


Article

A Framework for Assessing Manufacturing SMEs Industry 4.0 Maturity

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Featured Application: Proposal of framework to assess the Industry 4.0 maturity level of SMEs.

Abstract: Under the scenario of the fourth industrial revolution, the adoption of Industry 4.0 in the day-to-day business of small and medium enterprises (SME) entails expected challenges. Focusing primarily on more advanced levels of maturity, the existing maturity models are inadequate for assessing companies with low maturity levels, such as most of existing SMEs. A framework for a maturity model tailored to SMEs is proposed in this paper, allowing for a comprehensive and high granularity assessment of these companies' maturity levels, which then eases their integration into this industrial revolution. The proposed holistic model considers all Industry 4.0 dimensions while being detailed enough in its initial levels to properly assess SMEs at the same time.

Keywords: the fourth industrial revolution; advanced technology; readiness assessment; digital transformation; organization change



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1. Introduction

The overwhelming majority (99.8%) of enterprises active within the EU 28's non-financial business economy in 2015 were SMEs [1]. In the same year, these types of companies represented a share of 55.6% of the total gross added value of that same economy [1]. In 2017, Portuguese SMEs accounted for over two thirds of their economy's overall added value [1]. In countries like Germany, where the added value of SMEs is lower than the European average, these types of companies still account for more than half of their economy's overall added value [1]. SMEs are indispensable to all economies and can be described as a driving force for businesses, growth, innovation, and competitiveness, all while being a very important employer [2].

Society is currently undergoing an industrial revolution that goes by the name of The Fourth Industrial Revolution [3]. There is an urge for companies to take part in it as fast as possible in order to benefit from the competitive advantages and lead the way [4]—or at least, not to get left behind. This worldwide industrial revolution can be witnessed in different forms and initiatives, for example, the World Economic Forum has been succeeding in raising awareness of the impact of digital transformation in more than 220 organization across the globe [5]. This and other initiatives are paramount for this revolution's development and establishment, as it will bring multiple benefits for individual firms, whole supply chains, the industrial sector as well as for the society itself [6–9].

Although the adoption of Industry 4.0 (I4.0) and its components seems unavoidable in the long run, there are several struggles that prevent companies from promptly embracing this paradigm shift [3,4,9]. A survey conducted with a German equipment manufacturing association (VDMA) (Verband Deutscher Maschinen- und Anlagenbau) members postulates that I4.0 readiness increases sharply with the size of the company [3], suggesting that SMEs have an especially a hard time when it comes to approaching this concept. In

fact, years later, Martinsuo et al. identified the size of a company as a critical factor to understanding the process of adopting new manufacturing technologies [10]. The typical owner(s)-centered or family-owned organization and the limited financial budget of SMEs are some of the barriers that stymie these enterprises' position in the I4.0 maturity ladder.

Since its presentation, I4.0 has been a popular subject in the research environment, and [11,12] separate it into eight different topics: big data and analytics; autonomous robots; simulation; horizontal and vertical system integration; the industrial internet of things; cyber security; additive manufacturing; and augmented reality and the cloud. Within these topics, there are already various tools to aid in the involvement of companies in I4.0, but a tool for a systematic approach that predicts a company's hurdles in implementing I4.0 was not found to exist nor found to be in development. Additionally, the existing tools essentially focused on advanced technologies and occasionally on specific areas of this concept such as, technology or processes. Therefore, none of these tools were found to be broad enough to comprehend the whole concept of I4.0, nor did they have enough granularity in the initial maturity levels—which is paramount for the accurate maturity assessment for SMEs [13].

Based on the work of Mittal et al. [14], the main objective of the presented research is thus the development of a specialized I4.0 maturity model tailored to SMEs that encompasses "level 0". In their work, Mittal et al. defend that *"defining a level 0 for SMEs is a necessary starting point to elevate their position along both the short- and long-terms"*. Our proposed maturity model represents symbolizes this "starting point" [14]). The proposed model aids SMEs who are transitioning to I4.0 by creating a framework that combines different I4.0 dimensions with existing maturity models. Although none of these models are able to be either comprehensive enough or sufficiently detailed enough in their lower maturity levels, a combination of them permits an accurate maturity assessment for SMEs within this concept. At the same time, this model considers the most important hurdles that SMEs face when embracing I4.0 [15] and focuses on the integration of companies into this revolution. Therefore, the main contribution of this research is to provide a comprehensive I4.0 maturity model that is specifically suitable for SMEs and other companies with low maturity and helps these companies reap the full benefits of the industry paradigm shift towards I4.0.

2. Theoretical Framework

2.1. Industry 4.0

After witnessing three industrial revolutions in the past century, the industrial sector is currently undergoing the fourth industrial revolution [16]. This revolution is different from the others due to its predictable character, as it is the first time that an industrial revolution is being named as such before happening [16]. This opens a great number of opportunities to any kind of business that would be interested in catching this wave.

I4.0 is a concept related to this industrial revolution, and although there is still no generally accepted understanding of the term [17], its role in this revolution is paramount. In 2016, Hermann et al. [18] proposed the four design principles of I4.0 to help in the systematization of knowledge related to this phenomenon. The design principles are Interconnection, Information Transparency, Decentralized Decisions, and Technical assistance [18]. One possible interpretation of these design principles is that in an Industry 4.0 environment, everything needs to be connected, supporting the collection of enormous amounts of data that need to be contextualized, allowing for decisions to be decentralized and based upon context-aware information, while at the same time, workers need to be assisted by software and hardware to perform their higher-value tasks (based on [18]).

