

Extended Maturity Model for Digital Transformation

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Abstract. The integration of disruptive technologies into the industrial value chain has built the foundation for the fourth industrial revolution. For a company that wants to embark in this digital transformation, a set of issues remain doubtful, uncertain and unsolved. Thus, is essential to assist companies in transitioning to digital transformation technologies and practices. Maturity models (MMs) aim to assist organizations by providing comprehensive guidance towards the improvement of their capabilities in a standardized, objective, and repeatable way. This study pretends to adjust and extend the MM that seems to be more used by the Portuguese companies, with components and requirements which can overcome its gaps, thus suggesting ways for it completion and enrichment. Consequently, the literature is reviewed systematically to identify existing studies proposing MMs in the context of Industry 4.0 (I4.0). Twenty-one identified MMs are analysed by comparing their dimensions, context, purpose, wholeness, objectivity, and assessment type. Great variability was found which was reconciled in order to build a perspective as holistic as possible for the phenomenon of digital transformation. The proposed MM with an all-inclusive approach pretends to assess digital transformation through the appraisal of 28 dimensions organized in six categories. In addition to the dimensions, the framework to assist the assessment of the I4.0 practices is completed with a questionnaire that evaluates the fulfilment of the requirement of each dimension by maturity level and evidence that can confirm that evaluation.

Keywords: Digital transformation · Industry 4.0 readiness · Digital maturity model · Roadmap for Industry 4.0

1 Introduction

The materialization of the digital transformation on value chains across industries is made through several initiatives around the world. The increasing integration of the Internet of Everything (IoE) and disruptive technologies into the industrial value chain has built the foundation for the 4th industrial revolution. The designations differ but the one that has the most impact and perhaps best describes the use of Internet technologies in industrial

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value chain organization is the I4.0. However, Smart Manufacturing, Industrial Internet, Intelligent Manufacturing, Industrial Value Chain, are analogous terms that describe somewhat the same movement.

With I4.0 becoming a top priority for many research centres, universities, and companies, the manifold contributions from academics and practitioners have made the meaning of the term more unclear than solid [1]. Even the key promoters of the idea, the I4.0 Working Group [2] only describe the vision, the basic technologies the idea aims at, and selected scenarios, but do not provide a clear definition. As a result, a generally accepted understanding of I4.0 and a straight roadmap towards it, has not been published so far, hindering transformation efforts, causing indecision and uncertainty. The same can be observed about the other initiatives that under other designations and resulting from the efforts of other groups and institutions, contribute to the same result: smarter digital factories.

Thus, from the point of view of a company that wants to embark in this digital transformation, a set of issues remain doubtful, uncertain and unsolved. It is essential to assist companies in transitioning to digital transformation technologies and practices. Maturity Models (MMs) aim to assist organizations by providing comprehensive guidance towards the improvement of their capabilities in a standardized, objective, and repeatable way. MMs provide organisations with measuring for auditing and benchmarking, a measuring of progress assessment against well-known objectives, and an understanding of current strengths, weaknesses and opportunities, which can support informed decision making concerning strategy and organisation management.

The IMPULS Readiness Model, commissioned by the IMPULS Foundation of the German Engineering Federation (VDMA) carried out by IW Consult and the Institute for Industrial Management at RWTH Aachen University, was aligned closely with I4.0. It seemed to be at the outset, and the study confirmed it, the most popular model, possibly to which more merits are recognized according to the number of references stated in the literature. SHIFTo4.0 is the Portuguese equivalent to IMPULS and is based on it, suffering from the same virtues and limitations. Given the influence of the SHIFTo4.0 promoters, it will be expected that it will become the model adopted to measure the maturity of the digital transformation of Portuguese companies.

This paper describes our effort to complete and enrich IMPULS, thus SHIFTo4.0, with extra dimensions, components and requirements which can overcome the flaws that are pointed out to it, obtaining a more holistic model that addresses all the components of evaluating the maturity of the digital transformation in industrial organisations.

