

Review

Assessment of Industry 4.0 Maturity Models by Design Principles

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Abstract: The fourth industrial revolution and accompanying digital transformation has progressed dramatically in recent years. The new digital revolution, mostly known as Industry 4.0, introduces impressive changes in the way enterprises and organizations are operating in a globalized world and altering the well-established lifestyle of a society. Therefore, it is of utmost importance to identify the current capabilities of companies in the context of Industry 4.0. Current literature on Industry 4.0 maturity and assessment models underlies the importance of a proper development strategy with exact steps to perform. Design principles address the issue of systematizing the measurable and attainable steps for further development. The present study contributes towards the identification of the research gap in the presence of core Industry 4.0 design principles during the development of maturity models. The analysis of 12 chosen maturity models by eight core design principles was provided. This research can serve as a starting point for the development of a complex strategic roadmap and thereby to provide a successful transition from traditional manufacturing into Industry 4.0.

Keywords: Industry 4.0; design principles; sustainability; maturity models

1. Introduction

The term “Industry 4.0” has traditionally been used interchangeably with the Fourth Industrial Revolution, which infers the digital transformation of production and manufacturing of related industries and value creation processes. The previous three industrial paradigm shifts were mechanical manufacturing, mass production, and then the digital revolution. Industry 4.0 (I4.0) as a merger of three previous eras of production in some way opens up great opportunities, such as the introduction of new production technologies and automated control systems and increasing the efficiency of the analysis of production processes using cloud computing [1–6].

The foundational understanding of I4.0 concepts, benefits, and advantages is considered to be among the main barriers towards its adoption by companies and enterprises [7–9]. The companies that aim towards digital transformation have to be ready to make changes in enterprise operations and processes and, therefore, need to have strong capabilities. In that regard, the **design principles (DPs)** of I4.0 play a crucial role in the digital transformation of enterprises and organizations. Among the tools that are widely used for this is **maturity models (MMs)**. The authors state that MMs are intended to evaluate business processes of organizations from diverse perspectives also referred to as dimensions to reveal the strengths and weaknesses critical for the adoption of digital technologies [10]. Accordingly, DPs should be a focal point of MMs to correspond with the core concepts of I4.0. Within prominent literature about I4.0, several key DPs for building I4.0 can be highlighted [11]. These DPs can be considered as indicators of the thorough MM, with the help of which an accurate assessment and successful deployment of I4.0 systems and sustainable development in the organization is possible [12].

I4.0 concepts and technologies are tightly bonded with sustainability by providing circular economy, sustainable supply chains, and value chains, and enabling monitoring the full product lifecycle [13]. Additionally, some critical success factors for integrating I4.0 with sustainable development have been identified, such as transparency, resource efficiency, and creating knowledge through digitalization in the usage of Internet of Things (IoT) systems. Hence, the analysis of the enterprises and organization readiness towards I4.0 through the prism of DPs implies the core concepts of sustainable development. The implementation of DPs means the construction of I4.0, focused not only on the creation of intelligent processes and products but also on the intellectualization of the economy in general. There is a research gap in the method of developing the I4.0 MMs based on those DPs. In that regard, the main aim of this paper is to provide an analysis of maturity/assessment models from the perspective of having the core Industry 4.0 DPs.

As the foundation of the research, the main research questions of this study are:

- RQ1: What are the key DPs that are referred to as the pillars of I4.0 concept?
- RQ2: What are the most prominent Maturity Models that are dedicated to supporting I4.0 implementation in companies?
- RQ3: What are the research gaps in MMs that prevent Industry 4.0 adoption?
- RQ4: How Industry 4.0 MMs can be improved based on the identified research gaps?

To address the research questions, this article is structured as follows: Section 2 provides a research methodology consisting of 6 steps. Furthermore, in Section 3, an exhaustive literature review on I4.0 DPs and MMs is provided. Next, in Section 4, the analysis of maturity and assessment models in the presence of DPs is given. Consequently, the identification of gaps based on DPs in MMs is prepared, and the discussion of analysis and results obtained is provided in Section 5. Finally, in Section 6, the conclusion is presented.

2. Research Methodology

Systematic literature review (SLR) is a powerful tool for the synthesis of data from the existing body of knowledge, which provides authors with the quality and comprehensive data to support research [14]. SLR is also known as a source of unbiased information summarized from the available literature; therefore, this study follows the guidelines provided by [15] that are based on the best literature review methodologies.

The detailed overview of the steps illustrated in the flowchart is as follows:

Step 1: Search by keywords and initial screening.

A comprehensive search of the literature related to Smart Manufacturing and Industry 4.0 by the use of the “AND” operator was conducted. Since the methodology aims to consider two separate research topics and to avoid the repetition of the tasks, the twofold set of keywords and search strings obtained from a combination of generic terms such as “Industry 4.0”, “Digitalization”, “Smart Manufacturing”, and “Digital transformation” with the corresponding keywords design principles/maturity models or other related keywords/concepts, as shown in Table 1, were utilized. A search was performed within the scientific databases Scopus, Web of Science (WOS), and Google Scholar (GS) to cover not only journal and conference articles but also to collect industrial reports of the corporate entities engaged in the topic. The initial search resulted in the identification of 166 journal/conference articles and 71 industrial reports that can potentially contain information about Industry 4.0 DPs and MMs.

Table 1. Keywords and search strings used for initial screening.

Industry 4.0 Design Principles
“Industry 4.0 AND design principles”; “Industry 4.0 AND principles”; “Digitalization AND principles”; “Digital transformation AND principles”; “Sustainable AND development”; “Sustainability”; “Industry 4.0 AND Servitization”.
Industry 4.0 Maturity Models
“Industry 4.0 AND maturity model”; “Industry 4.0 AND readiness index”; “Digital maturity AND assessment”; “Industry 4.0 AND assessment model”; “Industry 4.0 AND maturity level”; “Industry 4.0 AND maturity evaluation”; “Roadmap AND Industry 4.0”; “Industry 4.0 AND manufacturer’s capabilities”; “Industry 4.0 AND capability maturity”.

Step 2–3: Identification of the exclusion criteria, review, and identification procedures.

To eliminate irrelevant documents and identify the papers that aim to answer the research questions, the exclusion criteria for the close-up review were determined, which include:

- EX1: A paper is only partially available in English—e.g., abstract and keywords are in English, but the rest of the paper is in the other language;
- EX2: A paper is not available in full text or the access to the document is restricted;
- EX3: A paper is of insufficient credibility—i.e., a document is informal and reflects personal viewpoints without referring to the valid resources;
- EX4: A paper does not provide the research on Industry 4.0—e.g., a document includes Industry 4.0 as a keyword, but does not use it as the main topic;
- EX5: A paper does not contain the information on the Industry 4.0 DPs both explicitly and implicitly;
- EX6: A paper does not or only partially contain the information on the Industry 4.0 MMs—e.g., a document includes the clarification of the assessment criteria, but does not discuss the maturity levels and vice versa;
- EX7: A paper does not contain a detailed explanation of the Industry 4.0 DPs or only mentions them implicitly;
- EX8: A paper is the review article of the existing MMs and does not propose any novel MM;
- EX9: A paper does contain the information on the newly proposed MM, but the purpose of the model is not related to Industry 4.0.

During the first iteration of the manual review and analysis of the papers, the criteria EX1–EX6 were applied, which as can be seen from Figure 1 resulted in the selection of the 17 articles and 8 reports on the I4.0 DPs, as well as 69 articles and 17 reports on the I4.0 MMs. The in-depth perusal of the literature set identified a substantial number of review papers focused on the comparison of the existing MMs. Although these papers were recognized as the reference for the research, based on the EX8, these articles/reports were removed. Likewise, articles that did not comply with the EX9 criterion were excluded.