Although there is no mutually agreed upon definition of I4.0, the authors propose an I4.0 description based on the required data–information–knowledge transformation process: the creation and deployment of knowledge derived from the data conveyed by underlying technologies. This description can be perceived as what the implementation of technology allows the company to achieve. This is mainly due to the data that technology

is able to acquire and process, which before that implementation, was not being considered or treated the appropriate way [19,20]. Therefore, the existence of strategies to support this transformation [21] as well as tools, such as maturity models, to identify the as-is and will-be scenarios are crucial to support companies and guide them down this path.

2.2. I4.0 Organizational Assessment Models

Organizational assessment models, also known as stages-of-growth models, stage models, or stage theories, are used to evaluate maturity in organizations [22]. A maturity model is a useful tool to assess enterprises and organizations and to illustrate the path ahead in order to achieve a more structured and organized way of doing business [22]. The main goal of a maturity model is to describe the stages or paths needed to reach maturity and to describe the characteristics of each stage or level as well as the logical relationship between successive stages [23,24]. In the context of I4.0, maturity models are especially important, as they contribute to the dissemination of the concept and provide companies with a broader understanding and implementation proposals to deal with this revolution [24].

2.2.1. Literature Review on I4.0 Maturity Models

As a first step, the authors performed a literature review with the goal to analyse how each model defines their maturity levels and what the most considered dimensions were. For this purpose, a survey was conducted with ScienceDirect, Google Scholar, Web of Science using the key words [OR] maturity model, readiness model, Industry 4.0, Industrie 4.0, Reifegradmodel, SME, Small Medium Enterprise, Digital Transformation where only publications in English, German, Portuguese, and Spanish were considered. From the surveyed articles, only seven works investigated Industry 4.0 maturity or readiness models and other works presented, for example, Industry 4.0 roadmaps [25–27] or migration models [28]. Similar to the work of Santos et al. in 2019 [29], we excluded the maturity models from consulting firms from this investigation, as they have different scopes and commercial purposes.

To obtain a clear comprehension of the differences between each model, it is important to clarify the differences between the levels of maturity and the model attributes. Levels are the number of steps or stages that the company needs to progress through before a full implementation of I4.0—for example, newcomers, outsiders, beginners, experienced individuals, leaders. Essentially, attributes decompose the maturity model into easily and understandable sections, such as dimensions or sub-dimensions (the latter is used when the maturity model subject is too complex and needs to be further deconstructed) [30]. The notion of “dimensions” can be understood as the number of areas within a company related to whichever concept the model is taking into consideration, such as organization, technology, product, operations, supply chain, etc.

2.2.2. I4.0 Maturity Models Analysis

In respect to the accuracy of the maturity measurement and therefore the easiness of I4.0 implementation in companies, the seven chosen works presented in Table 1 were taken into consideration: [3,29,31–35]. The seven chosen works presented in Table 1 include maturity and readiness models as well as some of their correspondent questionnaires. Within these works, there are different approaches to I4.0. These differences are reflected in the amount of detail provided by each models’ sub-dimensions. Some models focus on the technology used in the production sites as well as in the product itself, while the aim of other models is to assess which kinds of changes are allowed by these technologies. These seven artefacts cover the central domains of I4.0 while adopting different approaches towards it. Their structures and adjacent concepts were extremely relevant towards the development of the proposed model.

Table 1. I4.0 maturity/readiness models.

Model's Name	Source	N° of Dimensions	N° of Levels
IMPULS Industrie 4.0 Readiness 2015	[3]	6	6
Industrie 4.0/Digital operations self-assessment 2016	[4]	7	4
Industrie 4.0 Maturity Index 2017	[35]	4	6
Maturity model for assessing I4.0 2016	[32]	9	5
Guideline Industry 4.0 2016	[33]	2	5
Industry 4.0 Selbstecheck	[34]	4	5
An Industry 4.0 readiness Assessment tool	[31]	6	4
An Industry 4.0 maturity model proposal	[29]	5	6

The next step scrutinizes which dimensions are considered in each of the models (Table 1) to obtain an understanding of which company dimensions were considered to be of bigger importance in the context of I4.0. Taking into consideration the models [3,29,31–35], for the reasons stated earlier in this section, the left column in Table 2 refers to the names representing the assessed dimensions of such models. The crosses occur when the respective model includes the respective dimension. It is worth noticing that all models are abstractions of subjects, and for one to be considered a useful abstraction, it has to abstract salient properties [36]. In this regard, it was assumed in the performed analysis that the name of the dimension was not important, but rather it was the idea behind the dimension that mattered.

Table 2. I4.0 chosen models dimension analysis.

Models:	[31]	[35]	[3]	[34]	[33]	[31]	[29]
Product	X		X	X	X	X	X
Processes	X		X	X	X	X	X
People	X		X	X			X
Technology	X	X	X				X
Organisation		X	X	X		X	X
Strategy	X		X			X	X
Culture	X	X		X			X
Governance	X					X	
Information Systems		X					X
Data drive services			X				X
Supply chain						X	X

2.2.3. I4.0 Maturity Models Suitability to SMEs

The current maturity models are not ideally suitable for SMEs since most of these companies find themselves in the initial maturity levels, and I4.0 is a technologically advanced concept [12]. This topic was addressed by in 2020 by Amaral et al. [13] in an analysis that concluded that a more detailed and supported approach to the initial maturity levels is lacking in the literature if SMEs I4.0 maturity level is to be rigorously measured. On the one hand, increased detail and supported approach are needed due to the lack of concrete outcomes that SMEs can extract from these models. On the other hand, it is important to consider the complexity of the transformation that a company undergoes for the implementation of this concept, especially for SMEs [35]. In fact, there are some authors that suggest the development of tools that are adapted to these types of companies [32,37].

