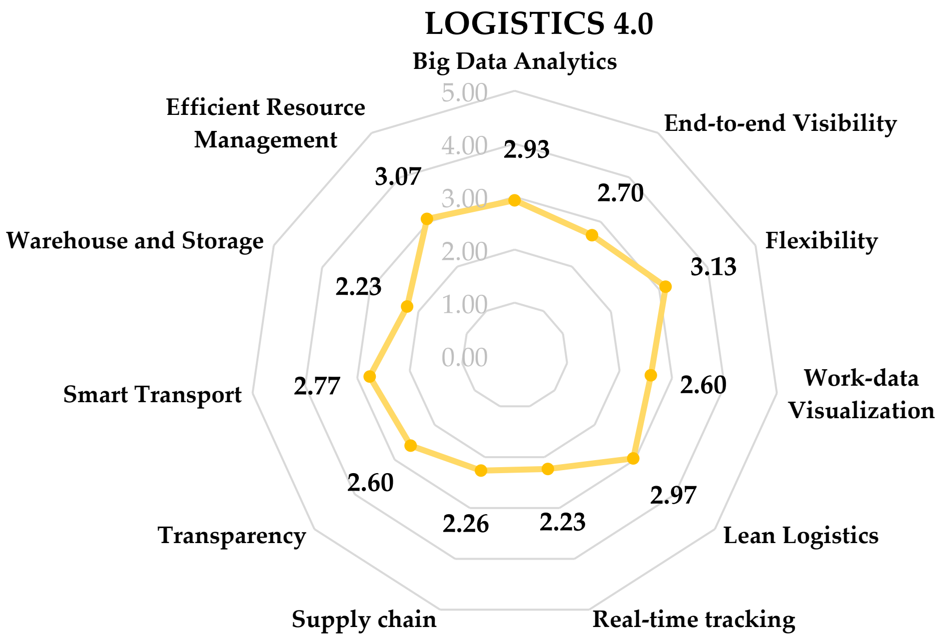

Figure 15. Maturity level of Logistics 4.0 subdimensions.

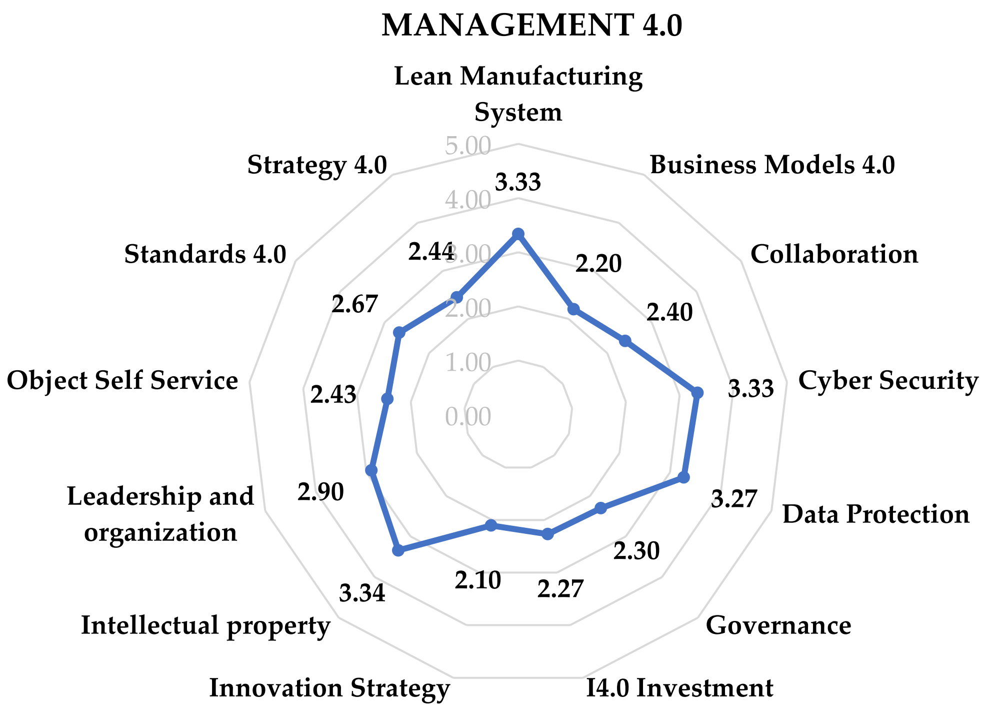

Figure 16. Maturity level of Management 4.0 subdimensions.

The maturity level of the company was evaluated, and we applied TF, which is presented as an S curve in Figure 18. Each dimension's maturity level is presented in Figures 19 and 20. Based on the Gompertz model, the technologies required for Factory 4.0 are expected to be completely adopted by 2030; by 2031 for Logistics 4.0; for Management 4.0, by 2031; and 2031 for Operator 4.0. Overall, technology adoption was forecasted to be completed in 2031. Based on the logistic model, the technologies required for Factory 4.0 are expected to be completely adopted in 2030; for Logistics 4.0, by 2034; by 2034 for Management 4.0; and 2034 for Operator 4.0. Overall, technology adoption was forecasted to be completed in 2034.

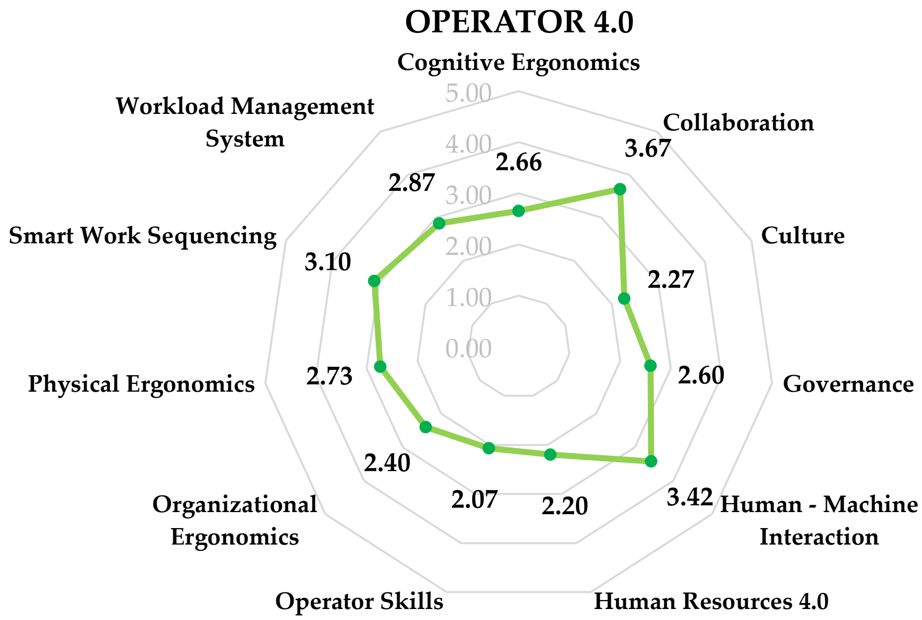

Figure 17. Maturity level of Operator 4.0 subdimensions.