The remainder of the paper is structured as follows. Starting by establishing some theoretical background, Sect. 2 summarizes the motivation for this work, recognising the problem, defining the restrictions, structuring and describing the research method. Section 3 describes the selected MMs distinguishing them from their origin: industry and academia. Section 4 explains the analysis performed for the selected MMs and the development of the proposed model. Finally, Sect. 5 concludes with remarks about the undertaken study and some considerations for future work.

2 Methodology

Paulk et al. [3] define maturity as a specific process for explicitly defining, managing, measuring, and controlling the evolutionary growth of an entity. A maturity model consists of a sequence of maturity levels for a class of objects. It represents an anticipated, desired, or typical evolution path of these objects shaped as discrete stages [4]. Typically, these objects are organizations or processes. Maturity models, as a technique, has been proven to be valuable in measuring different aspects of such processes or organizations. The bottom stage stands for an initial state that can be by an organization or process having little capabilities in the present domain. In contrast, the highest stage represents a notion of complete maturity.

Practitioners and academics have developed numerous maturity models for many domains to measure competency, influenced by SEI Capability Maturity Model's pioneering spirit. Some of them become a standard like current CMMI itself [5] and Software Process Improvement and Capability Determination (SPICE) [6].

According to [7], the IMPULS Readiness Model, was aligned closely with the four dimensions of Industrie 4.0 (I4.0): smart factory, smart products, smart operations and data-driven services, and two additional universally applicable dimensions: strategy and organization, and employees. SHIFTo4.0 is the Portuguese self-diagnosis tool that allows companies to assess their state of digital maturity, obtaining guidelines to improve the way forward towards I4.0. Promoted by the Portuguese Institute to Support SMEs (IAPMEI), the design of SHIFTo4.0 was based on IMPULS, having been adapted to the Portuguese reality predominantly by ISQ, an influential institution on the Portuguese industrial environment with a history of standardization contributions. But SHIFTo4.0 does not go one step further than IMPULS and suffers from the same gaps that can be pointed out to the model commissioned by the IMPULS Foundation.

A maturity model is a very important technique for Industry 4.0 in terms of companies seeking for assessing their processes, products and organizations [8]. The better the model, the more complete that diagnosis will be. Despite the reasonable number of I4.0-related maturity models, gaps in the existing models continue to be identified in the literature. Gracel and Lebkowsk [9] state that some areas in the models should be extended, e.g., deep technology insights. In the opposite direction, Schumacher et al. [10] proposed an empirically grounded novel model where the main goal was extending, which according to the authors, was the dominating technology focus of developed models, by the inclusion of lacking organizational aspects.

Given the national strength of the organizations promoting SHIFTo4.0 and realizing the usage already made of the model, it was understood that this work which aims to arrive at a model as complete as possible, capable of addressing all the challenges and I4.0 hurdles, should not start from scratch. This study will take IMPULS as a starting point and will look for other models, on one hand for bridge the breaches identified in IMPULS and on the other hand, striving for alternative components and requirements which can overcome deficiencies, thus suggesting ways of complementing and enriching a model that is already been used by the Portuguese industry.

A systematic literature review according to the guidelines proposed by Kitchenham [11] was applied to find existing maturity models for digital transformation. Literature

was surveyed taking into account the identification of all the maturity models that could contribute to complement IMPULS's approach.

Databases like Scopus, Web of Science, IEEE Xplore; ACM Digital Library; Springer Link and Google Scholar were surveyed with variations of similar terms and expressions around Industry 4.0 maturity model, Industry 4.0 capability maturity, Industry 4.0 readiness, digital transformation maturity model, among others. Article search was performed since the year of 2011, the appearance of the Industry 4.0 concept, to late 2020. Immediate duplicates removal based on titles was performed and also exclusion based on titles and abstracts for papers that notoriously did not present a MM. This research work refers to surveying maturity models and not papers describing them. So, hundreds of sources and articles were found, which together refer to only a limited set of different MMs. A great diversity can be seen in the nature of the proposals, some influenced by other MMs, others with a disparate number of maturity levels, as well others not providing the dimensions of the model neither their items and yet others that refer to non-academic initiatives. The goal here was to select different MMs for digital transformation that reflects the most diverse approaches. As part of the second elimination phase, the studies were evaluated in terms of their suitability by examining their keywords, titles, and abstracts, before reading the papers fully. The search resulted in an initial set of more than a hundred papers, of which the references were analysed and selected, if relevant. This snowballing process was essential to identify industry-driven MMs about which there is no published academic work. Three more MMs were identified by reviewing references. We arrived at a set of 21 maturity models, represented by the respective papers or technical reports that define and characterize them.