As a final remark, the I4.0 maturity models presented in the literature lack of granularity in the initial maturity levels, resulting in an ineptitude of these models to provide guidelines to companies that are positioned in those levels.

2.3. Contextualization of SMEs Hurdles

Before the analysis of existing publications regarding SME hurdles to implement I4.0, it is important to define what an SME is. EU recommendation 2003/361 provides an insight

on the definition of SMEs, stating that “The category of micro, small and medium-sized enterprises (SMEs) is made up of enterprises which employ fewer than 250 persons and which have an annual turnover not exceeding EUR 50 million, and/or an annual balance sheet total not exceeding EUR 43 million” [38]. Nevertheless, regardless of size, I4.0 can be integrated into all aspects of an organization, from the shop-floor to the top management, and everything in between [6].

For the development of this model, we considered the categories for the list of hurdles presented in Amaral and Peças [15]. These mentioned categories disclose both the difficulties that are inherent to SMEs, and the struggles that exist in the development of approaches to ease their integration in I4.0. In this regard, if a maturity model is to be developed for these types of companies, it should consider their problems of implementing the concept under assessment. In fact, from the 13 works presented in Table 2, only [5,6,34] contemplate both a model and a list of hurdles that companies may have when implementing this concept. Nevertheless, it is not clear whether these models contemplate these obstacles, since no systematic approach that correlated the hurdles and the development of the respective models were found in these works, confirming the literature gap postulated at the beginning of this research.

To conclude, there is a need for a comprehensive model that not only has more detail than the ones presented in the literature, i.e., granularity, especially in the initial levels, while keeping its holistic approach to the concept, but that also considers the hurdles and obstacles that SMEs face when implementing I4.0 initiatives.

3. Materials and Methods

The approach followed in this investigation consists of an extensive literature review with two main focuses: The first focus will be research on maturity/readiness models and roadmaps for I4.0 implementation and assessment (presented in Section 2.2.1). This first section, focused mainly on research in the literature, allows for comprehension of what is being done in both the academic and practical spheres regarding I4.0 maturity assessment in industry. From this section, the incapacity of the existing models to properly assess I4.0 maturity of SMEs could be confirmed (see Section 2.2.3), as postulated by Mittal et al. in 2018 [14].

From the exposed gap in the literature, it can be concluded that the investigation needs to continue. The second part of the chosen methodology entails the development of a maturity model which has its basis in performed literature reviews. For the said maturity model to be consummated, it should first encompass a framework (presented in Section 4.2). Once the structure is defined, inputs and outputs are proposed (address Section 4.4), engendering a complete maturity model.

The followed approach is in alignment with the first four steps proposed by Amaral et al. 2020, where the authors propose the development of a maturity model focused specifically on SMEs [13]. This set of actions was specifically developed to guide researchers and practitioners to help “SMEs to successfully approach and implement Industry 4.0” ([13], p. 1104).

4. Results–Theory Building

Pöppelbuß et al. [22] emphasize the idea that the development of a maturity model is a difficult task due to the number of dimensions and sub-dimensions involved. The conclusion of Section 2.2 relates to the assessment focus that the models have, in other words, that the initial levels of maturity are not detailed enough. Nevertheless, this does not mean that their concept assessment is incorrect. In this regard, to obtain a grounded framework that is supported by the work previously developed in this area of research, we propose a combination of dimensions and sub-dimensions from previously developed models (presented in Table 2, Section 2.2.2). By considering the existing I4.0 maturity/readiness models in our model’s development process, the authors grant the alignment of the proposal of this work with the relevant literature, although its contribution

focuses only in a specific area, which is the tool's suitability for enterprises adopting I4.0, specifically SMEs.

4.1. Maturity Model's Framework Dimensions

As concluded in the latter section of this article and in line with Mittal et al. [14], there is a need for the development of an I4.0 maturity model that is tailored made for SMEs. This sub-section addresses each of the main elements that constitute the proposed I4.0 maturity model.

Table 2, presented in Section 2.2.2, represents the first major basis for the development of the proposed framework of this work since, with this analysis, it is possible to understand which dimensions are the most important for each of the chosen models. The below dimensions that the proposed model is inspired by can be described through three main aspects: (1) the analysis presented in the Table 2; through this analysis, the most important dimensions of I4.0 considered by these sources as dimensions that should be assessed in any company were extracted; (2) the combination of the outcomes of this analysis with the main categories of the hurdles that SMEs experience [15] through the process of implementing I4.0 initiatives; and (3) the need for an increase of granularity in the initial levels that this model should have in order to be suitable for SMEs.

4.1.1. Technology—What will Foster the Change?

As stated above, to approach I4.0, it is necessary for enterprises to have certain technologies, or at least an appropriate infrastructure, for their implementation. What is important to retain from this dimension is the need to assess the technologies that are the basis for I4.0 implementation. These technologies are the first concrete step in the direction of I4.0 and they are the support for the related concepts of the fourth industrial revolution [33]. While there are already several of technologies available with this objective in mind, the benefits of I4.0 will only unfold with a clever combination of these technologies [33]. The aim of this dimension is thus not to list technologies nor to assess if the company has them or not since their importance is different from company to company. The real aim of this dimension is to allow the understanding of which kind of infrastructure each company has in order to support the implementation of technologies.

4.1.2. Production Processes—What Creates Value in this Change?

In a company's production site, it is necessary to assess how the company manages their activities, data, information, and knowledge [31,35]. This dimension assesses how production is affected with the implementation of different technologies, and how the company collaborates within itself [39]. This dimension is related to the assessment of how the company uses the data provided by the implemented technology, and which knowledge it encapsulates [40,41]. It also embraces how production manages its processes, disregarding the use of technology in the first place.