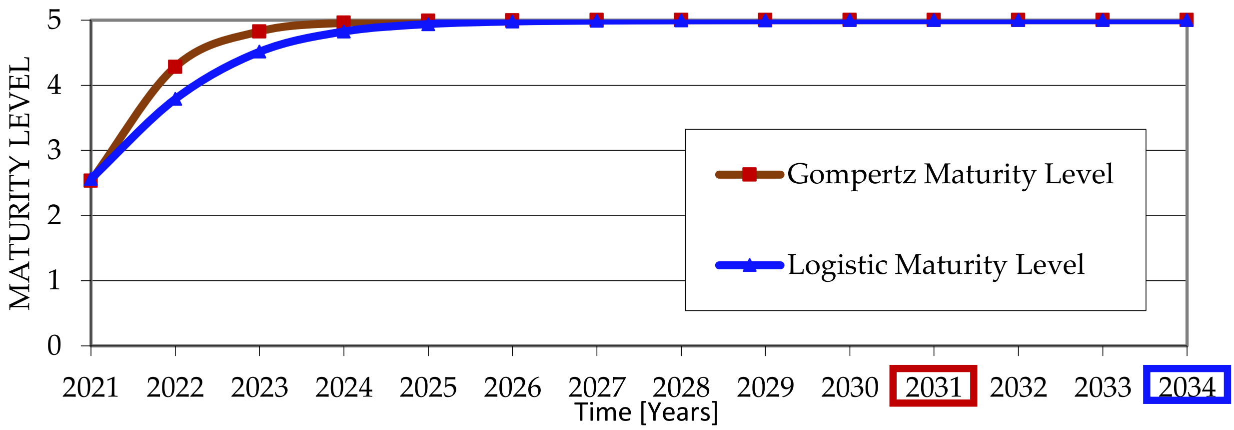

Figure 18. TF for the case study enterprise.

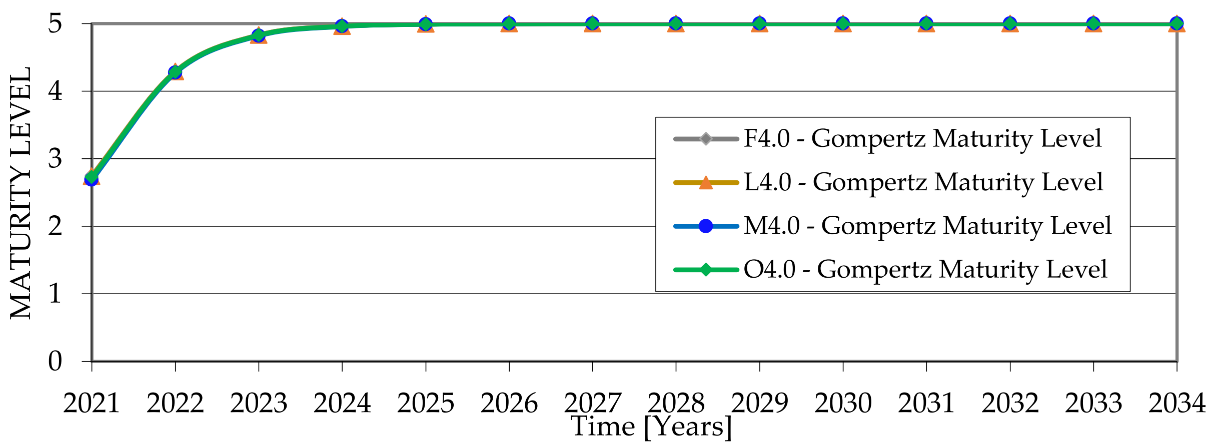

Figure 19. S curve of the Gompertz model for the I4.0 dimensions of the enterprise.

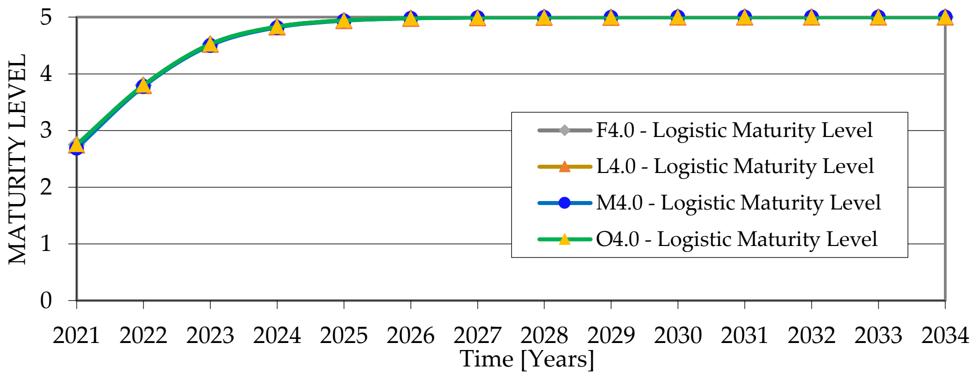

Figure 20. S curve of the logistic model for the I4.0 dimensions of the enterprise.

The methodologies of TF provide procedures for evaluating, displaying, and, in some cases, collecting data. There are four different types of forecasting methods [96]: (1) judgmental or intuitive methods, (2) extrapolation and trend analysis, (3) models, and (4) scenarios and simulations.

In this study, extrapolation and trend analysis methods were used for technological forecasting. The TF model must be tested to understand the model's efficiency. Therefore, the below terms were calculated and are provided in Table 8.

Table 8. Major performance assessment methods and metrics.