3 Maturity Models for Digital Transformation

However, there are no standard or published evaluation criteria for maturity models in the domain of Digital Transformation, a set of assessment criteria is identified based on CMMI [5] and SPICE [6] in order to objectively analyse these 21 models. They are summarized in Table 1. Models were studied to try to break them down into their constituent parts and systematically assess the strengths and weaknesses of each one. The literature sources used in Table 1 can be classified into two basic categories: academic literature, and non-academic literature.

The number of maturity stages, the number of the categories of dimensions, the research context as stated by the authors, the source of the assessment data, and the granularity of the dimensions (the level of detail with which dimensions and their attributes are described and characterized), are depicted for each MM on Table 1.

3.1 Models Developed by Practitioners

The IMPULS MM [7] proposes six maturity levels that measure I4.0 readiness. It contains an action plan to boost the readiness of the organisations. According to the model, the level of maturity of a given dimension is defined by the lower level of maturity of the respective areas of interest that compose it. According to the level of maturity obtained by the model, organizations can be classified into three types: Newcomers (level 0 and

Table 1. Category-organized dimensions for model propositions for smart factories.

Maturity model	Origin	Stages	Cat.	Research context as stated by the authors	Assessment data	Granularity	Agg.
IMPULS [7]	Industry	6	6	I4.0 readiness	Questionnaire	Requirements of each dimension by maturity level	No
PWC [12]	Industry	5	6	Digital readiness for I4.0	Questionnaire	Textual description of the dimensions by maturity level	No
Schumacher [10]	Academia	5	9	I4.0 maturity	Questionnaire	Only item names and incomplete	Yes
METI [13]	Academia	6	5	I4.0 capability maturity model	n.a	Textual description of the stages	Yes
Deloitte [14]	Industry	n.a	5	Digital maturity model	n.a	Undescribed dimensions without items list	No
SIMMI4.0 [15]	Academia	5	4	I4.0 maturity	Interview/self-assess	Textual description of the dimensions by maturity level	No
Forrester Rch [16]	Industry	4	4	Digital maturity model	Paid assessment tool	Brief affirmations checklist under each dimension	No
Acatech [17]	Industry	6	4	I4.0 maturity index	n.a	Textual description for each capability	No
DREAMY [18]	Academia	5	4	Digital readiness assessment maturity model	n.a	No detail beyond the designation of the dimensions	No
Canetta [19]	Academia	4	5	Digitalization maturity model	Interviews	No detail beyond the designation of the dimensions	Yes
Sjödin [20]	Academia	4	3	Maturity model for smart factory	n.a	2 items list for each dimension by maturity level	No
Pessl [21]	Academia	5	5	Roadmap for I4.0	On-site approach	Only details the human dimension	Yes
ManuTech [9]	Academia	4	8	Manufacturing technology maturity model	n.a	Textual description of each dimension	Yes

(*continued*)

Table 1. (*continued*)

Maturity model	Origin	Stages	Cat.	Research context as stated by the authors	Assessment data	Granularity	Agg.
Scremin [22]	Academia	5	3	Maturity of manufacturing companies	n.a	Textual description for each indicator	No
Akdil [8]	Academia	4	3	Maturity and readiness model for I4.0	Assessment survey	Textual description of the dimensions by maturity level	Yes
M2DDM [23]	Academia	6	6	Maturity model for data-driven manufacturing	n.a	Textual description of the features	Yes
Defence Sector [24]	Academia	4	3	I4.0 maturity levels	Questionnaire	Textual description of each dimension	No
WMG [25]	Industry	4	6	I4.0 readiness assessment	Questionnaire	Requirements of each dimension by maturity level	No
Almamalik [26]	Academia	6	5	Maturity model for I4.0	Surveys	Undescribed dimensions without items list	Yes
Betrieb [27]	Industry	5	4	I4.0 self-check	Questionnaire	Requirements of each dimension by maturity level	No
Rockwell [28]	Industry	5	n.a	IT readiness	n.a	No dimensions identification	No