4.1.3. People—Who Will Drive this Change?

There is a growing need for people to grasp the overall context and to understand the interactions between all of the actors involved in the manufacturing process [6]. For a fluid change from a company's current state towards an I4.0 environment, workers need to be assessed [3,35]. This assessment needs to focus essentially on their skillset, what the company is actively doing in order to develop their capabilities, and most of all, the employee's willingness to change. Without the worker contribution, the implementation of I4.0 measures is not possible [6]. Therefore, it makes sense to first analyze this dimension as the basis of the whole change.

Data lie on the heart of this industrial revolution [4], but they are meaningless alone. It is necessary to extract knowledge from the data provided by technology as well as to manage them [42,43]. This dimension thus gives a special importance to knowledge, how to create it, and how to manage it.

4.1.4. Smart Product—What Will Allow This Change?

One of the key aspects of this industrial revolution is the shift of the business models of these enterprises to models of a business “as a service” [31]. To achieve this goal, it is necessary to have the most precise and the most comprehensive amount of information possible about the customer. I4.0 already provides concrete measures to achieve this objective, e.g., allowing the company to be connected with the product itself while already in possession by the customer, highly fuels data and information gathering [3]. This dimension is not related to what the product can influence, but rather to which features, and characteristics can be implemented in the product in the context of I4.0. “Smart Product” as a dimension answers essentially the same question as technology, “What will foster the change?”, but from the point of view of the enterprise’s business model.

4.1.5. Organization—How Will the Enterprise Change?

This dimension covers how the company is organized throughout this journey—the leadership style or who is empowered to take decisions—along with an understanding of which type of collaboration exists in the enterprise’s value chain. Moreover, the existence of KPIs to control the company and how they are related to I4.0 metrics is a key feature when organizing an enterprise that aims to implement this concept [31]. Finally, the existence of coordination throughout this process is assessed as well as its autonomy and goals.

4.1.6. Change—What Are We Changing?

Shifting a company’s views to I4.0 requires a commitment for any small, medium or big company [31]. The change of the current paradigm that the enterprise is in to a new and less certain way of doing business, needs to be managed. The financial effort that the company undertakes in the implementation of this concept is also key in this change. This dimension was chosen to incorporate this model because it also considers the adaptation of SMEs.

This dimension is interconnected with all of the above-described dimensions, and it can be considered to be the overview of the proposed model. In fact, this dimension assesses how the company manages this change process, and two of its sub-dimensions are directly related to two other model’s dimensions. Although three of the models mentioned above also consider this dimension, they call it “strategy”. In this proposed model, this dimension is named “change”, as this term better captures what is really being assessed. The term “strategy” can create misinterpretations due to the notion of “business strategy”, when it is clear that the authors of the mentioned models are considering strategy related to how to change. As such, for the sake of clarity, it will be simply referred to as “change”. This designation is also aligned with one of the ten critical success factors for I4.0 highlighted by Sony et al. in 2019 [44]. In fact, throughout the implementation of IT solutions, the company is able to embark in a process that can be seen as change. On this matter, Verkatraman in 1994 [45] has developed a model to assess how companies can undergo a change process with IT. Some years later, Levy et al. 2002 [46], published a study that considered up to 41 SMEs, and its outcome was that, these types of companies can have different paths (contrary to what was previously defined by Verkatraman [45]) in this learning and change process, although, the applicability of this model to SMEs as well as its maturity levels (or steps) was effectively proven.

4.2. Maturity Model’s Framework Structure

The structure of the proposed framework can be seen in Table 2, where the dimensions of the present model are integrated between themselves. This Figure 1 depicts the “change” dimension overseeing all of the other dimensions. This means that every dimension will effectively affect the change process of the company. This representation is inspired in the work of David Siepmann in 2016 “Industrie 4.0—Grundlagen und Gesamtzusammenhang” [47], where in chapter 2 of his work, “Komponenten der Industrie 4.0”, the author proposes a methodology for I4.0 division and presents a scheme/figure representing it.

His work is essentially based on technology, focusing especially on cyber–physical systems, and it is not a maturity model.

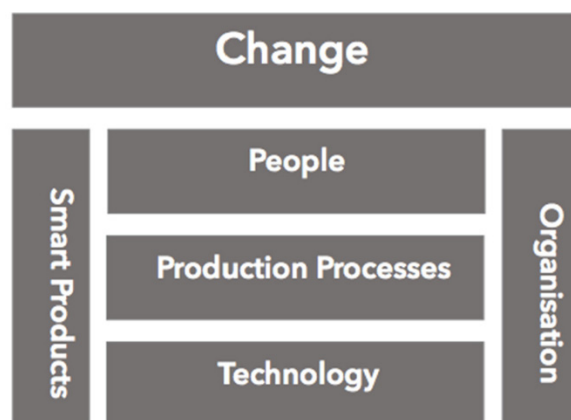


Figure 1. Proposed framework’s structure.

This visual mapping of the proposed model’s dimensions helps to clarify its structure and the connection of its core dimensions. There are essentially three main parts, each related to one of the three layers proposed by David Siepmann [47]. The first level is represented in this figure by “technology”, the second level by “production processes” and the third by “change”.