Technique and Indicator	Concept	Operational Definition	Gompertz Model	Logistic Model
Mean Squared Error (MSE)	Average of the squares of the prediction errors	$\text{MSE} = \frac{1}{n}\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2$	0.0372	0.0262
Root Mean Squared Error RMSE	Standard deviation of the prediction errors	$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}$	0.1929	0.1619
Mean Absolute Error (MAE)	Average of the absolute difference between the prediction errors	$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}\left\lvert Y_i - \hat{Y}_i\right\rvert$	0.1929	0.1619
Root Mean Squared Logarithmic Error (RMSLE)	Root mean squared log error	$\text{RMSLE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\log(Y_i+1) - (\hat{Y}+1)^2}$	0.0319	0.0266
Mean Absolute Percentage Error (MAPE)	Mean AbsolutePercentage Error	$\text{MAPE} = \sum_{i=1}^{n}\frac{\lvert Y_i - \hat{Y}_i\rvert}{Y_i}\times 100$	7.08%	5.94%
Mean Absolute Deviation (MAD)	Mean Absolute Deviation	$\text{MAD} = \frac{\sum_{i=1}^{n}\lvert Y_i - \hat{Y}_i\rvert}{n}$	0.0708	0.0594

The calculations proved that the model was sufficient to use. The forecasting performance, measured by root mean square error (RMSE), can roughly divide the models into three groups [97]:

1. RMSE < ~0.1
2. 0.1 < RMSE < ~0.2
3. 0.2 < RMSE

5. Discussion

With an industrial background, we highlighted the theme of transitioning from a conventional manufacturing model to an agile, smart, and optimized manufacturing model. The literature review focused on maturity models and framework models, which resulted in the development of a viable maturity model based on a strong framework. Several researchers have studied the incorporation of maturity models into the determination of the I4.0 maturity level [14,28,29,33–45]. This subject has already been widely discussed in the literature, with a focus on the benefits of Industry 4.0 and the potential challenges that enterprises will encounter when implementing these technologies [98–111]. Moreover, critical factors of I4.0, managerial capacity, digital information sharing, enterprise strategy, and industrial performance objectives are extensively discussed in the literature [12,110,112,113]. Although the Industry 4.0 vision is well-explained in the literature, less research has focused on the integration of I4.0 and proposing a framework toward the I4.0 revolution for smart manufacturing enterprises. Therefore, research studies providing a bridge or link between academia and real-world businesses are lacking. None of the studied maturity models from the literature fully cover all the criteria of scope, fitness of purpose, completeness, clarity, and objectivity. We described the construction of a maturity model and framework that cover all of the criteria to bridge the gap in the scientific literature. Moreover, we provided technology forecasting to emphasize the technology growth for an enterprise. The proposed modular and generic maturity model has four dimensions, five levels, 60 second-level dimensions, and 246 subdimensions; the proposed MM framework has four layers and seven hierarchy levels.

A survey was specifically designed for the proposed maturity model and framework to gather information from the enterprise. Using this survey, adoption of I4.0 technologies was observed for the enterprise. However, the respondents' understanding and experience played a vital role in the precise evaluation of organizational maturity. As a result, this research is limited to the responses provided by the participants, restricting the maturity assessment as a reference of the participants' expertise.

The research findings showed that the enterprise requires more attention regarding the use of renewable energy sources, predictive and preventative maintenance, the application of machine learning, the application of augmented reality, and additive manufacturing technologies in the Factory 4.0 dimension. In the Logistics 4.0 dimension, the enterprise should automatize the warehouse and storage systems, and real-time product tracking is recommended as a first step toward the I4.0 transition. In the Management 4.0 dimension, applications for awareness of I4.0 and cost–benefit strategy studies are suggested as the company has scored lower for these second-level dimensions. In the Operator 4.0 dimension, the definition of the operator role in I4.0, required operator skills, and I4.0-based training should be organized to enable smooth technology integration.

Examining the findings, the maturity of the company was presented in a 3D framework structure, providing readers with a more detailed picture of the company. The findings showed that the company individually engaged in a strategy of I4.0 adoption that other enterprises in the same sector may not have chosen to pursue. The company's overall maturity score was found to be 2.73 out of 5.00. Maturity of the company was considered with proposed F/W, and the company was evaluated to be at the cell level of hierarchy at which the company is in the early stage of the I4.0 integration. Based on the technology forecasting findings, the forecasted year of full integration of I.40 is between 2031 and 2034 if the enterprise takes actions to create a roadmap toward a smooth I4.0 transition.

The enterprise should follow these actions as a roadmap in the early stage of technology integration:

- Develop concepts for pilot projects and conduct a cost–benefit analysis based on existing use cases from research or industry associations;
- Develop pilot applications of artificial intelligence for processes and machines;
- Continually improve data collection and review the corresponding system of indicators and targets;
- Quantify the benefits of data collection;
- Examine what information can be obtained from the data already collected. Can patterns be identified? Do they provide the basis for simulations? Do they yield a consistent digital model of the value added and which gaps need to be closed?
- Information sharing is still limited to only a few departments. An analysis should be run to determine where bottlenecks exist between systems and where potential can be leveraged by integrating information sharing into the system.

- Production should be analyzed to determine where it makes sense to introduce autonomous control into processes. Partnering with other companies or sharing knowledge with research institutions can help hasten progress.
- The areas in which IT security solutions are needed should be defined.
- A clear scheduling and maintenance strategy should be adopted.
- To achieve greater Industry 4.0 readiness, it is important to gradually expand the add-on functionalities of products.
- Identify the areas in which potential could be leveraged by offering augmented reality.
- Industry 4.0 is already being implemented in departmental pilot initiatives, but the strategic relevance is lacking. A viable Industry 4.0 strategy must be developed.
- Cost–benefit analysis of Industry 4.0 investment should be periodically included in top management meetings.
- Include operators in communication and socio-technology meetings that involve the policies of the organization, processes, and structures.

6. Conclusions

I4.0 is a vision defining the future of industry. The potential lies primarily in high-flexibility, resource-friendly, and high-productivity manufacturing. It enables highly customized products and goods to be mass-produced under the given economic conditions. Engineering, development, service, logistics, operation, and marketing are all interconnected in complex, real-time-optimized, value-added cross-enterprise networks. The aim of this study was to explore a large-scale automobile parts manufacturing enterprise's adoption of I4.0 technologies by examining knowledge and implementation of I4.0 technology through engineering businesses, future gains from this development, and significant obstacles to transitioning to I4.0.

We focused on the awareness, knowledge, readiness, willingness to invest, challenges, and benefits of I4.0. A questionnaire was designed for primary data acquisition from a large manufacturing enterprise. Finally, based on available and acquired data, a new MM and framework model were developed and then applied to forecast the I4.0 technology adoption in the manufacturing enterprise. While conducting this study, we used a large number of survey questions required to evaluate the company's maturity level. The limitation of the study was finding participants who were aware of I4.0 from the management level and were willing to answer the survey questions. Additionally, the respondents' understanding and experience played a vital role in the precise evaluation of the maturity model. However, respondents may not feel encouraged to provide accurate, honest answers; additionally, respondents may not feel comfortable providing answers that present themselves unfavorably. Here, our research is limited to the answers provided by the respondents. As a result, this research is limited to the responses provided by the participants, restricting the maturity assessment as a reference to the participants' expertise.