1), Learners (level 2), and Leaders (level 3 and 4). The PricewaterhouseCoopers (PWC) MM [12] has online self-assessment in six practical steps that a company needs to take to lead tomorrow's competitive digital landscape. The emphasis is on digital maturity in five levels per phase. The application as a consulting tool for assessment is required in three of the six dimensions. The MM no details items neither the development process offered Forrester Research MM [16] defines four maturity levels and includes the same number of dimensions: culture, technology, organization, and insights.

Acatech, the German Academy of Science and Engineering [17] proposes an I4.0 maturity index based on two main pillars: corporate structure (4 dimensions) and corporate processes (5 dimensions), within the company in which the maturity model is going to be used. Each one of the four structural dimensions has two main principles, and the company's maturity of that dimension is related to a combination of both. The dimensions contain altogether 8 sub-dimensions and 27 maturity topics. Based on research at the University of Warwick (WMG), in conjunction with our industrial collaborators Crimson & Co and Pinsent Masons, an Industry 4 readiness assessment tool has been developed [25]. The MM considers six core dimensions, with 37 sub-dimensions that

determine four readiness stages. The MM can be used for self-assessment and provides a benchmark of current I4.0 readiness across a group of 53 companies from 22 countries. Betrieb Machen 4.0 [27], from Mittelstand Kompetenzzentrum Chemnitz is an I4.0 self-check that appears to have been elaborated grounded on VDMA Guideline Industrie 4.0. The Guideline Industrie 4.0 [29] - Guiding principles for the implementation of I4.0 in small and medium-sized businesses, is not a MM, but resembles one since the toolbox it presents classifies five different steps, which can be perceived as maturity stages. Betrieb MM [27] appears to extend these guidelines, maintaining five steps/maturity levels and adding two new dimensions to product and production, the two only dimensions considered in the original toolbox. With the addition of the two new dimensions Work (People) and Organisation (Company), the Betrieb MM [27] ends up structuring its maturity assessment approach in four dimensions and eleven sub-dimensions. Rockwell Automation [28] in a partnership with other major technology companies such as Microsoft, Cisco and Panduit, presents a MM with five stages of measures and best practices for changing technology and organisational culture with the aim of developing a connected company. Although Rockwell MM is widely mentioned by the authors of other models, it does not give any description of the dimensions.

3.2 Models Developed by Academia

Schumacher et al. [10] developed a MM based on 62 items of maturity concerning technology and organization. These items are grouped into nine company dimensions each being evaluated within five levels of maturity. The MM developed by academics of the Middle East Technical University METI [13] are based on SPICE, and has a succession of six capability stages: incomplete, performed, managed, established, predictable, optimizing, based on five areas: process transformation, application management, data governance, asset management, and organizational alignment. SIMMI4.0 [15] consists of five maturity levels with four dimensions: vertical integration, horizontal integration, digital product development, and cross-sectional technology criteria. The digital readiness assessment maturity model (DREAMY) [18] guides manufacturing companies toward digitalization. The MM consists of five maturity levels and four dimensions: processes; control and monitoring; technology; and organization. The MM proposed by Canetta et al. [19] is based on 36 questions divided into five areas: strategy, processes, products and services, technology, and human resources. Based on the questions, four different levels of maturity are derived. Sjödin et al. [20] build their MM on three principles: people, introduction of agile processes and configuration of modular technologies. These principles are classified into four maturity levels. Pessl et al. [21] propose a model with five unnamed maturity stages and five dimensions or fields of action: purchasing, production, intralogistics, sales, and human. The authors only detail the human dimension.