To reach a structure as the one proposed in Figure 1, the authors of the present article introduce two improvements on the work of Siepmann [47]. The first improvement proposed introduces the dimension of “people” above “production processes” and “technology” dimensions. “People” has not been considered in Siepmann’s work but is duly aligned with the theory of the “Golden Triangle”, because when considering technology and processes, people are the one piece that can never be neglected. For a brief explanation of this theory, please refer to source [48]. The second improvement that is represented by the introduction of both lateral dimensions of “organisation” and “smart product”. They are both considered lateral since they correlate with the three centre dimensions at the same time. Organization must be orthogonal to all of the mentioned dimensions (except “change”), for the reasons explained next. On the one hand, the organization dimension is required to evaluate how the company is controlling its processes (KPIs), but on the other hand, it also has to measure how the technology and its implementation are being coordinated [31]. Finally, it is important to assess how the human resources of the organization are organized, which type of leadership takes place as well as the workers’ autonomy level.

As mentioned in the description of the proposed model’s dimensions, CPS offers a strong opportunity to replace the purchase of a product with a service [31]. The product can be technology itself (purchase), or it can be perceived as a service, where it is intrinsically the connection between processes and people. Parallel to David Siepmann’s work [47], “change” overviews all of the other dimensions. The introduction of the two referred lateral dimensions (organisation and smart products) implies that they also are overviewed by the “change” dimension.

With these six described dimensions, and according to all models that were the foundation of this model, the proposed framework covers all main areas of I4.0. This way, an enterprise can be assessed in a holistic way rather than only partially. Although each dimension is essential and could not have been left out or incorporated into any other dimension, they are related as explained above. A quick analysis of the questions related to “change” in the context of each dimension, together with an examination of Figure 1, can clarify the relationship between them.

As explained before, one of the main features of this framework is the embodiment of the typical hurdles that SMEs have when implementing I4.0 measures. Figure 2 portrays the influence that these hurdles have on the model through the 10 presented white squares. This impact is only feasible through the model's sub-dimensions (presented in Table 3). This influence/impact connotes that the hurdles were taken into consideration in the thought process of the development of such sub-dimensions, and some of them are even sub-divided in necessary sets of actions to overcome that specific hurdle. The white squares represent the sub-dimensions that have been influenced by the contextualized hurdle categories discussed in Section 2.3



Figure 2. Framework's sub-dimensions and impact of hurdles.

Table 3. Proposed model sub-dimensions.

Dimensions	Technology	Production Processes	People
Sub-dimensions	1. Digital modeling	5. Cross company collaboration	8. Skill set
	2. Equipment infrastructure	6. Data collection and processing in production	9. Skill acquisition
	3. IT Security		10. Willingness to change
	4. Cloud usage	7. Production planning	11. Confidence in processes & IS 12. Knowledge creation 13. Knowledge management
Dimensions	Product	Organization	Change
Sub-dimensions	14. Functionalities for data storage	18. Cooperation with the network	22. Digitalization strategy
	15. Data collection and processing in production	19. Leadership style	23. Adaptation of Business Model
	16. Connectivity of the product	20. Coordination of I4.0	24. Innovation management
	17. Individualization of the product	21. Measurement	25. Investments 26. Enterprise's commitment

Figure 2 also illustrates the relationship between the framework's dimensions and sub-dimensions. From Figure 2, it is possible to understand that each dimension encompasses several sub-dimensions. For a correct assessment of the maturity level of a company, this increased degree of detail is necessary to create a transparent and incisive model.

4.3. Maturity Models Assessment Comprehensiveness Comparison

Having the focus of the proposed model defined, the authors performed a comprehensiveness assessment analysis to understand to what extent this developed tool tackles the concept of I4.0. To reach this understanding, the model was compared to its seven base

models (discussed in Section 2.2.2). Assuming that this comparison is vital when a model has been based on other models for its development, for it is possible to make conclusions out of the model's comprehensiveness level, Figure 3 illustrates this comparative analysis, which comes in the form of a pictographic comparison between the developed model and the chosen models. This mapping of the dimensions of the chosen models in the current model can be divided in two sections. First, the background: the white squares represent all the 26 sub-dimensions that this model incorporates (just as they do in Figure 2); second, the dark grey colour highlights the sub-dimensions which were considered by their respective model in the currently proposed model.