The maturity level of the enterprise was evaluated based on the proposed framework structure. For Factory 4.0, Logistic 4.0, Management 4.0, and Operator 4.0, the company's maturity level was evaluated as 2.75/5.00, 22.74/5.00, 2.69/5.00, and 2.73/5.00, respectively. Then, the overall maturity level was calculated as 2.73/5.00, which means the company has reached 54.52% of I4.0 integration based on the proposed framework. Therefore, the company requires significant effort to finalize the I4.0 integration. Smart grid, simulation, smart operations, scheduling and maintenance, augmented reality, and additive manufacturing were the second-level dimensions recognized as insufficient in the Factory 4.0 dimension. Smart warehouse and storage and real-time tracing were the second-level dimensions recognized as lacking in the Logistics 4.0 dimension. For Strategy 4.0, innovation strategy and governance were the second-level dimensions requiring more attention for the enterprise in the Management 4.0 dimension. The enterprise needs to make additional effort in the cognitive ergonomics and operator culture in second-level dimensions of the Operator 4.0 dimension. Comparing all dimensions, Factory 4.0 had the highest maturity level and

Management 4.0 had the lowest. Based on our findings, creating a roadmap toward I4.0 integration is strongly suggested for the enterprise.

TF helped us to predict the year of completion of I4.0 integration. Two different TF models were used to produce more accurate predictions. The Gompertz model predicted the completion of I4.0 integration in 2031, whereas the logistic model predicted the completion in 2034. Forecasting model performance was also considered by calculating the standard deviation of the prediction error (RMSE) and the mean absolute percentage error (MAPE), which were calculated as 0.1929 and 7.08% for the Gompertz model, and 0.1619 and 5.94% for the logistic model, respectively. When both models were compared, the expected year of full I.40 integration is between 2031 and 2034.

This research contributes to the following:

- Exploring the adoption of I4.0 based on the literature.
- Proposing an MM and F/W method to provide insight for smart manufacturing enterprises into the current situation regarding I4.0 adoption.
- Develop a survey to collect data from the real-world company.
- Adopt a TF that helps with the explicit identification of gap areas and predicts the growth in I4.0 knowledge, awareness, and adoption.
- Provide insight into the current situation by exploring solutions for I4.0 integration and obtain the maximum potential of I4.0.

This paper also provides a foundation and motivation for further research. Areas of recommended further research include:

- The application of the proposed MM and F/W to various companies in other industrial sectors.
- The application of the proposed MM and F/W to various companies in the same country or same region to assess I4.0 maturity level of the country or region.
- A combination of more than one MM to provide more accurate prediction compared with the use of an individual model.
- Other technology forecasting methods can be applied.

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References

1. Akay, M. Endüstri 4.0 ile Akıllı Tarıma Geçiş. General Directorate of Agricultural Research and Policies. 2018. Available online: https://www.researchgate.net/profile/Melek-Akay-2/publication/326550785_ENDUSTRI_40_ILE_AKILLI_TARIMA_GECIS/links/5d2d95ff92851cf440874342/ENDUeSTRI-40-ILE-AKILLI-TARIMA-GECIS.pdf (accessed on 10 January 2021).
2. UNIDO. Industry 4.0—The opportunities behind the Challenge. In Proceedings of the 17th UNIDO General Conference, Vienna, Austria, 1 December 2017.
3. Stiftung, B. Sozialer Zusammenhalt in Deutschland. Radar gesellschaftlicher Zusammenhalt. 2017. Available online: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjo06K00IrxAhXMh1wKHYQyDpIQFjACegQIBBAE&url=http%3A%2F%2Fu.epd.de%2Fwzs&usg=AOvVaw0pkNTtfM4tviDoO1wFF8Ov (accessed on 21 December 2020).
4. Jovanovski, B.; Seykova, D.; Boshnyaku, A.; Fischer, C.J.I. The impact of Industry 4.0 on the competitiveness of SMEs. *Int. Sci. J.* **2019**, *4*, 250–255.