As regards DPs, the share of such papers constitutes only around 10% of the constructed pool of literature. Some of the papers do not explicitly discuss and provide clarifications on the principles or implicitly mention them in the text; therefore, according to the EX7, these documents were eliminated. After the second iteration of the review, 12 articles, and 5 reports corresponding to the I4.0 DPs identification, 13 articles and 8 reports containing data about the most relevant MMs were considered in this study. The full list of identified MMs is illustrated in Table 2, while the I4.0 DPs identified are explained in detail in the following section.

Step 4–6: Comparing maturity models, finding research gaps, and results and discussion

According to the review, none of the authors consider both of the I4.0 DPs and MMs in one publication, except [10] that provide the matching tables of the principles, MM dimensions, and associated technology enablers. Moreover, the existing review articles focusing on the comparison

of MMs that were removed at stage 2 did not consider the presence of the Industry 4.0 principles in the structure of the models. Therefore, this study strives to fill the research gap by providing an overview of development methods and comparison of identified 16 MMs by DPs in Section 4. Finally, the results and conclusions synthesized from the comprehensive review of the MMs by DPs and identified gaps were used for responding to the research questions and discussed in Section 5.

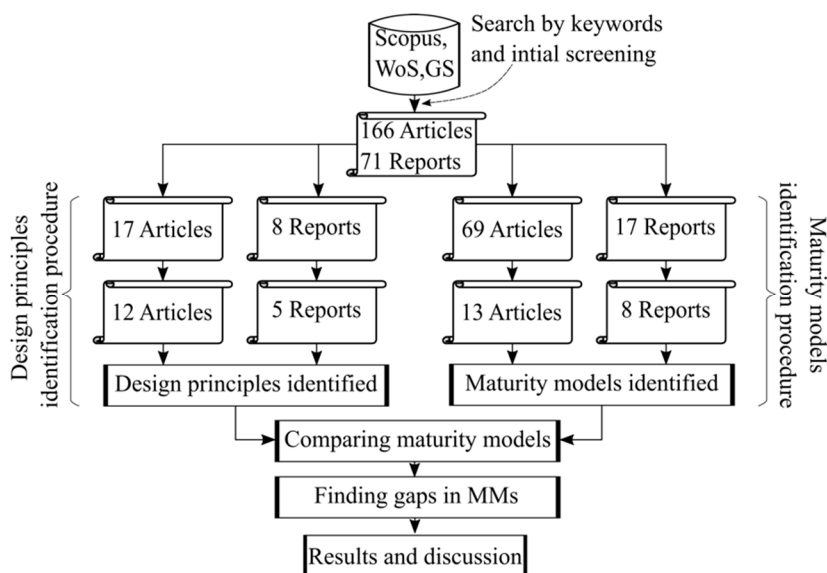


Figure 1. Methodology flowchart applied in the paper.

3. Literature Review

3.1. Industry 4.0 Design Principles

DPs address the issue of the gap in the knowledge for implementing Industry 4.0 and aim to systematize it [16]. It serves as a basis and the very first steps, which need to be taken to enhance the potential of I4.0 [17]. After conducting a thorough literature review, it was identified that the design principles currently have very tight intersections with characteristics of I4.0 in general. More than that, these terms started to be used interchangeably in various resources [18,19]. Thus, because of the different perceptions by authors of the design principles, it is a challenging task to list all those mentioned. However, the thorough literature review helped to identify the most often mentioned 6 design principles, which are Interoperability, Virtualization, Decentralization, Real-time capability, Service orientation, and Modularity. Each indicated design principle contains the idea to bring a more sustainable approach to any industry transforming to I4.0. Additionally, the reason for adding 2 additional design principles, even though they are not so frequently mentioned, Smart product (as the idea of the product which harms the ecology as less as possible) and Corporate Social Responsibility (CSR, with the idea of creating better working conditions for employees while not harming the environment) was to pay more attention to sustainability, which is among the major goals of the 4th Industrial Revolution.

The first design principle is *interoperability (DP1)*, which relates to the ability of devices, equipment, people, and other objects to communicate and share data. Applying new technologies may not embrace the full capabilities of it without a proper system of information exchange [11]. Interoperability fulfills this need by providing systematic communication between humans and humans, machines and human, and machines and machines [20]. Interoperability may be achieved through different tools (enablers) such as the Internet of Things (IoT), Internet of People (IoP), and Internet of Everything (IoE), etc. [21].

Virtualization (DP2) reflects the capabilities of the system to turn physical world data into virtual [16]. Virtual data can enrich the decision maker's perception by the possibility to monitor the conditions of the equipment in real-time, to perform the "what if" scenario, and identify bottlenecks in the systems [11,22,23]. Digital data may be enriched by enablers such as sensors, augmented (AR), and virtual reality (VR) [24]. As a result, the cost of data collection and its management will decrease, and it will allow avoiding third-party applications and intermediaries [25].

Decentralization (DP3) is an important attribute to gain agility and flexibility [26]. Decentralization is the capability of the cyber-physical systems (CPS) to commit actions and take decisions autonomously. Additionally, it is among the major keys to achieving better productivity. Technologies supporting decentralization are CPS, IoT, smart actuators and sensors, artificial intelligence (AI), and others, which are able to communicate, share information, and control all manufacturing processes. Thus, systems will be sensitive to all minor changes, which allows making the process of reconsideration of the fixed plans much easier, more flexible, and even provide potential solutions [27].

Real-time capability (DP4) means a capability that can collect, transfer, analyze, monitor, and share the data in real-time [16]. Real-time data processing and analysis can speed up the decision-making process, help to track production processes, identify anomalies, identify optimization opportunities, and even observe microtrends. Scanners, robots, Radio Frequency Identification (RFID), and other devices with connected IoT are among the technologies that are able to capture real-time data [28]. Cloud computing and big data can be a perfect tool for data analysis and processing in real-time, having analytics embedded into the system, and helps to identify bottlenecks in the supply chain. In general, this approach forecasts the failures or required maintenance, optimizing the process, and increasing productivity [29].

Nowadays, the new business strategy assumes the creation of new complete solutions to the customers instead of offering products only. Therefore, businesses need to focus not only on product creation but on a **service orientation (DP5)**. This can be achieved by the integration of people with smart tools with the help of the Internet of Service (IoS) [16]. In other words, the connection of CPS with services that the company offers allows creating a new type of service, which is useful to other companies, people, and even to other systems. Thus, IoS as a platform combines services within the company and outside of it, offered both by humans and other intelligent systems. It creates additional value through the efficient integration of all parties, allowing companies to be up to date and create new revenue channels [30].

Modularity (DP6) is the capability of the businesses to change or adapt to different situations, whether it causes external or internal needs [19]. Additionally, the modular system can be changed and can be adapted to changes [28]. This helps to save implementation and adoption time and quickly and effectively respond to demand fluctuations. Furthermore, the modular approach positively affects and increases the sustainability of the processes, if used in production, design of the product, or even delivery [21]. Enablers such as industrial robotics, additive manufacturing, AR, and VR advance the modular systems and increase agility and flexibility [31]. However, modular systems supported by big data, IoP, and simulation tools, which analyze customer and market tendency, simplify the customization process, making it another revenue channel of the company [32].

Smart product (DP7) is a modern product with embedded devices, which can collect, store, and transfer data [11]. Modern smart products are connected with manufacturing processes by providing information about the manufacturer, the current status of the product, and the overall life-cycle history. Moreover, the capabilities of the products allow them to perform analytics and computing algorithms. All these capabilities are the key features of smart products, which eliminate the boundaries between the physical and digital worlds [33]. However, the features of the smart products not only defined by tools but with the transformation to the products, which can be recycled, thus improving the ecological situation and applying sustainable development goals [34].