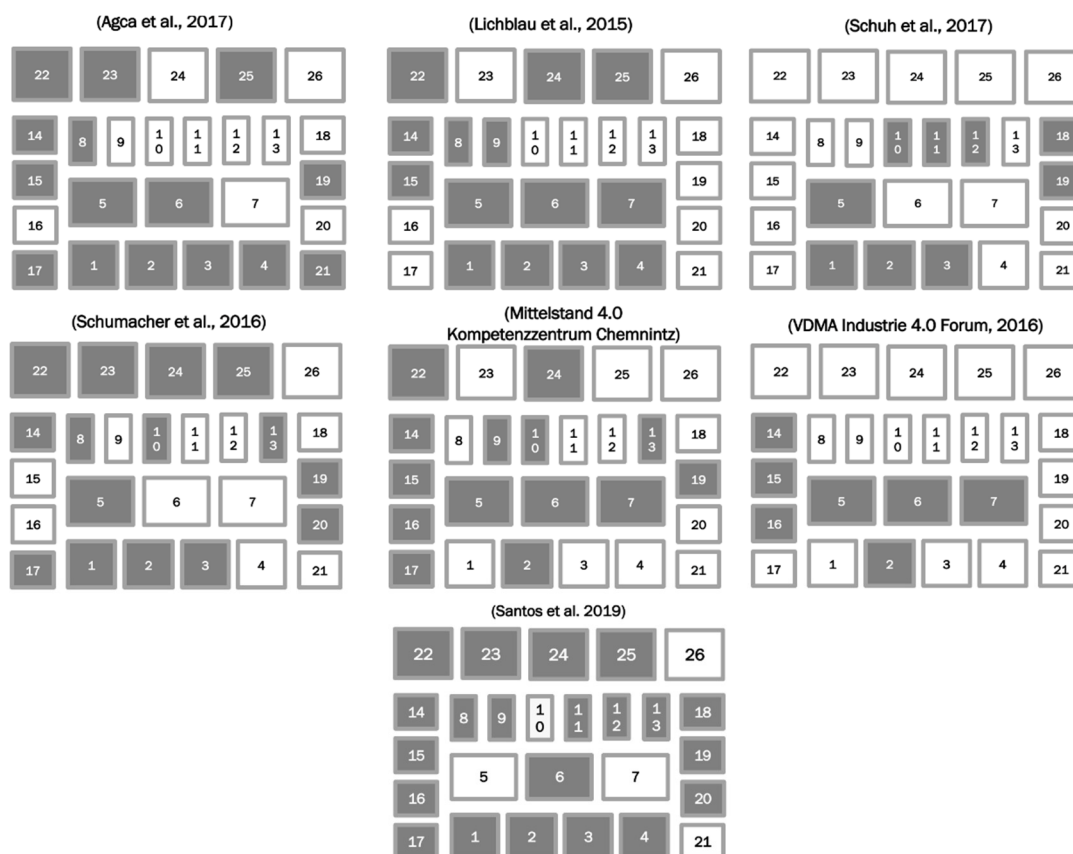


Figure 3. Pictographic comparison of proposed framework's dimensions and base model.

From this analysis, it is clear that no other considered model covers all of the sub-dimensions of the currently proposed maturity model. The two dimensions that are the most covered by these seven models are technology, production processes, and smart products, while the least covered dimensions are change (the dimension targeted to strategy) and people. Considering that our model is a holistic perspective of the Industry 4.0 concept, this coverage of the current I4.0 maturity models is not unexpected as most of the investigations around industrial revolutions is done by technologies and engineers. Still, we would like to highlight the 2019 work of Santos et al. [29], as the comprehensiveness level of their model is interestingly similar to our model. These analyses (Figures 2 and 3) show that the developed model's framework considers not only more sub-dimensions when compared to all of the other models, but that these sub-dimensions are also increasingly targeted to SMEs since almost half of them took the categories of the main hurdles that SMEs have when implementing I4.0 into consideration (please be directed to Figure 2 in Section 4.2.

4.4. Maturity Models Inputs and Outputs

After an understanding of the proposed framework and its differences with the existing ones, the natural next step is to understand what kind of inputs and outputs this framework considers. Here, the fourth and last followed step of the ones proposed by Amaral et al. 2020 [13] is presented. This section includes an explanation of the types of inputs of this framework, which comes in the form of a questionnaire, where each question is related to a sub-dimension. It also entails a description of the two different outputs that this framework provides. Bearing in mind that the definition of a model stands for the transformation of a certain input into an output [32], the combination of this framework with certain inputs and outputs engenders a model.

These model's inputs are introduced in the proposed framework in the form of a questionnaire. Each question can be considered as an evaluating item that assesses the topic related to its respective sub-dimension. It should be noted that there might be different ways to ask the same question depending on the receiver, i.e., depending on the knowledge of I4.0 and the overall understanding of the company's business, the same question should be asked in different ways to different collaborators. Therefore, this work provides only the field/item (sub-dimension) upon which a question should be asked rather than the question itself. To ease the process of attributing a maturity level to each sub-dimension, each question comes along with six pre-defined answers, which can also help in the formulation of the question. Each answer represents a different maturity level in the sub-dimension related to the question, as can be appreciated in Figure 4.

Willingness to change					
Level 0	Level 1	Level 2	Level 3	Level 4	Level 5
People are comfortable with their work and afraid of making mistakes	There is no will to learn from mistakes	People recognise the value of mistakes	People are open to innovation in the current business	People are open to explore innovation in new business	Employees are responsible for shaping the
Innovation management					
Product development, Production technology, IT, Integrative management, Services					
Level 0	Level 1	Level 2	Level 3	Level 4	Level 5
In no form	In 1 area	In 2 areas	In 3 areas	In 4 areas	In 5 areas
Equipment infrastructure					
Level 0	Level 1	Level 2	Level 3	Level 4	Level 5
No sensors or actuators	Sensors and integrators controlled with PLC	Processing capability	Machines can exchange information	Open systems interconnection	System for controlling Open systems

Figure 4. Three examples of sub-dimensions and respective answers (that correspond to maturity level).

Although not presented in any of the research articles and models, when approaching professionals that have applied them, it was understood that contrary to what was thought at the beginning of this journey, the overall maturity level of I4.0 is not the most important information to extract from a maturity assessment. In fact, there are not many substantial outcomes to be obtained from an overall level of maturity (except, for example, sectorial benchmarking), in the sense that there is not any tangible step for an enterprise to take for it to become more involved in I4.0. After all, the overall maturity level is a combination of maturity levels from each dimension, thus not being very insightful. In fact, an average value might not be very representative of the performance of a multi-component system. In contrast, analyzing each of the system's components allows a more refined and accurate analysis to be executed.

One way to overcome the above-mentioned issue is for the model to provide information about the maturity levels associated with each dimension instead of only delivering an overall maturity level. To illustrate this reasoning we present two exemplifying maturity levels (see Figure 5a,b).