5. Sanchez, D.O.M. Sustainable Development Challenges and Risks of Industry 4.0: A literature review. In Proceedings of the 2019 Global IoT Summit (GIoTS), Aarhus, Denmark, 17–21 June 2019; pp. 1–6.
6. Ramirez-Peña, M.; Sotano, A.J.S.; Pérez-Fernandez, V.; Abad, F.J.; Batista, M. Achieving a sustainable shipbuilding supply chain under I4. 0 perspective. *J. Clean. Prod.* **2020**, *244*, 118789. [CrossRef]
7. Dastbaz, M. Industry 4.0 (I4.0): The Hype, the Reality, and the Challenges Ahead. In *Industry 4.0 and Engineering for a Sustainable Future*; Dastbaz, M., Cochrane, P., Eds.; Springer International Publishing: Cham, Switzerland, 2019; pp. 1–11.
8. Alcácer, V.; Cruz-Machado, V. Scanning the Industry 4.0: A Literature Review on Technologies for Manufacturing Systems. *Eng. Sci. Technol. Int. J.* **2019**, *22*, 899–919. [CrossRef]
9. Weston, R.H.; Cui, Z. Next Generation Manufacturing Systems. In Proceedings of the Global Design to Gain a Competitive Edge, London, UK, 1 January 2008; pp. 701–710.
10. Erboz, G. How to define industry 4.0: Main pillars of industry 4.0. Managerial Trends in the Development of Enterprises in Globalization Era. 2017, pp. 761–767. Available online: https://www.researchgate.net/profile/Gizem-Erboz-2/publication/326557388_How_To_Define_Industry_40_Main_Pillars_Of_Industry_40/links/5fc553374585152e9be7f201/How-To-Define-Industry-40-Main-Pillars-Of-Industry-40.pdf (accessed on 13 March 2021).
11. Saad, S.M.; Bahadori, R.; Jafarnejad, H. The smart SME technology readiness assessment methodology in the context of industry 4.0. *J. Manuf. Technol. Manag.* **2021**. [CrossRef]
12. Moeuf, A.; Pellerin, R.; Lamouri, S.; Tamayo-Giraldo, S.; Barbaray, R. The industrial management of SMEs in the era of Industry 4.0. *Int. J. Prod. Res.* **2018**, *56*, 1118–1136. [CrossRef]
13. Hübner, M.; Liebrecht, C.; Malessa, N.; Kuhnle, A.; Nyhuis, P.; Lanza, G. A process model for implementing Industry 4.0-Introduction of a process model for the individual implementation of Industry 4.0 methods. *Wt Werkstattstech* **2017**, *107*, 266–272.
14. Schumacher, A.; Erol, S.; Sihn, W. A maturity model for assessing Industry 4.0 readiness and maturity of manufacturing enterprises. *Procedia Cirp* **2016**, *52*, 161–166. [CrossRef]
15. Matt, D.T.; Rauch, E.; Riedl, M. Knowledge transfer and introduction of industry 4.0 in SMEs: A five-step methodology to introduce industry 4.0. In *Analyzing the Impacts of Industry 4.0 in Modern Business Environments*; IGI Global: Hershey, PA, USA, 2018; pp. 256–282.
16. Rauch, E.; Unterhofer, M.; Rojas, R.A.; Gualtieri, L.; Woschank, M.; Matt, D.T. A maturity Level-Based assessment tool to enhance the implementation of industry 4.0 in small and Medium-Sized enterprises. *Sustainability* **2020**, *12*, 3559. [CrossRef]
17. Chonsawat, N.; Sopadang, A. Smart SMEs 4.0 maturity model to evaluate the readiness of SMEs implementing industry 4.0. CMUJ. *Nat. Sci.* **2021**, *20*, e2021027.
18. UNIDO. What Can Policymakers Learn From Germany's Industrie 4.0 Development Strategy? In *Inclusive and Sustainable Industrial Development Working Paper Series*; UNIDO: Vienna, Austria, 2018; Available online: https://www.researchgate.net/profile/Fernando-Santiago-5/publication/326905127_What_can_policymakers_learn_from_Germany\T1\textquoterights_Industrie_40_development_strategy/links/5b73d8bd92851ca65061e857/What-can-policymakers-learn-from-Germanys-Industrie-40-development-strategy.pdf (accessed on 15 February 2021).
19. Horick, C. Industry 4.0 Production Networks: Cyber-Physical System-based Smart Factories, Real-Time Big Data Analytics, and Sustainable Product Lifecycle Management. *J. Self-Gov. Manag. Econ.* **2020**, *8*, 107–113.
20. Peters, E.; Kliestik, T.; Musa, H.; Durana, P. Product decision-making information systems, real-time big data analytics, and deep learning-enabled smart process planning in sustainable industry 4.0. *J. Self-Gov. Manag. Econ.* **2020**, *8*, 16–22.
21. Coatney, K.; Poliak, M. Cognitive Decision-Making Algorithms, Internet of Things Smart Devices, and Sustainable Organizational Performance in Industry 4.0-based Manufacturing Systems. *J. Self-Gov. Manag. Econ.* **2020**, *8*, 9–18.
22. Davidson, R. Cyber-Physical Production Networks, Artificial Intelligence-based Decision-Making Algorithms, and Big Data-driven Innovation in Industry 4.0-based Manufacturing Systems. *Econ. Manag. Financ. Mark.* **2020**, *15*, 16–22.
23. Duft, G.; Durana, P. Artificial Intelligence-based Decision-Making Algorithms, Automated Production Systems, and Big Data-driven Innovation in Sustainable Industry 4.0. *Econ. Manag. Financ. Mark.* **2020**, *15*, 9–18.
24. Hyers, D. Big Data-driven Decision-Making Processes, Industry 4.0 Wireless Networks, and Digitized Mass Production in Cyber-Physical System-based Smart Factories. *Econ. Manag. Financ. Mark.* **2020**, *15*, 19–28.
25. Sartal, A.; Bellas, R.; Mejías, A.M.; García-Collado, A. The sustainable manufacturing concept, evolution and opportunities within Industry 4.0: A literature review. *Adv. Mech. Eng.* **2020**, *12*. [CrossRef]
26. Simpson, J.; Weiner, E. *The Oxford English Dictionary*; Oxford University Press: Oxford, UK, 1989; Volume 17, pp. 655–656.
27. Kohlegger, M.; Maier, R.; Thalmann, S. Understanding Maturity Models. Results of a Structured Content Analysis. 2009. Available online: https://www.researchgate.net/profile/Stefan-Thalmann/publication/290265437_Understanding_maturity_models_results_of_a_structured_content_analysis/links/5867d72f08ae8fce4915c649/Understanding-maturity-models-results-of-a-structured-content-analysis.pdf (accessed on 28 November 2020).
28. Gökalp, E.; Şener, U.; Eren, P.E. Development of An Assessment Model For Industry 4.0: Industry 4.0-MM. In Proceedings of the International Conference on Software Process Improvement and Capability Determination, Tessaloniki, Greece, 9–10 October 2018; pp. 128–142.
29. Akdil, K.Y.; Ustundag, A.; Cevikcan, E. Maturity and readiness model for industry 4.0 strategy. In *Industry 4.0: Managing The Digital Transformation*; Springer: Manhattan, NY, USA, 2018; pp. 61–94.