Corporate Social Responsibility (CSR) (DP8) is self-regulation which is integrated into the business model [11] and assumes that business activities do not harm society. With the development

of new technologies, the skill level of the employees arises in parallel. Therefore, companies need to focus on the development and upgrading of the employees' skills through continuous training and workshops [35]. Additionally, the I4.0 concept enables great opportunities for the development of sustainability in factories, which positively affects the environment by resource usage decrease, energy-efficient use, fewer emissions, and others [36].

3.2. Industry 4.0 Maturity Models

Maturity Models are the means of measurement and matching a concrete set of capabilities required for the companies to reach the desired state [37]. They are designed as the logical path represented by separate maturity levels so that the most mature company is the one that possesses all the capabilities to reach its objectives. These models are expected to disclose the current organizational deficiencies that need to be fixed before commencing the maturation process specifically defined by each maturity stage. Additionally, it can be used for benchmarking to compare a state of company progress at different points of time along its development path, and to identify the performance gap concerning other market players [38].

MMs vary in measurement criteria, number of maturity levels, methodology, etc. Taking that into account and according to the methodology used in the paper, overall, 16 models were selected and used for further research. The models are introduced in Table 2 with a short description, which includes the main points about the models.

Table 2. Maturity models description.

No.	Maturity Model	Description
MM1	Acatech Industrie 4.0 Maturity Index [39]	Focus on manufacturing enterprises and aimed to be a guidance for organizations to develop their own strategy for Industry 4.0 (I4.0) implementation. Contains 6 value-based development stages and 4 structural areas. Five maturity levels with explanations of each level are included. Questionnaire includes 77 questions; however, it is not publicly available.
MM2	Digital Readiness Assessment Maturity Model (DREAMY) [40]	Focus on the manufacturing industry, with the aim to assess the process of digital transformation. Four dimensions and 5 maturity levels with clear definition provided for each level. Maturity assessment survey consisted of 200 questions.
MM3	IMPULS—Industrie 4.0 Readiness [41]	Aimed to examine willingness and abilities of the companies in the area of mechanical and plant engineering to apply the I4.0 concept. Comprises 6 dimensions and 6 maturity levels with a description for each level. Assessment survey has 24 questions, and online assessment available. A detailed report after assessment is provided, with guidance on how to improve the current level for each dimension.
MM4	The Connected Enterprise Model [42]	The model offers technology as I4.0's main enabler and focuses on large enterprises. Four dimensions listed; however, no information provided related to aspect dimensions and the creation process. An action plan with 5 stages to assess the company is presented.

Table 2. Cont.

No.	Maturity Model	Description
MM5	Industry 4.0 Maturity Model [43]	Software process improvement and capability determination (SPICE) was used as a basis and more oriented towards multinational enterprises (MNEs). It includes 5 dimensions and 6 levels of maturity from “incomplete” till “optimizing”. Lacks a method of assessment and survey questions.
MM6	Industry 4.0 Maturity Model [37]	Nine organizational dimensions with 62 sub-criteria presented. Focus on manufacturing companies and MNEs mainly. Five maturity levels for each dimension provided. The assessment method is a questionnaire from 123 questions. Sub-criteria and questions not provided in the report.
MM7	Maturity and Readiness Model for Industry 4.0 Strategy [10]	Four maturity levels with 3 main dimensions provided in detail. A thorough analysis of technologies for I4.0, and a clear methodology on which the model was based is provided. The full questionnaire is presented in the paper with an example from the retail sector. Enhancement could be made in the development of final reports after assessment surveys on how to improve the company’s current position.
MM8	Reference Architecture Model Industrie 4.0 (RAMI4.0) [44]	RAMI differs from traditional MMs and does not intend to evaluate companies’ maturity level towards I4.0. Instead, it is in the format of a map showing how to structure issues of I4.0 and involve all stakeholders. It also includes all IT components, presented in a layer, and life-cycle model. RAMI was already recognized as a fundamental model that drives organizations to implement I4.0.
MM9	System Integration Maturity Model Industry 4.0 (SIMMI 4.0) [45]	Focuses not to assess organizations towards I4.0 as a whole but aims to assess its IT capability. Four dimensions and 5 maturity stages included. Fifteen questions divided into five sections provided, along with assessment methods of the final level.
MM10	Three-Stage Maturity Model [46]	Three main dimensions with 5 maturity levels presented. Model could be applied by small and medium-sized enterprises (SMEs); however, it will be difficult without guidance, since it lacks of details regarding assessment methods or survey questions, which makes it difficult to assess comprehensiveness of the model.
MM11	Digital Operations Self-Assessment (PwC) [47]	Focuses on digitization of the organization and oriented to large enterprises. Seven dimensions and 4 maturity levels included. Online self-assessment tool available, also steps for development of Industry 4.0 strategy implementation and pilot initiatives suggested.
MM12	Maturity Model for Industrial Internet [48]	Focuses more on adoption of IoT technology in manufacturing enterprises. Five maturity levels presented in the report; however, it lacks information regarding defined dimensions as well as assessment tools and methods.

Table 2. Cont.

No.	Maturity Model	Description
MM13	Singapore Smart Industry Readiness Index—SIRI [49]	Based on 3 building blocks and 8 Pillars. Sixteen dimensions with 6 maturity levels are also presented. All parts include a detailed description, as well as a comprehensive explanation of the general concept of I4.0 and its benefits.
MM14	Digitalization Maturity Model for the Manufacturing Industry [50]	Detailed description of 9 dimensions included. It also consists of 5 maturity levels and 90 process areas. Focuses on the manufacturing industry; however, the scope of the model underlies the supply chain area, mostly. No information about evaluation given, neither any questionnaire provided.
MM15	Maturity Model for Data Driven Manufacturing (M2DDM) [51]	Focuses on analysis of IT architecture of the companies in the manufacturing sector. Six dimensions included with 6 maturity levels. Reports lack information about model development methodology as well as assessment methods.
MM16	WMG Model [52]	F maturity levels, 6 dimensions, and 29 sub-dimensions included. The difference of this model is in the assessment tool which is used in table format. Additionally, maturity level is calculated for each dimension, which makes analysis more detailed. Online assessment also available, as well as report provided.

4. Analysis of the Maturity Models by Design Principles

As the analysis of the application of I4.0 design principles in maturity models was provided, there was an obstacle in the form of restricted access to the full information about some maturity models. Particular maturity models—MM2, MM10, MM12, MM14—were not used in the following analysis.

In this section, the analysis of MMs based on the availability and presence of Industry 4.0 DPs is provided. The analysis contains the presence of design principles: DP1—Interoperability, DP2—Virtualization, DP3—Decentralization, DP4—Real-time Capability, DP5 – Service Orientation, DP6—Modularity, DP7—Smart Product, DP8—Corporate Social Responsibility. Furthermore, within the analysis, to what extent a particular design principle is present in the MM (Basic, Low, Moderate, and High) and examples of this(in dimensions, sub-dimensions, maturity levels, and questions) are presented.

During the provision of analysis part, the objectivity of research was prioritized so that findings would be based on the nature of MMs and the thorough and extensive literature review provided. The main aim of this part was to be as asymptotically accurate as possible to provide high reliability and credibility of analysis of MMs by DPs. For each DP, the level of presence was provided for MMs. “Basic” level represents certain DP in the model presented at a very low level or that information is not available in open access. “Low” level represents that certain characteristics of particular DP are present within the structure of MM and are implicitly stated. “Moderate” level represents that the majority of particular DP characteristics are present in MM and explicitly stated. “High” level indicates incorporation of all the aspects and components of a particular DP in the MM structure. The summary of the analysis of 12 MMs by 8 design principles of Industry 4.0 can be seen in Table 3, which is discussed in detail below.