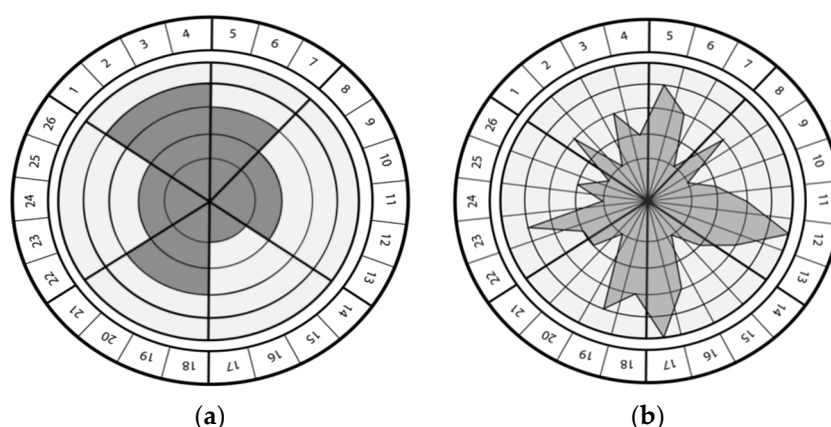


Figure 5. (a) Example of a company's dimensions maturity level in I4. (b) Example of a company's sub-dimensions maturity level in I4.0.

The first output of this model is a radar chart that presents the maturity level of each dimension (an example can be seen in Figure 5a); the second chart is the more insightful one. This second chart structure is the same as the previous one, but here it is possible to consult the sub-dimensions for maturity level. An example of this chart is shown in Figure 5b. It is possible to directly extract the maturity level of each sub-dimension instead of merely each dimension. As such, instead of merely presenting an aggregated value, the model's output directly provides each sub-dimension's maturity level. More evidence of the bigger relevance of the dimensions' values over the overall maturity level is that the models that propose the usual obstacles/hurdles that companies face as they try to achieve higher maturity levels associate each obstacle with each model's dimension (the readiness model from IMPULS published in 2016 is a very good example [3]). Therefore, the maturity level of each dimension is considered in the present work to be more relevant than the overall maturity level.

To conclude, the purpose of this model is to give an indication of the I4.0 maturity level of the company it assesses. No adaptation or adjustment is done to either its dimensions or to its sub-dimension maturity levels. Further comparison or benchmarking analysis (from the same sector or not) should be performed posteriori this assessment.

5. Discussion

5.1. Framework Application and Comparison

To emphasize this model's contribution to the literature, the authors performed an I4.0 level assessment of a one-of-a-kind production SME using the proposed model and the IMPULS model [3], referred as the most comprehensive and incisive model found in the literature by Schumacher et al. in 2016 [32] and the most transparent and detailed model presented in the literature, according to Pessl et al. in 2017 [26].

The company chosen to apply the model has neither repetitive production nor an assembly line. The company also does not possess any machines, such as CNCs or molding machines. The workforce of the shop floor is responsible for value creation, and the only support machines that exist are tools such as screwdrivers and grinding machines. At the first glance, this company does not seem suitable to embark on the endeavour that I4.0 is. In fact, Strandhagen et al., 2017 [49] pointed out in their work that repetitive production companies have an easier transition to I4.0 than non-repetitive production enterprises. It is important to underline that the proposed model was not in any way developed specifically for this company.

For the assessment of this company's maturity level, a multi-disciplinary team constituted of collaborators from the top management all the way to the shop floor was chosen to answer the questionnaire. This process was closely followed by the authors of this investigation to ensure the understanding of all items.

After the attribution of this company's I4.0 maturity level, the feedback received from the top management collaborator was encouraging. On the one hand, the collaborator affirmed that he could confirm his company is in the measured maturity level, which is a first confirmation that the assessed level is an accurate representation of the company's maturity. On the other hand, the expected company's maturity level was lower than the one presented, in fact, if a different maturity model was used, the maturity level would have been indeed lower (see next section). This feedback gives a first hint that the developed model is targeted for companies being introduced to I4.0.

The first and second rows of Table 4 show the company's different maturity levels for each of the models. For a proper comparison of both models, the weight scale used by [3]'s model was used to assemble the developed model's dimensions into an overall maturity level. This weight scale represents the weight that each dimension has in the overall maturity level (output). Each model can have its own, but since we are comparing our proposed model with [3]'s model, this model's weight scale is used (presented in the third row of Table 4). The calculations of the weight of each dimension of both models are presented in the fourth and fifth line of Table 4. The overall maturity level of the assessed company measured by [3]'s model is "0.383", and in the proposed model, it is "1.961". This means that for [3]'s model, this company is in maturity level 0, thus not belonging to the I4.0 company spectrum, but for the proposed model, this company is in maturity level 3 when considering both the same weight scale and the six categories used in IMPULS work. Being maturity level "5", the representation of the full implementation of I4.0, the company is then considered to be 7.65% in this endeavor by the [3] model and 39.18% as measured by the developed model. These findings highlight the differences between both models in terms of their assessment range.

Table 4. I4.0 maturity models comparison.

Model Dimensions	Strategy & Organization	Smart Factory	Smart Operations	Smart Products	Data Driven-Services	Emplo Yees	Total
IMPULS [3]	0	0	2	0	0	1	3
Proposed Model	2	1	3	2	2	2	12
Weight scale	0.254	0.143	0.102	0.185	0.138	0.179	1
IMPULS [3] overall maturity level	$0 \times 0.254 = 0$	$0 \times 0.143 = 0$	$2 \times 0.102 = 0.204$	$0 \times 0.185 = 0$	$0 \times 0.138 = 0$	$1 \times 0.179 = 0.179$	0.383 (7.65%)
Proposed model's Overall maturity level	$2 \times 0.254 = 0.508$	$1 \times 0.143 = 0.143$	$2 \times 0.102 = 0.306$	$2 \times 0.185 = 0.370$	$2 \times 0.138 = 0.276$	$2 \times 0.179 = 0.358$	1.961 (39.18%)

Furthermore, it is possible to conclude in this particular case that on the one hand, all of the companies that have the same or a lower level of maturity in the [3] model are considered to be in the same level of maturity, which is level 0. However, on the other hand, these same companies would be divided into three different groups in the developed model. This division exhibits the augmented degree of granularity presented in the developed model, in comparison to the [3] model.