The ManuTech Maturity Model (MTMM) [9] was conducted in Polish manufacturing companies and prescribes a lower number of maturity stages than the average – only four, and eight dimensions: core technologies, people & culture, knowledge management, real-time integration, infrastructure, strategic awareness & alignment, process excellence, and cybersecurity. Scholars of the Politecnico di Milano and Polytechnique

Montréal developed a framework for assessing the maturity of manufacturing companies in I4.0 adoption (Scremin et al.) [22]. The framework delineates maturity in five stages per indicator, taking into account three dimensions with eight indicators: analytic skills, infrastructure for IIoT, absorptive capacity, business strategy, networking and integration, technology strategy, impact on efficiency, and benefits for IIoT adoption. Akdil et al. [8] propose The Maturity and Readiness Model which considers four maturity stages determined by three major dimensions: smart products and services, Smart business processes, and strategy and organization. Dimensions are organized in 13 associated fields. The Maturity Model for Data-Driven Manufacturing (M2DDM) [23] is a MM that solely target IT architectures for data-driven manufacturing. It only analyses the IT architecture of manufacturing companies, in deep, to provide a development path toward servitization. There are six maturity stages and six features: real-time capabilities, digital twin, advanced analytics, information integration, service-oriented architecture, data storage and compute. Bibby and Dehe [24] designed a MM to be applied to 12 companies in the defence sector. It has four maturity levels and only three dimensions, but each dimension has its sub-dimensions. Each sub-dimension needs to have a minimum score to be positioned in each maturity stage. Almamalik [26] developed a MM using a multi-mixed methodology, combining systematic literature study analysis, semi-structured interviews with experts, and surveys for validation. The MM consists of five dimensions and 34 sub-dimensions of analysis to evaluate the Indonesian manufacturing companies in six stages of I4.0 readiness.

Some of the academic MMs are built on aggregation analysis of other models, mainly non-academic models. In addition to widespread recognition and spread across several models, influences from CMMI [5] and SPICE [6], some models testify that part of their structure came explicitly from other models in the selected list. For instance, in the aggregation analysis of the Akdil et al. MM [8], IMPULS [7] is used together with PWC [12], Rockwell Automation [28], and the academic MM of Schumacher et al. [10]. Figure 1 illustrates all the aggregation linkages identified in the selected MM. Some of the models refer to some of the most well-known reference architectures for factories, like RAMI4.0 [30] and IIRA [31].

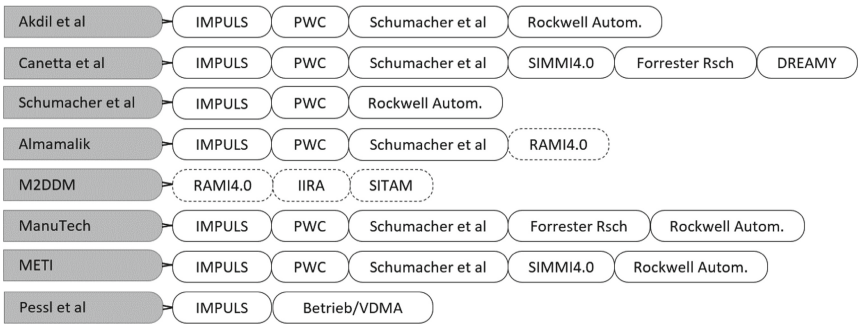

Fig. 1. Selected MMs that are built on an aggregation of other models.

4 Proposed Maturity Model

The whole procedure of the comparative analysis consists of four phases. After having identified the maturity models from previous research, we deeply analyse and characterize them based on the different dimensions and requirements. We use the available literature and summarize the required data in an Excel sheet in the format of a large matrix. Since the main objective of the study is to complement IMPULS [7], the comparative analysis started from it to identify and organize the dimensions of the other models selected in the literature review. We used the available literature and summarize the required data in Excel in the format of a large matrix. The spreadsheet was used to display the categories of dimensions and the dimensions of the IMPULS MM and to identify and associate similar or closer dimensions from the other studied models.

4.1 Phase 1

The categories were organized based on the meta-categories presented by IMPULS: Universal, Virtual and Physical, although the distinction between virtual and physical is somewhat childish when it comes to a by nature hybrid context where cyber-physical systems are increasingly most frequent and important. It is difficult to disassociate the physical from the virtual.