Table 3. Assessment of maturity models by I4.0 design principles. (B: Basic, L: Low, M: Moderate, and H: High).

MM/DP	MM01	MM03	MM04	MM05	MM06	MM07	MM08	MM09	MM11	MM13	MM15	MM16
DP1	H	H	L	M	M	H	H	L	H	H	H	H
DP2	H	H	M	H	H	H	H	M	H	H	H	H
DP3	H	M	L	M	M	H	H	M	H	H	L	B
DP4	H	H	M	H	H	H	H	M	H	H	H	H
DP5	M	H	L	L	H	H	B	H	M	H	H	H
DP6	H	H	H	H	H	H	H	H	H	M	M	H
DP7	M	H	M	M	H	H	H	B	H	M	B	H
DP8	M	H	L	M	H	H	B	B	H	H	B	H

(1) MM1: DP1 (High) is measured in the model through the assessment of human–machine connectivity, integration and transparency of IT systems, standardization of data interfaces, and compliance with IT security standards in Task-based interface design, Vertical and Horizontal IT integration, Standardized data interfaces, and Upgrade IT security sub-dimensions. MM1 evaluates the DP2 (High) in Deliver contextualized information, Efficient communication, and Task-specific user interface sub-dimensions of the model that is expected to facilitate the provision of the context-specific and valuable data across the organization and beyond. DP3 (High) is measured in Decentralized (pre-) processing of sensor data sub-dimension of the model. This sub-criterion emphasizes the importance of embedded systems, sensors, and actuators in developing CPS and also for production efficiency, as autonomous systems that can perform independently and reduce decision-making latencies. DP4 (High) assessment is present in the Automated data analysis sub-dimension; real-time information is a key element of data-based decision-making that should cover all the production activities. Moreover, in the Efficient communication sub-criterion, it is stated that real-time access to necessary data speeds up the approval procedures. DP5 (Moderate) principle is present in the Focus on customer benefits sub-dimension of the model as part of the Organizational Structure assessment. This highlights the importance of constantly reviewing competencies to satisfy customers. DP6 (High) is in perfect alignment with the adaptability maturity level of the model (Stage Six), which includes the requirement for IT systems to uptake certain decisions to provide predictive capacity. The goal of the adaptability is to facilitate the decision-making extracted from the digital shadow and to enact required measures in the shortest time frame, without human interaction. DP7 (Moderate) principle is analyzed in data acquisition through sensors and actuators sub-criterion of the model. Many of the companies that attempt to build CPS do not use the sensing information to its full potential, but rather collect information to observe the basic physical parameters of the products [39]. Thus, based on this, the assessment of the data acquisition features of the products can be recognized as DP7. Lastly, MM1’s sub-dimension about providing digital competencies states that the advancement of information technologies necessitates the appropriate training of the workforce from the companies, which directly corresponds to the DP8 (Moderate) principle. In sum, MM1 covers 5 design principles at a high level and 3 of them at a moderate level, which indicates that the model does imply the usage and appliance of I4.0 design principles.

(2) MM3: DP1 (High) and DP2 (High) are both measured in the Smart Factory dimension. I4.0 involves digital modeling through the gathering, storage, and processing of data, which facilitates a more efficient delegation of resources and information. However, the operational data do not carry any benefit unless processed via the digital model of production, which correlates with DP2 [41]. DP3 (Moderate) occurs in the Autonomous Processes sub-dimension of the Smart Operations criterion wherein the concept of self-guiding manufacturing entailing the autonomous governance and self-optimization of the production by the work pieces themselves is explained, which in turn is the main idea behind DP3. DP4 (High) is also widely presented in the Smart Factory dimension assessment (real-time data collection and analysis bring transparency into business operations and makes the

production process more flexible enabling simulations that add to the quality of the business). MM3 is in complete accordance with DP5 (High). Data-driven Services dimension indicates the main objective of it is to transform the existing business models to better suit customer expectations. DP6 (High) is presented in the evaluation of to what extent are the processes automatized (maturity level 5 (Top performer) indicates that the companies that ace in the I4.0 implementation have already some areas of production characterized by the presence of self-guiding work pieces and self-reacting processes). DP7 (High) is discovered in the Smart Product dimension (evaluates the availability of the ICT functionalities in the final products as well as of those engaged in production, to what extent the data collected from the usage phase are analyzed, and in which sense these data influence the creation of new services). Lastly, DP8 (High)—the Employee dimension measures employees' skills in various areas related to I4.0 and the company's efforts to acquire new skills. In summary, this is one of the most iconic I4.0 maturity assessment models that is frequently reviewed in the literature. It provides a thorough examination of the principles and capabilities required for the digital transformation of the mechanical and other engineering industries. Moreover, it covers almost all design principles to a high extent, which indicates that the model was developed in great accordance with I4.0 core concepts.

(3) MM4: DP1 (Low) is presented in Stage 1 (evaluation of the existing hardware/software systems, controls, and devices). Then at Stage 1, the extension of the facility and new technologies begins, and companies have the first opportunity to control equipment performance in real-time, which can be characterized as the basic feature of DP1. DP2 (Moderate) is presented at Stage 3 maturity level (teams organized for the IT/OT upgrade, define, and organize the organization's working data). Moreover, certifications and regulatory compliance programs become available for customers in real-time [42]. Stage 4 (Analytics) maturity level of the model indicates that IT/OT capabilities shift the culture so that the real-time access to the data starts to be used for the prevention of problems. Built-in mechanisms automatically respond to the problems with the help of analytics, which along with continuous improvement principles lead to substantial savings. This adaptability capacity corresponds to DP3 (Low). DP4 (Moderate) is indicated at the 3rd stage maturity level (defined and organized working data capital (WDC) standardize and normalize all the data to maintain the flow of the critical for decision-making information across the IT/OT networks). This information in turn can be used for real-time monitoring of business processes and decision-making. DP5 (Low) is not explicitly included in the report. However, in the description of the Stage 5 maturity level, companies that reside at Stage 4 that involve the emergence of the data analytics and continuous improvement principles could have a resistance that prevents optimum collaboration until they determine how the improved collaboration can influence the quality of the products and prices. Hence, it is reasonable to assume that at this stage companies already consider DP5. DP6 (High): at the last 5th stage of maturity (Collaboration), the company begins to coordinate activities from the outside suppliers and customers. The established IT/OT systems develop responsiveness for the market trends, political events, and even weather conditions to minimize the extent of negative outcomes. At this stage, predictive maintenance emerges that contributes to the improved quality of the products, effective planning, and execution of the tasks. DP7 (Moderate) appears at the Stage 3 maturity level, where the IT/OT systems incorporate the data gathered from OT devices to be further used for critical decisions. In the previous stage, IT and OT departments collaborate to design intelligent networks, which cannot be deployed without smart products. DP8 (Low): across the whole structure, the model emphasizes the impact of the culture on the progress of a company. It is indicated that there might be resistance from engineers and technicians toward the renovation of the IT/OT systems. Additionally, as the company moves through the stages, the digital literacy/skills of employees develop accordingly, as the managers begin to have different perspectives on data management. In summary, MM4 provides a multifaceted development roadmap toward the enablement of full-fledged IT/OT systems that contribute to the creation of competitive advantages. Furthermore, it managed to cover the basics of I4.0 design principles. However, it can be used only as a reference source for the companies attempting to adopt the I4.0 because it is only

available in a descriptive manner unless the company subscribes to the service provision from the Rockwell Automation.