30. Fallaha, M.; Cinar, Z.M.; Korhan, O.; Zeeshan, Q. Operator 4.0 and Cognitive Ergonomics. In *Industrial Engineering in the Digital Disruption Era. GJCIE 2019*; Calisir, F., Korhan, O., Eds.; Lecture Notes in Management and Industrial Engineering; Springer: Cham, Switzerland, 2020.
31. Temur, G.T.; Bolat, H.B.; Gözlü, S. Evaluation of Industry 4.0 Readiness Level: Cases from Turkey. In Proceedings of the International Symposium for Production Research, Vienna, Austria, 13–15 September 2017; pp. 412–425.
32. Bauer, W.; Horváth, P. Industrie 4.0-Volkswirtschaftliches Potenzial für Deutschland. *Controlling* **2015**, *27*, 515–517. [CrossRef]
33. Rockwell Automation. The Connected Enterprise Maturity Model. *Int. Comm. Illum.* **2014**, *27*, 515–517. [CrossRef]
34. IMPULS. Industrie 4.0 Readiness. VDMA's IMPULS-Stift. 2015, pp. 1–76. Available online: http://industrie40.vdma.org/documents/4214230/5356229/Industrie%204.0%20Readiness%20Study%20English.pdf/f6de92c1-74ed-4790-b6a4-74b30b1e83f0 (accessed on 15 February 2021).
35. Hankel, M.; Rexroth, B. The Reference Architectural Model Industrie 4.0 (RAMI 4.0). ZVEIApril. 2015, p. 410. Available online: http://przemysl-40.pl/wp-content/uploads/2010-The-Reference-Architectural-Model-Industrie-40.pdf (accessed on 15 February 2020).
36. Back, A.; Berghaus, S.; Kaltenrieder, B.J.I.f.W. Universität St. Gallen. Digital Maturity & Transformation Studie. *Digit. Matur. Transform. Stud.* **2015**, *1*, 1–75.
37. Jodlbauer, H.; Schagerl, M. Reifegradmodell industrie 4.0-ein vorgehensmodell zur identifikation von industrie 4.0 potentialen. Informatik. 2016. Available online: https://www.semanticscholar.org/paper/Reifegradmodell-Industrie-4.0-Ein-Vorgehensmodell-Jodlbauer-Schagerl/8d7fdd5f24f971b8a23511ea1b9a0ccd9774b7ce (accessed on 26 May 2020).
38. Lanza, G.; Nyhuis, P.; Ansari, S.; Kuprat, T.; Liebrecht, C. Empowerment and implementation strategies for Industry 4.0. *ZWF Z. Für Wirtsch. Fabr.* **2016**, *111*, 76–79.
39. Menon, K.; Kärkkäinen, H.; Lasrado, L.A. Towards a Maturity Modeling Approach for the Implementation of Industrial Internet. In Proceedings of the Pacis, Chiayi, Taiwan, China, 27 June 2016; p. 38.
40. Qin, J.; Liu, Y.; Grosvenor, R. A Categorical Framework of Manufacturing for Industry 4.0 and Beyond. *Procedia CIRP* **2016**, *52*, 173–178. [CrossRef]
41. PricewaterhouseCoopers (PWC). Industry 4.0 Building the Digital Enterprise. 2016. Available online: https://doi.org/www.pwc.com/gx/en/industries/industrial-manufacturing/publications/assets/pwc-building-digital-enterprise.pdf (accessed on 22 April 2020).
42. Leyh, C.; Bley, K.; Schäffer, T.; Forstenhäusler, S. SIMMI 4.0-a maturity model for classifying the enterprise-wide it and software landscape focusing on Industry 4.0. In Proceedings of the 2016 Federated Conference on Computer Science and Information Systems (FedCSIS), Gdańsk, Poland, 11–14 September 2016; pp. 1297–1302.
43. Schuh, G.; Anderl, R.; Gausemeier, J.; Ten Hompel, M.; Wahlster, W. *Industrie 4.0 Maturity Index: Die Digitale Transformation von Unternehmen Gestalten*; Herbert Utz Verlag: Munich, Germany, 2017.
44. De Carolis, A.; Macchi, M.; Negri, E.; Terzi, S. A maturity model for assessing the digital readiness of manufacturing companies. In Proceedings of the IFIP International Conference on Advances in Production Management Systems, Novi Sad, Serbia, 30 August–3 September 2018; pp. 13–20.
45. The University of Warwick (WMG). *An Industry 4 Readiness Assessment Tool*; WMG-University Warwick: Coventry, UK, 2017.
46. Wagire, A.A.; Joshi, R.; Rathore, A.P.S.; Jain, R. Development of maturity model for assessing the implementation of Industry 4.0: Learning from theory and practice. *Prod. Plan. Control* **2020**, *32*, 1–20. [CrossRef]
47. Lin, S.-W.; Miller, B.; Durand, J.; Bleakley, G.; Chigani, A.; Martin, R.; Murphy, B.; Crawford, M. The Industrial Internet of Things Volume G1: Reference Architecture. Industrial Internet Consortium. 2017. Available online: https://www.iiconsortium.org/pdf/SHI-WAN%20LIN_IIRA-v1%208-release-20170125.pdf (accessed on 2 July 2020).
48. Mettler, T. A Design Science Research Perspective on Maturity Models in Information Systems. 2009. Available online: https://www.alexandria.unisg.ch/214531/ (accessed on 19 July 2020).
49. DIN Deutsches Institut für Normung. DIN Standards. Available online: https://www.din.de/en/innovation-and-research/industry-4-0 (accessed on 19 July 2020).
50. Rojko, A. Industry 4.0 Concept: Background and Overview. *Int. J. Interact. Mob. Technol. (Ijim)* **2017**, *11*. [CrossRef]
51. da Silva Correia, M.A. *Industrie 4.0 Framework, Challenges and Perspectives*; Hochschule RheinMain: Munich, Germany, 2014.
52. Adolphs, P.; Epple, U. Statusreport: Referenzarchitekturmodell Industrie 4.0 (RAMI4. 0). Verb. Der Elektrotechnik. 2015. Available online: https://www.zvei.org/fileadmin/user_upload/Presse_und_Medien/Publikationen/2016/januar/GMA_Status_Report__Reference_Archtitecture_Model_Industrie_4.0__RAMI_4.0_/GMA-Status-Report-RAMI-40-July-2015.pdf (accessed on 5 August 2020).
53. Zezulka, F.; Marcon, P.; Vesely, I.; Sajdl, O. Industry 4.0–An Introduction in the phenomenon. *IFAC-Pap.* **2016**, *49*, 8–12. [CrossRef]
54. CEN-CENELEC-ETSI Smart Grid Coordination Group. CEN-CENELEC-ETSI Smart Grid Coordination Group Smart Grid Reference Architecture. CEN-CENELEC Manag. Cent. 2012. Available online: https://ec.europa.eu/energy/sites/ener/files/documents/xpert_group1_reference_architecture.pdf (accessed on 12 March 2021).
55. Fraile, F.; Sanchis, R.; Poler, R.; Ortiz, A. Reference Models for Digital Manufacturing Platforms. *Appl.Sci.* **2019**, *9*, 4433. [CrossRef]
56. Kosanke, K. The European approach for an open system architecture for CIM (CIM-OSA)—ESPRIT Project 5288 AMICE. *Comput. Control Eng. J.* **1991**, *2*, 103–108. [CrossRef]