This increased level of detail enables the developed model to be more adapted to SMEs, or at least, companies which are being introduced to I4.0, since it is possible to extract an increased degree of insight from the proposed model than from the [3] model. In fact, this specific case shows that since all of these enterprises are divided into three different groups (instead of just one), the requirements of each group should be lower, thus easier to implement and also to understand. This latter conclusion can be confirmed by comparing the requirements of the first maturity level of the [3] model and the requirements of the first, second, and third levels of the proposed model.

5.2. Practical Contribution

The practical purpose of a maturity model, such as the one proposed in this article, can be seen as the enabling of a company to rigorously evaluate its own maturity and reflect the fitness of its current strategies [32]. As explained in Section 4.4 of this article, the

developed maturity model encompasses a sequential list of the possible maturity levels for each sub-dimension. This method of categorizing the model's inputs (see Figure 4) allows the company to examine whether the current strategy will allow the enterprise to scale up the shown I4.0 ladder, or if the strategy is not aligned with I4.0 related measures. In this regard, the company can use the proposed model by mapping any new digitalization propositions with the maturity model and predict if it is going to affect its maturity level or not. In other words, if the digitalization proposition is merely efficiency increase driven, or if it has implications in other areas of the enterprise which allow the company to be more involved in the I4.0 sphere. This mapping is exemplified in the last paragraph of Section 5.2.

From another perspective, this work facilitates enterprises to self-assess their I4.0 maturity level using the questionnaire associated to this model while providing detailed outputs in the form net charts of dimensions or sub-dimensions of I4.0 maturity levels (see Figure 5a,b). Moreover, the two provided outputs grant specialists the choice to, when reporting the assessment results, address to the enterprises' I4.0 maturity level differently, depending on their target group, i.e., depending on the audience level of I4.0 knowledge and awareness.

5.3. Scientific Contribution

The scientific purpose of an I4.0 maturity model helps to collect data about the current maturity level of manufacturing companies and their I4.0 strategies as well as to extract potential success factors [32]. As researchers, the authors of the presented article should ask themselves what the scientific contribution of such an I4.0 maturity model is through meaningful questions such as: "how can this model have a scientific purpose if each company will use it in a different way?". Indeed, the data collected from the model does have a different meaning for different companies, or types of companies. One way to overcome this challenge is to restrain the findings to different sectors of industry, instead of generalizing it to all of the manufacturing companies. Although it might not make sense to compare, for example, the data collected from the model between a company that produces water bottles and a company that sells cars, it would make sense to compare plastic manufacturing companies between themselves, or automotive enterprises amongst themselves. This way, for the model to contribute scientifically to research, it is possible to extract insightful success factors for different types of sectors if there are any to be extracted. Nevertheless, it is important to keep in mind that even within these sectors, each enterprise would have their own goals and specific needs.

For this measurement, there is an urge for the use of an external expert/auditor when using the maturity model, as once stated by Schumacher et al. [32], most of companies do not have enough knowledge to properly assess their I4.0 maturity level. The latter statement is of utter importance if we take into account that the characteristics of SMEs is the "need for independence combined with a low propensity to delegate and consult" [50]. Finally, through the pictographic comparison depicted in Section 4.3, between the proposed model and the seven models chosen for its development, the higher existing comprehensiveness level of the proposed maturity assessment tool is clear. This existing assessment width grants the developed maturity model a more holistic appraisal of the I4.0 enterprise maturity level, resulting in a more comprehensive measurement.

6. Conclusions

Industry 4.0 will deliver greater flexibility and robustness together with the highest quality standards in engineering, planning, manufacturing, operational, and logistic processes [51,52]. Taking into consideration that there is a great need for a systematic approach to introduce I4.0 in enterprises, especially for a tool indicating the maturity level [26], the current research contributes to this objective with a new tested comprehensive maturity model for I4.0, targeted for companies that are being introduced to this concept, especially SMEs. Attending that SMEs represent the majority of active companies in some

economies [38] and are responsible for generating more than half of the added value of several economies [1], the proposed tool paves the way for future literature in the I4.0 level assessment for this type of enterprises.

As such, the outcome of this investigation consists of a tool that can be used by companies to assess their Industry 4.0 level of maturity, which can further bolster SME awareness of this industrial revolution and their positioning in it. Understanding the current state of each business might be crucial to explore future possible pathways in this revolution.

One of this framework's most relevant caveats is its target group, as it does not contemplate the full integration of an enterprise with the I4.0 concept. It is developed for SMEs, which are being introduced to this concept. For future work, we suggest the full application of this framework across one or more manufacturing sectors so that a model can be constructed. This would allow an understanding of the overall maturity level across each sector and the success factors associated with specific companies that have higher maturity levels. Moreover, this application would also permit the proposed model to be refined and validated because with several assessments, it might be feasible to understand some possible necessary elements that have been left out or to re-evaluate the different phases of the process of implementing I4.0, as considered in the model. Finally, we suggest developing a roadmap for the introduction of I4.0 in companies as well as whole sectors. This tool could take advantage of the model proposed in this article since its purpose is to accommodate companies introducing I4.0 measures, especially SMEs.

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