(4) MM5: DP1 (Moderate) is indicated in the Application Management assessment dimension, which aims to value the design of information systems and claims that the interfaces and applications' data flow of a company should be structured, standardized, controlled, and interoperable. These are perceived as DP1's main characteristics. DP2 (High): at the initial stages of I4.0 transformation as indicated in the model, each item of the enterprise system ought to be reflected digitally. Furthermore, at Level 2 (Managed) of the maturity, physical entities of the company have their own digital shadow. Thus, both of the requirements correspond to DP2. DP3 (Moderate) is reflected a maturity Level 3 (Established), where machines and equipment installed with sensors and actuators are vertically integrated with Enterprise Resource Planning (ERP) systems. High integration level of physical assets along with business processes reduce the decision-making burden, to grant a degree of independence for operational systems. DP4 (High) can be seen in the Data Governance dimension, which measures the data gathering, usage, big data and analytics, and data-driven services. This allows organizations to perform real-time decisions, and at Level 4 (Predictable), companies use data to control operations in real-time. DP5 (Low) analysis is also present in the Level 4 (Predictable) maturity stage of the model, where the diverse functionalities of the enterprise are integrated to reach better optimization, which involves the integration of Supply Chain Management (SCM) and Customer Relationship Management (CRM) applications. The integration of these applications does imply the service orientation of the company. DP6 (High) is present in the model's final level of the maturity scale, where it is stated that the business transforms into an innovative structure, which entails the utmost degree of synergy between product and service development. Moreover, the company commences to learn from the data and embarks on the continuous improvement of the processes, which along with the self-optimization, altogether conforms to modularity. DP7 (Moderate) is evaluated in the Asset Management dimension, which measures the support of advanced technologies such as IoT, Cloud Computing, Industrial Wireless Networks, and so on throughout the organization. The networking equipment, hardware, and other applications are mentioned as critical factors for the implementation of these technologies, which conforms with the principle. DP8 (Moderate) is included in the Organizational Alignment dimension. Overall, MM5 offers the profound scrutiny of the enterprises by covering all the design principles. Although the model is well-structured and logically organized, it does not provide real case application examples, thus decreasing its application value. Additionally, the methodology of MM5 was outlined but not explained in detail.

(5) MM6: DP1 (Moderate) can be seen in the Value Creation Processes dimension, which measures the data exchange between machines, humans, and robots. Moreover, the digital compatibility and collaboration item of the Product dimension also comply with DP1. DP2 (High) is presented in the Data and Information dimension, which measures digital modeling, simulation, and process visualization inside an organization and reflects the availability of the digital operational data. Open access for such data contributes to faster data exchange, which is the very goal of DP2. DP3 (Moderate) occurs in the Value Creation Process dimension. It gauges the degree of remote control and autonomy of machine park, which means that the smart systems of a firm have an appropriate degree of autonomous decision-making through the enablement of the networked communication among machines and equipment, hence reducing the operational delays, which can be recognized as the characteristics of DP3. DP4 (High) is evaluated in the Data and Information and Technology dimensions. Technological readiness of the physical and virtual infrastructure of the company associated with Technology, as well as automated extraction, exchange, analysis, and transfer of data among the enterprise-wide IT systems related to Data and Information contribute to real-time access, exchange, and analysis of the data. DP5 (High) is analyzed among two of the maturity items. Product individualization is measured in the Product dimension, while the customer integration and IT collaboration in product development are evaluated in the Customer and Partners. The focus of the company on product customization, immediate interaction with customers, and collaboration in product development are the hallmarks

of DP6. As the hardware enabler of DP6 (High), the Technology dimension of MM6 contemplates the adoption of the technologies necessary for the increased flexibility and agility of the organization, which along with the data analysis, simulation of future scenarios, and data-based decision-making associated with the Data and Information dimension provide the company with the self-optimization capacity and correspond to DP6. DP7 (High) is covered in the Product dimension by analyzing maturity items such as product individualization, the flexibility of product features, gathering product information, and the internet connection of the products. DP8 (High) is measured in Employee dimension, which analyses the perception of the I4.0 technologies, digital competencies, awareness of cybersecurity, and willingness for training on the job of the workforce [37]. In conclusion, MM6 is a well-designed analysis tool for I4.0 capabilities that cover the majority of the design principles to a high extent. It can be used for the calculation of the maturity index for the companies because the methodology is publicly available. MM6 contains a practical implementation case, which partially discloses the evaluation process. The model can be used as a practical means for the establishment of the digitalization roadmap due to its rigorous design and easy to understand methodology.

(6) MM7: DP1 (High) is explicitly indicated in every dimension and all four maturity levels of MM7. The list of measuring principles and corresponding technologies is provided for every dimension, where interoperability is widely present. DP2 (High) is indicated in the Smart Business Processes dimension that evaluates the functional operations of companies. One of the questions aims to detect whether a company is offering remote diagnosis and repairs services, which reflects a feature of DP2. DP3 (High) is also widely present in every maturity level of MM7. For example, at Level 2 (Survival), companies are ready for decentralization, as the business processes in terms of integration, data exchange, collection, and use are at the middle level, while at Level 3 (Experienced), companies are characterized by the high degree of decentralization that is implemented in almost all processes. DP4 (High) is analyzed throughout the whole survey, particularly the questions such as: “What is the level of real-time traceability of the operations in the digital environment? (Digital-twin concept)” and “Do you conduct real-time profitability analysis?”, all in alignment with this principle. DP5 (High) is measured in the strategy and organization dimension, where it is stated that companies should be aware of the “as a service” business model, which involves offering the products that support advanced technologies and contribute to the high individualization of the products. Moreover, digitally mature organizations should generate more than 10% of the revenue from the use of data-driven services. Both requirements closely correlate with service-orientation. DP6 (High) is defined differently, and in [10], agility is used instead of modularity, which means the same. This is reflected in a few questions—for example, in the Smart Processes dimension: “How is the data you collect used in production?” detects whether a company uses the data for optimization of resource consumption. Furthermore, the question: “How is the data you collect used in logistics and procurement?” evaluates the supplier risk management that detects supplier failures early on. DP7 (High) is measured in the Smart Products and Services dimension. At the highest maturity level, companies’ products should be capable of communicating with other systems, collecting, and storing data. Lastly, the Strategy and Organization dimension provides an analysis of DP8 (High). It requires companies’ employees to have an appropriate competence in digital technologies, regular training for the digital transformation in the company, and data-driven organizational units composed of data scientists. Overall, MM7 contains all the design principles necessary for the I4.0 to a high extent. The methodology of the model is fully available so that it can be immediately used as an assessment tool of the capabilities required for the digital transformation. However, it does not provide any recommendations for the future improvement of maturity for organizations.