57. Liu, F.; Tong, J.; Mao, J.; Bohn, R.; Messina, J.; Badger, L.; Leaf, D.J.N.s.p. *NIST Cloud Computing Reference Architecture*; Special Publication (NIST SP): Gaithersburg, MD, USA, 2011; Volume 500, p. 292.
58. Wei, S.; Hu, J.; Cheng, Y.; Ma, Y.; Yu, Y. The Essential Elements Of Intelligent Manufacturing System Architecture. In Proceedings of the 2017 13th IEEE Conference on Automation Science and Engineering (CASE), Xi'an, China, 20–23 August 2017; pp. 1006–1011.
59. American National Institute of Standards and Technology. *Software Requirements Specification to Distribute Manufacturing Data*; American National Institute of Standards and Technology: Gaithersburg, MD, USA, 2017.
60. IBM. Announcing the IoT Industrie 4.0 Reference Architecture. Available online: https://www.ibm.com/cloud/blog/announcements/iot-industrie-40-reference-architecture (accessed on 31 March 2020).
61. Porter, A.L. Tech forecasting an empirical perspective. *Technol. Forecasting. Soc. Chang.* **1999**, *62*, 19–28. [CrossRef]
62. Meade, P.T.; Rabelo, L. The technology adoption life cycle attractor: Understanding the dynamics of high-tech markets. *Technol. Forecasting. Soc. Chang.* **2004**, *71*, 667–684. [CrossRef]
63. Carrillo, M.; González, J.M. A new approach to modelling sigmoidal curves. *Technol. Forecasting. Soc. Chang.* **2002**, *69*, 233–241. [CrossRef]
64. Frank, M.J.; Seeberger, L.C.; O'reilly, R.C. By carrot or by stick: Cognitive reinforcement learning in parkinsonism. *Science* **2004**, *306*, 1940–1943. [CrossRef] [PubMed]
65. Vanston, L. Forecasts for internet/online access. In *Forecasting the Internet*; Springer: Manhattan, NY, USA, 2002; pp. 45–58.
66. Chen, S. Strategic Management of E-Business. 2005. Available online: https://d1wqtxts1xzle7.cloudfront.net/31426495/strategic_eBusiness1.pdf?1371783176=&response-content-disposition=inline%3B+filename%3DStrategic_E_Business.pdf&Expires=1623252754&Signature=ZtTxeI5y9bV0rksdjoH~{}cuuiWJ3dRw2dF-WILKCYBX79NUjSxGJKzKqO9nF0kLX5LlgB7xZTt7I8I4CCGy1uAD8xWuOgTLhsXeWYllFHJwz~{}-EmnzVXQ4VWTcf7ffwf4TwM9~{}20lvUgKTBHWYgp1kEfEFisHqmAetqSeGhJva8c4zahD5AV~{}MPRH8vRzncyilVocqygOf3R5FPZdHZWtPSyu5mMRBMqkJJnpqYItEKQsk9x-AXNYWexdKXZzIT596KDybthuBghJco~{}StvPWssarx2PrDLmUMU82GfoqmR9HvE-c7Ia9d6T9N~{}qiMab-Gb9IeBs2tuCEFItFYvVz~{}w__&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA (accessed on 30 December 2020).
67. Saunders, M.; Lewis, P.; Thornhill, A. *Research Methods for Business Students (no. Book, Whole)*; Pearson Educ. Ltd.: HarlowEssex, UK, 2016.
68. Shoemaker, P.J.; McCombs, M.E. Survey research. *Mass Commun. Res. Theory* **2003**, *80*, 231–251.
69. Neuman, L.W. *Social Research Methods, 6/E.*; Pearson Education India: New Delhi, India, 2007.
70. Taylor-Powell, E.; Hermann, C. *Collecting Evaluation Data: Surveys*; University of Wisconsin: Madison, WI, USA, 2000.
71. Koska, A.; Goksu, N.; Erdem, M.B.; Fettahlioglu, H.S. Measuring the Maturity of a Factory for Industry 4.0. *Int. J. Acad. Res. Bus. Soc. Sci.* **2017**, *7*. [CrossRef]
72. A Categorical Framework of Manufacturing for Industry 4.0 and beyond. ScienceDirect. 2016. Available online: https://www.sciencedirect.com/science/article/pii/S221282711630854X (accessed on 5 June 2021).
73. Unterhofer, M. *Assessment Model for Industrial Companies to Define the Maturity Level of Industry 4.0 Implementation*; Free University of Bozen-Bolzano: Bolzano, Italy, 2018.
74. Barbato, M.; Ceselli, A.; Premoli, M. Evaluating Automated Storage and Retrieval System Policies with Simulation and Optimization. In *Advances in Optimization and Decision Science for Society, Services and Enterprises*; Springer: Manhattan, NY, USA, 2019; pp. 127–137.
75. Weber, C.; Königsberger, J.; Kassner, L.; Mitschang, B. M2DDM—A Maturity Model for Data-Driven Manufacturing. *Procedia CIRP* **2017**, *63*, 173–178. [CrossRef]
76. Anderl, R.; Anokhin, O.; Arndt, A. Efficient Factory 4.0 Darmstadt—Industrie 4.0 Implementation for Midsize Industry. In *The Internet of Things: Industrie 4.0 Unleashed*; Sendler, U., Ed.; Springer: Berlin/Heidelberg, Germany, 2018; pp. 117–131.
77. Paksoy, T.; Kochan, C.G.; Ali, S.S. *Logistics 4.0: Digital Transformation of Supply Chain Management*; CRC Press: Boca Raton, FL, USA, 2020.
78. Romero, D.; Stahre, J.; Taisch, M. The Operator 4.0: Towards socially sustainable factories of the future. *Comput. Ind. Eng.* **2020**, *139*, 106128. [CrossRef]
79. Naqbi, M.Y.K.K.A. Management 4.0 The impact of technologies in management organization. Information Technology innovations in Economics, Finance, Accounting, and Law. 2020, p. 1. Available online: http://www.alexpander.it/12-Management40.pdf (accessed on 5 June 2021).
80. Barreto, L.; Amaral, A.; Pereira, T. Industry 4.0 implications in logistics: An overview. *Procedia Manuf.* **2017**, *13*, 1245–1252. [CrossRef]
81. Winkelhaus, S.; Grosse, E.H. Logistics 4.0: A systematic review towards a new logistics system. *Int. J. Prod. Res.* **2020**, *58*, 18–43. [CrossRef]
82. Kuehnle, H. Post mass production paradigm (PMPP) trajectories. *J. Manuf. Technol. Manag.* **2007**, *18*, 1022–1037. [CrossRef]
83. Ruppert, T.; Jaskó, S.; Holczinger, T.; Abonyi, J. Enabling technologies for operator 4.0: A survey. *Appl. Sci.* **2018**, *8*, 1650. [CrossRef]
84. Romero, D.; Stahre, J.; Wuest, T.; Noran, O.; Bernus, P.; Fast-Berglund, Å.; Gorecky, D. Towards an operator 4.0 typology: A human-centric perspective on the fourth industrial revolution technologies. In Proceedings of the International Conference on Computers and Industrial Engineering (CIE46) Proceedings, Tianjin, China, 29–31 October 2016.