(7) MM8: DP1 (High) takes place in the Communication layer of the model. At this layer, at least one information system must maintain a connection with the object that can be machinery, human, or any sub-system. This connectivity between the systems and objects and vice versa is the main characteristic of DP1. DP2 (High) principle is reflected in the Information layer of the model. The basic requirement for the I4.0 compliant communication is the availability of the virtual representation of

an I4.0 component in the object itself or in an IT system that might possibly contain an individual component's data, CAD drawings, lifecycle phases, manuals, etc. [44]. DP3 (High) appears in the Functional layer of MM8. It is defined as the place where the decision-making logic is established. Besides the Functional layer, the business tasks can also be executed on the Integration layer that captures the changes in the physical assets, which in turn trigger the events in the Information layer. The Functional layer integrates all the pre-processed data coming from below, which align with DP3. DP4 (High) appears in the Life Cycle and Value Stream dimension. It is reported that I4.0 can bring about substantial improvement in the value streams. All the digital manufacturing stakeholders including factories, partners, suppliers, customers, etc. have a real-time view of the product lifecycle and associated value-added process, which corresponds to the essence of DP4. DP6 (High) is also considered in MM8. In particular, based on the definition of the I4.0 component provided in the report, among its intrinsic capabilities is nestability, which is referred to as the highest degree of modularity, so that an independent component may be grouped to form a single component that can be further exploited as a part of another component. This modularity in turn is applied to the Business layer, where the processes adjust themselves to changes. According to the Functional layer of MM8, an I4.0 component apart from data should also possess a technical functionality, which includes the planning software, value-added, and specific technical functionalities relevant for a particular business model. This definition of the necessary product functions matches DP7 (High). In summary, MM8 takes into consideration almost all of the design principles associated with I4.0. Although the degree of details of the model is high, it does not cover such less technical aspects as the service orientation and corporate social responsibility. MM8 can be used as a guiding map to I4.0, but not for the evaluation of the companies with regard to their current capabilities. Furthermore, it can contribute to the common understanding of the idea behind the I4.0 and the general digital literacy of the industry.

(8) MM9: DP1 (Low) is measured in the Vertical and Horizontal dimensions of the model where the enterprise modules are analyzed on the transparency of data flow and data security. DP2 (Moderate) is analyzed by digital product development and cross-sectional technology model criteria. MM9 is focused on the classification of enterprise-wide IT and software landscape; therefore, the analysis of an enterprise's technological abilities implies the digitization of all the data flow and the maintenance of equipment through cloud services, which somewhat reflects the essence of decentralization. DP3 (Moderate) is analyzed via all dimensions of MM9 because each of them partially provides information about the actual state of IT appliances including big data, IoT, cloud services, and data security. DP4 (Moderate) is also measured in each dimension of MM9 because the usage of well-developed IT infrastructure with optimized full digitization characteristics by an enterprise implies the real-time capability of enterprise processes. The highest stage of MM9 corresponds to the characteristics of simulation and optimization of value and information flows in real-time. The availability of DP5 (High) platforms in an IT landscape is implied from Stage 2 to the highest Stage 5 maturity level of the model. Stage 5 provides the information that capabilities of the enterprise's IT infrastructure to promptly adjust to new risks and immediately solve occurring problems correspond to DP6 (High). In summary, MM9 covers the majority of design principles to a moderate and high extent.

(9) MM11: DP1 (High) is analyzed by the Market and Customer Access, Value Chains and Processes, and IT Architecture dimensions in the model. This is implied by contributing digital technologies such as mobile devices, IoT platforms, cloud computing, advanced human-machine interfaces, and big data analytics. DP2 (High) is measured by the Value Chain and Processes and IT Architecture dimensions of MM11. According to the authors, the usage of digital technologies is the base for the virtualization of all the data flow, data security, value chain processes, as well as the IT landscape of an enterprise. Likewise, DP3 (High) is evaluated in the Value Chain and Processes dimension and the highest maturity stage of the model Digital Champion. According to the authors, companies should maintain a fully digitized and integrated ecosystem with self-optimized, virtualized processes, and decentralized autonomy of the value chain processes, which is the exact match with the principle. DP4 (High) is analyzed by the Value Chain and Processes and IT Architecture dimensions of

MM11, where companies are driven by digitization and integration of vertical and horizontal value chains. This, in turn, implies the usage of digital technologies and well-developed real-time integrated planning, execution, and data availability [47]. DP5 (Moderate) is explicitly present in the model as well because the authors state that data collection and analysis methodologies should provide the basis for the mass customization of the products and services. Furthermore, deepening digital relationships with customers will allow fulfilling customer needs in an effective way. DP6 (High) is present in the Value Chain and Processes, and Business Models, Product, and Service Portfolio dimensions of the model. The authors emphasize that for companies, it is critical to use predictive analytics for real-time optimization of the value chain processes to internal/external changes, making them resilient, flexible, and adaptable. DP7 (High) is permeated at all the maturity stages of the model, where it is stated that the usage of digital technologies such as sensors, augmented reality, IoT platforms, and 3D printing would provide sufficient operations in the value chain so that the products and services attain the characteristics of smart products. DP8 (High) is measured in the Organization and Culture dimension of the model as the authors make the point that the biggest challenge for companies towards I4.0 is transforming organization and culture, which requires long-term change programs. In sum, MM11 covers almost all of the design principles to a high extent.

(10) MM13: DP1 (High) is deeply analyzed by 3 dimensions under the Technology building block at 3 distinct design levels: Shopfloor, Enterprise, and Facility. The ability to access the data with ease across assets and systems is the key to unifying and integrating all enterprise modules into a developing infrastructure, which is a core concept of interoperability. DP2 (High) is measured in the Integrated Product Lifecycle dimensions MM13. Authors state that digital technologies used by organizations would allow implementing the “digital twin” concept (virtual representation of physical assets, processes, and systems involved in the value chain), which corresponds to virtualization. DP3 (High) is analyzed by Vertical Integration, Horizontal Integration, and Leadership Competency dimensions of MM13 because it allows the decision-making process to be decentralized and provides the autonomy of enterprise modules. DP4 (High) is implied in the Connectivity pillar and maturity levels of the model as mature companies and organizations (Band 4 and above) should maintain real-time communication across all modules of an enterprise by providing access to needed information securely and easily. DP5 (High) is analyzed in the Automation pillar under Technology building block, Horizontal Integration, and Inter- and Intra-Company Collaborations dimensions, where the need for adaptation to rapidly changing customer needs allowing the real-time adjustments in value chain processes and providing mass-customization for the customers is emphasized. DP6 (Moderate) is analyzed in the Organization building block with Talent Readiness and Structure and Management pillars. The flexibility to adapt to changing requirements by replacing or expanding individual modules is essential for mature companies. DP7 (Moderate) is not explicitly present in the model. However, from the structure of the MM13, it can be seen that the core idea of a Smart Product, which is the products that have high integration with other modules of an enterprise, intelligent support, maintenance, and real-time communication capability, is sustained by Intelligence and Automation pillars of the model. DP8 (High) is evaluated in Workforce Development and Learning and Leadership Competency dimensions of the model because the authors claim that to maintain the highest standards of I4.0, one should attain the development of workforce capabilities, skills, and competencies to achieve organizational excellence [49]. Likewise, management’s readiness to leverage the latest concepts and technologies would allow a high level of competitiveness on the global market, which fully correlates with corporate social responsibility. In summary, MM13 is among the new and trendy models and covers all the design principles to a great extent. The model is described rigorously with rubrics for each dimension and maturity bands.

(11) MM15: DP1 (High) is measured by the Service-Oriented Architecture dimension of the model, wherein it is stated that the realization of dynamic composition and automated interoperability is meant to be carried out by smart and adaptable enterprise systems. The maturity levels of MM15 also indicate the importance of data and system integration and data analytics, which refers to the interoperability

principle. DP2 (High) is measured in the Level 4 maturity stage of the model, where communication and cooperation of assets in a data-driven factory are enabled by digital twin. The usage of digital twin covers the core concepts of virtualization. Likewise, the concept of digital twin implies the high autonomy and decentralization of assets of an enterprise, which is a foundation for DP3 (Low). Additionally, it is stated that even though decentralized decision-making processes are taken as a high priority, the involvement of invigilators will allow the controlled interventions that cannot be taken by smart assets of a data-driven factory [51]. DP4 (High) is analyzed by the Real-time Capabilities dimension of the model, which involves real-time analytics to react within a certain time and events occurring. Furthermore, the highest maturity level of the model (Self-optimizing Factory) implies the deployment of real-time analytics by cloud and ICT technologies. DP5 (High) is analyzed by the Service-oriented Architecture dimension in which data provisioning is achieved through the implementation of service-oriented architecture [51]. This framework would allow establishing efficient and responsive communication networks with partners and customers, which sufficiently covers the principle. DP6 (Moderate) is analyzed by the Real-time Capabilities dimension of the model. According to MM15, highly mature companies need to maintain the self-organizing and self-optimizing enterprise systems which rely on data flow throughout the enterprise modules [51]. Authors point out that proper model development requires relying on context-sensitive data to provide real-time responses, which fully reflects the main idea of the principle. In summary, MM15 assesses the extensive characteristics of data-driven factories by analyzing their maturity on a 5-level scale with the main focus on data communication and networks. It also covers the majority of design principles to moderate and high extents.

(12) MM16: DP1 (High) is measured by the Machine and Operation System Integration (M2M) sub-dimension of the model. Additionally, the highest maturity level of MM implies mature organizations (Expert level) to have machines and systems to be fully integrated into enterprise infrastructure. DP2 (High) is measured under Digital the Modelling sub-dimension of the model. The mature organizations and enterprises should possess the full deployment of digital modeling techniques and their features in all modules at the factory-level. In terms of DP4 (High), the model does provide the analysis of it by Inventory Control using real-time data management and Real-time tracking and automated scheduling sub-dimensions. In both sub-criteria, the need for real-time data availability is crucial for companies at a mature level. According to the model structure, the availability of digital features in products and services offered by organizations is an essential ability to maintain the full capability of I4.0 in the Products and Services dimension. Moreover, the model also analyses the integrated market channels deployed by organizations, indicating that mature companies should maintain integrated customer experience management across all communication channels. This greatly sums up the presence of DP5 (High) in the model structure. DP6 (High) is measured by Self-optimizing processes and Supply chain flexibility sub-dimensions. In both sub-criteria, the driving factor to implement DP6 is real-time data-driven communication throughout enterprise modules with the usage of digital technologies. DP7 (High) is measured by Product customization, Digital features of the product, and Data-driven services sub-dimensions. MM16 outlines the importance of maintaining the digital features of companies' products. This feature will allow the collection of customer data which can be used for future data analytics to improve the value chain processes of an enterprise and allow product customization. In terms of DP8 (High), it is measured by People capabilities, Leadership, and Collaboration sub-dimensions. MM16 measures the digital and analytical skills of employees, the understanding of key principles of I4.0 by the top management, and the level of collaboration with other partners and companies to develop a strategic roadmap. In summary, MM16 provides a good analysis of the core organization's capabilities regarding their preparation towards I4.0 transformation, with an indication of areas to work on to achieve the required result. Furthermore, it covers almost all of the design principles to a high extent.

5. Results and Discussion

5.1. Identification of Gaps in the Maturity Models

In this section, the research gaps observed during the SLR to answer RQ2 are defined and discussed in detail. These research gaps can be addressed to improve the existing MMs through the consideration of DPs that underly I4.0 concepts and support sustainability principles. Based on the critical investigation of the 12 MMs, the three main research gaps were identified.

5.1.1. Research Gap 1 (RG1): Deficiency of Academic MMs

The first conspicuous gap is deficiency of academic MMs. Figure 2 presents the count of scores—High, Moderate, Low, and Basic; the most complete is [10] MM7, an academic model that managed to cover all the eight (out of eight) DPs to a full extent. Other than that, among the next six MMs with the coverage of the six or more DPs to High extent, only [37] MM6 is academic [10]. Likewise, among the other five models that covered the DPs with greater variability of scores, the one that account for the least coverage is [45] MM9, which was developed in academia as well.

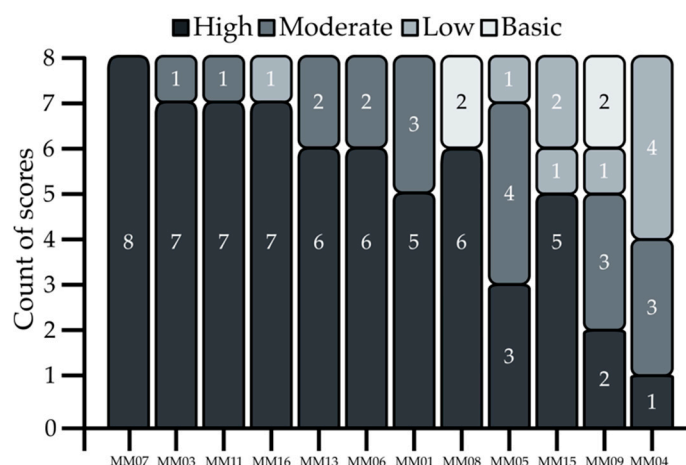


Figure 2. Results of the assessment of maturity models by I4.0 design principles.

Despite these drawbacks, academic MMs can be useful for companies on their way to digital transformation due to their rigorousness and accessibility. For example, [37] MM6 provides a clear and detailed explanation of its methodology—in particular, how the assessment and calculation of the maturity level are performed, which makes it highly useful and applicable for companies. However, it is evident that academic MMs need to be improved in terms of inclusion of DPs to consider all aspects of I4.0 and provide companies with the guiding tool that would render a measurable effect on their business performance.

5.1.2. Research Gap 2 (RG2): Limited Access to Industrial MMs

The second identified research gap is the limited access to industrial MMs. Although the industrial MMs generally prevail the academic, the commercial publishers do not provide the full access to the methodology, surveys, and roadmaps of the models. For instance, the MMs such as these developed by [41] MM3 and [47] MM11 are quite comprehensive in terms of providing the information and have an integrated online self-assessment tool that partially unveils survey questions—some of the modules are not accessible for the external users. To access the model and make use of its full methodology, companies either need to hire a consultant or purchase/subscribe to the service of the MM provider. Therefore, industrial MMs are unlikely to be useful for companies that embark on digital transformation, especially SMEs that may lack the resources to perform the maturity assessment using the industrial MMs.

5.1.3. Research Gap 3 (RG3): Lack of Coverage of Design Principle

The third research gap in the reviewed MMs is the lack of coverage of design principles. The manual review of the MMs was challenging as most of the authors of MMs do not explicitly comment on the presence of DPs, and only MM7 has sufficiently extended information on the principles included in the model. As can be seen from Figure 3, which counts the scores of DPs that correspond to High, Moderate, Low, and Basic coverage in Part (a), as well as presents the coverage percentage of each of the eight DPs by the reviewed twelve MMs in Part (b), the most frequently overlooked DPs are Corporate Social Responsibility (CSR) (DP8), Decentralization (DP3), and Smart Product (DP7). The percentage coverage of design principles by maturity models was calculated based on the assumption that the score High corresponds to 100%, Moderate—75%, Low—50%, and Basic—25% coverage of any of the DPs.