85. Çınar, Z.M.; Abdussalam Nuhu, A.; Zeeshan, Q.; Korhan, O.; Asmael, M.; Safaei, B. Machine learning in predictive maintenance towards sustainable smart manufacturing in industry 4.0. *Sustainability* **2020**, *12*, 8211. [CrossRef]
86. Kans, M.; Ingwald, A. Business model development towards service management 4.0. *Procedia CIRP* **2016**, *47*, 489–494. [CrossRef]
87. Röglinger, M.; Pöppelbuß, J.; Becker, J. Maturity models in business process management. *Bus. Process Manag. J.* **2012**. Available online: https://www.emerald.com/insight/content/doi/10.1108/14637151211225225/full/html (accessed on 5 June 2021). [CrossRef]
88. Ayres, R.U.; Kneese, A.V. Production, consumption, and externalities. *Am. Econ. Rev.* **1969**, *59*, 282–297.
89. Lee, H.-j.; Lee, S.; Yoon, B. Technology clustering based on evolutionary patterns: The case of information and communications technologies. *Technol. Forecast. Soc. Chang.* **2011**, *78*, 953–967. [CrossRef]
90. Adamuthe, A.C.; Thampi, G.T. Technology forecasting: A case study of computational technologies. *Technol. Forecast. Soc. Chang.* **2019**, *143*, 181–189. [CrossRef]
91. Ryu, J.; Byeon, S.C. Technology level evaluation methodology based on the technology growth curve. *Technol. Forecast. Soc. Chang.* **2011**, *78*, 1049–1059. [CrossRef]
92. Porter, A.L.; Cunningham, S.W.; Banks, J.; Roper, A.T.; Mason, T.W.; Rossini, F.A. *Forecasting and Management of Technology*; Wiley Online Library: Hoboken, NJ, USA, 2011.
93. Winsor, C.P. The Gompertz curve as a growth curve. *Proc. Natl. Acad. Sci. USA* **1932**, *18*, 1. [CrossRef] [PubMed]
94. Oh, H.-S. The Selection of Technological Forecasting Models in Life Analysis. 1988. Available online: https://lib.dr.iastate.edu/rtd/9709/ (accessed on 5 June 2021).
95. Kucharavy, D.; De Guio, R. Application of logistic growth curve. *Procedia Eng.* **2015**, *131*, 280–290. [CrossRef]
96. Council, N.R. *Persistent Forecasting of Disruptive Technologiesâ—Report 2*; National Academies Press: Washington, DC, USA, 2010.
97. Meade, N.; Islam, T. Forecasting with growth curves: An empirical comparison. *Int. J. Forecast.* **1995**, *11*, 199–215. [CrossRef]
98. EU; BCG; TUSISAD. *Digitalization for Productivity and Growth The Future of Productivity and Growth in Manufacturing Industries*; Boston Consulting Group: Boston, MA, USA, 2016.
99. Mittal, S.; Khan, M.A.; Romero, D.; Wuest, T. A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs). *J. Manuf. Syst.* **2018**, *49*, 194–214.
100. Özlü, F. The Advent of Turkey's Industry 4.0. *Turk. Policy Q.* **2017**, *16*, 29–38.
101. PricewaterhouseCoopers (PWC). *Endüstri 4.0: Çözüm Ortaklığı Platformu Dijital Dönüşümü Anlamak*; PWC: London, UK, 2015.
102. Roland Berger. *Industry 4.0—Challenge for the F&B industry in Turkey, Advantage or Competitive Disadvantage*; Roland Berger: Munich, Germany, 2017.
103. Schröder, C. The challenges of industry 4.0 for small and medium-sized enterprises. Friedrich-Ebert-Stiftung. 2016. Available online: https://www.researchgate.net/profile/Christian-Schroeder-24/publication/305789672_The_Challenges_of_Industry_40_for_Small_and_Medium-sized_Enterprises/links/57a1dfe808ae5f8b258a5e69/The-Challenges-of-Industry-40-for-Small-and-Medium-sized-Enterprises.pdf (accessed on 20 January 2021).
104. Stark, R.; Kind, S.; Neumeyer, S. Innovations in digital modelling for next generation manufacturing system design. *CIRP Ann.* **2017**, *66*, 169–172. [CrossRef]
105. The Boston Conculting Group (BCG). *The_Fourth_Industrial_Revolution_and_Its_Implications*; BCG: Boston, MA, USA, 2017.
106. Weyer, S.; Schmitt, M.; Ohmer, M.; Gorecky, D. Towards Industry 4.0-Standardization as the crucial challenge for highly modular, multi-vendor production systems. *Ifac-Pap.* **2015**, *48*, 579–584. [CrossRef]
107. PricewaterhouseCoopers (PWC). *Industry 4.0–Opportunities and Challenges of the Industrial Internet*; PricewaterhouseCoopers: London, UK, 2014.
108. Zhou, K.; Liu, T.; Zhou, L. Industry 4.0: Towards future industrial opportunities and challenges. In Proceedings of the 2015 12th International conference on fuzzy systems and knowledge discovery (FSKD), Zhangjiajie, China, 15–17 August 2015; pp. 2147–2152.
109. Park, S.H.; Kim, J.; Lee, S.; Lee, D.Y.; Lim, S.; Lee, J.; Kim, S.H. Organic thin-film transistors with sub-10-micrometer channel length with printed polymer/carbon nanotube electrodes. *Org. Electron.* **2018**, *52*, 165–171. [CrossRef]
110. Moeuf, A.; Lamouri, S.; Pellerin, R.; Tamayo-Giraldo, S.; Tobon-Valencia, E.; Eburdy, R. Identification of critical success factors, risks and opportunities of Industry 4.0 in SMEs. *Int. J. Prod. Res.* **2020**, *58*, 1384–1400. [CrossRef]
111. Horváth, D.; Szabó, R.Z. Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities? *Technol. Forecast. Soc. Chang.* **2019**, *146*, 119–132. [CrossRef]
112. Birkel, H.S.; Müller, J.M. Potentials of Industry 4.0 for Supply Chain Management within the Triple Bottom Line of Sustainability–A Systematic Literature Review. *J. Clean. Prod.* **2020**, 289. Available online: https://www.sciencedirect.com/science/article/pii/S0959652620356584 (accessed on 5 June 2021).
113. Müller, J.M.; Veile, J.W.; Voigt, K.-I. Prerequisites and incentives for digital information sharing in Industry 4.0–An international comparison across data types. *Comput. Ind. Eng.* **2020**, *148*, 106733. [CrossRef]