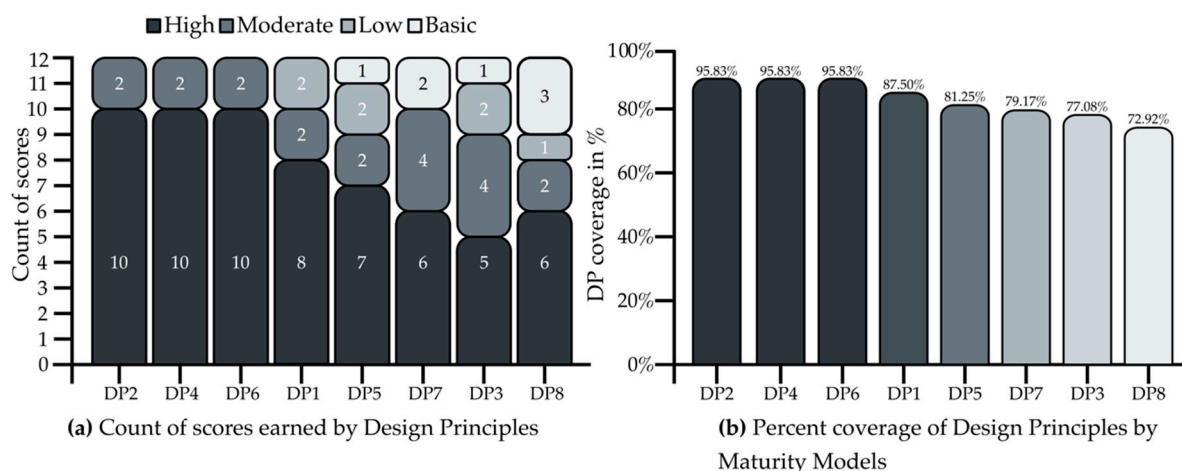


Figure 3. Assessment of design principles by the level of coverage by maturity models.

DP8 (CSR) emphasizes the necessity of upgrading employees’ skills to adapt to I4.0 associated changes. Similarly, DP7 and DP3 are not considered in several models as well. The former establishes the specific requirements for products to possess the interconnectivity, traceability, and other advanced features to constantly improve skills of employees to conform with I4.0 requirements, while the latter is the high-level decentralization of decision-making processes in an organization. Based on this, it can be seen that the principles weakly related to I4.0 technologies and those that become relevant for the companies at the last stages of digital transformation are not strongly presented in the models. This might be because the span of DPs covered in a model depends on the I4.0 perception. For instance, if MM1 envision I4.0 as the transformation of manufacturing firms into learning, agile companies, the MM11 characterizes I4.0 as the evolution of enterprises into data-driven organizations. Therefore, MMs can have different DPs of I4.0 in focus and might significantly underperform in certain aspects. In addition, the purpose of MM is not the less crucial factor that correlates with the coverage of DPs. As an example, MM9 is useful for assessing a company’s IT system landscape according to digitalization requirements; this is why it does not consider Smart Products and CSR, which resulted in the lower coverage of these principles in the analysis. Overall, to be helpful in guiding companies in their digital transformation, MMs should consider all of the identified DPs.

The above-discussed research gaps impede the digital transformation in companies making their readiness/maturity evaluation process hard to accomplish.

5.2. Discussion of Obtained Results

By inspecting the core principles of each MM stated in the literature review, several differences were identified. For example, models such as MM2, MM8, and MM9 have their main focus on the operational and technological aspects of I4.0, which indicates that there is a variance in the

understanding of all core concepts of Industry 4.0 with multifaceted aspects including management organization and aligned strategy. However, several other models such as MM10 and MM6 have their main focus on managerial and strategic aspects of I4.0, with little focus on technological and digital aspects of it. Nevertheless, the maturity models such as MM1, MM3, MM13, and MM16 offer a comprehensive way of assessing I4.0, focusing on both strategic and technological aspects of it.

The gap analysis identified the pattern that the majority of models that do comply with all core DPs of I4.0 have been developed by the commercial entities, whereas the concentration of gaps was higher in those developed within an academic sphere. Additionally, even though the MM might have covered all core DPs, the majority of those models do have implicit information about that.

The paramount result of this paper is the analysis of 16 maturity and assessment models based on the main I4.0 DPs, which can be seen on Figure 2. Although there is growing literature on I4.0 MMs and their framework development, there is still a research gap in assessing the current capabilities of an enterprise and concrete steps needed for further development in the context of I4.0. Among those 12 MMs analyzed, in terms of having permeating information about I4.0 DPs, the MM7 was chosen to be fully corresponding to that condition.

6. Conclusions

This paper complements the existing knowledge base in I4.0 through the establishment of an interconnection between two immense research topics: I4.0 DPs and MMs. To facilitate the structuring of the paper, the four research questions were defined and answered during the systematic literature review. The study begins with the identification of the DPs that are intrinsic to the digital transformation, then continues with the definition of the relevant I4.0 MMs that are devoted to guiding the firms in their digitalization journey. Thereby, eight DPs, as well as sixteen MMs (Table 2) disseminated among commercial/academic publications, were detected and compiled with detailed clarifications (RQ1/RQ2). Next, the identified MMs were critically reviewed, compared, and contrasted with the inclusion of the DPs. Finally, the performed steps helped to synthesize the implications derived from the comparison of MMs and shape three research gaps that hinder the adoption of I4.0 in companies. In particular, identified research gaps are as follows (RQ3):

- The academic MMs are publicly available for external users, but often are incomplete or underdeveloped. Therefore, such models might not be effective for shaping and implementing the digital transformation strategy inside organizations (RG1).
- Commercial MMs are more complete in terms of DPs than those developed within academia. Although the well-established commercial MMs provide the comprehensive evaluation of firms' readiness/maturity, the access to their full methodology is restricted. Therefore, making use of such models requires substantial investments, which is not always affordable for SMEs, I4.0 beginners, or firms from developing or transitional economies (RG2).
- The presence of DPs is not explicitly commented on by authors of MMs. The most frequently overlooked DPs are Corporate Social Responsibility (CSR) (DP8), Smart Product (DP7), and Decentralization (DP3). The underperformance in the coverage of these DPs by MMs mainly occurs because MM framing is bound to the I4.0 perception, a focus on certain aspects, and a development purpose, which contributes to the substantial divergence between the models. Companies struggle to choose the right solution or to pick up a complete MM, which inhibits the digital transformation (RG3).

Answering RQ4, to cope with the aforementioned issues, the recommendations to improve current MMs include:

- Despite the rigorousness and providing open access to methodology, surveys, and roadmaps of MMs they need to be substantially improved and consider the DPs discussed in this paper at the appropriate level. There is a strong need for an enhanced academic MM that will incorporate all the DPs associated with I4.0. Such an MM building approach will address the aforementioned

research gaps and provide a meaningful readiness/maturity assessment solution for the firms that strive to adopt Industry 4.0. To do this, authors may refer to [44] MM8 that provides the decent and multifaceted architecture of I4.0 MMs.

- Given that commercial MMs are well-structured in terms of DPs but provide only limited access to their methodology, surveys, and roadmaps, industrial MMs need to provide companies with at least basic functionality free of charge or for an affordable price. By doing this, the I4.0 transition would be accelerated, which would contribute to the emergence of more complete I4.0 MMs.
- MMs should explicitly consider the presence of DPs in the structure of the models to guarantee the holistic approach that will help companies in their transition to I4.0. In particular, the consideration of DPs such as Corporate Social Responsibility (CSR) (DP8), Smart Product (DP7), and Decentralization (DP3) needs to be improved in the MMs. Resolving these issues would contribute to unification of the I4.0 vision among stakeholders and the structure of MMs, which in turn will increase the number of successful digital transformations in companies and their overall progress.

The primary limitation of this research lies in its sole foundation in the literature review. Besides the problems with access to the full methodology of the models, as it was mentioned, there might be a certain bias in commercial publications that could be potentially reflected in the analysis. Moreover, as the MM review process involved both the explicit and implicit discussion of DPs in papers, the results of the MMs comparison presume some deviations.

To conclude, this research study revealed valuable insights into the existing MMs and laid the foundation for the development of a novel MM. The findings discussed in this paper contribute to the I4.0 body of knowledge and will be helpful for all the stakeholders involved in digital transformation. The future research plans that follow are the development of multifaceted MMs that will incorporate all of the identified DPs. Additionally, a clear explanation of the methodology used could be considered, such as the inclusion of eight design principles in the MM, the level to which they are presented in the model, as well as examples of each principle in the model.

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