Most MM have dimensions and corresponding sub-dimensions. With some heterogeneity, always according to the objectives of the study, these dimensions and /or their sub-dimensions, which in some models are very high in number, were placed in the spreadsheet, to be aligned with the equivalent dimensions of IMPULS. Four different circumstances emerged from this attempt:

1. The dimension analysed is circumscribed or equivalent to a similar dimension in IMPULS. In these cases, the dimension is displayed in the respective MM column and the same row as the equivalent IMPULS dimension. For example, *Strategy: Implementation I4.0 roadmap* [10] is equivalent to IMPULS's *Strategy* dimension.
2. The dimension is agglutinating and generic to a whole category of IMPULS dimensions. In this case, the dimension is shown in the category title row. E.g. *Products and Services* [19] was in the title row of the IMPULS Smart Products category.
3. The dimension is circumscribed to one of the IMPULS dimension categories, but it is distinct from all the dimensions that IMPULS defines as being part of that category. In these cases, the dimension is enclosed in the respective category, not being aligned with any IMPULS dimension. For instance, *Organizational Structure: Agile management* [17] is confined to the *Smart Factory* category but has no equivalent IMPULS dimension.
4. The dimension is not equivalent to any IMPULS dimension, nor is it circumscribed to one of the IMPULS dimension categories. In these cases, the dimension is kept apart from the existing categories, without belonging to any. E.g., *Sales and Distribution channels* [8] was not included in any of the categories established in IMPULS.

The process described above resulted in new rows in the spreadsheet, meaning new dimensions beyond IMPULS in which, instances of dimensions proposed by the various

MMs have accumulated. These new rows were created by affinity in the rows immediately adjacent to the respective existing dimensions. E.g. *Operations: Automated Resource Management* [14] and *Manufacturing and Operations: Automation* [25] were placed together on an adjacent row to IMPULS' *Distributed Control*. (Fig. 2).



	IMPULS	PWC	Deloitte		Schumacher et al.	
Universal	Strategy & Organization		S: Brand Management	S: Strategic Management		
	strategy		S: Ecosystem Management		S: Implementation I4.0 roadmap	
	Definition of indicators					
	investments		S: Finance & Investment		S: Available resources for realization	
	innovation management	Organization & Culture		S: Stakeholder Management	Cult: Open-innovation and cross company	L: Management competences and methods
		Business Models, Product & Service	S: Portfolio, Ideation & Innovation	OC: Leadership & Governance	L: Willingness of leaders	S: Adaption of business models
		Compliance, Legal, Risk, Security & Tax			G: Labour regulations for I4.0	G: Protection of intellectual property
			OC: Culture			
	Employees				L: Central coordination for I4.0	
	skill sets		OC: Organisational Design & Talent		Peo: ICT competences of employees	
	skill acquisition		OC: Workforce Enablement		Peo: Openness of employees to new	
					Cult: Knowledge sharing	Cult: Value of ICT in company
					Peo: Autonomy of employees	
Virtual	Smart Operations	Value Chains & Processes	O: Agile Change Management			
	Vert and Hor integration				O: Interdisciplinary, interdepartmental	
	Distributed control		(1)O: Real-time Insights & Analytics;	O: Smart and Adaptive Process Management	G: Suitability of technological standards	O: Decentralization of processes
			O: Automated Resource Management			
	IT Security		T: Security			
	Cloud usage					
			O: Integrated Service Management			
			O: Standards & Governance Automation			
	Data-driven					
	data-driven services					
	share of revenues					
Physical	Smart Factory		T: Applications		T: Utilization of mobile devices	
	Equipment Infrastructure		T: Connected Things		T: Utilization of M2M communication	
	Digital Modelling				O: Modelling and simulation	
	data collection					
	data usage		T: Data & Analytics			
	IT systems	IT Architecture	T: Technology Architecture		T: Existence of modern ICT	
	Smart Products				P: Digitalization of products	
	ICT add-on functionalities				P: Product integration into other systems	
	Data analytics usage phase					
					P: Individualization of products	
	Market	Market & Customer Access	C: Customer Engagement	C: Customer Trust & Perception	C: Customer's Digital media competence	
			C: Customer Experience	S: Market & Customer	C: Digitalization of sales/services	
			C: Customer Insights &		C: Utilization of	

Fig. 2. Excerpt of the large matrix built for the comparative process.

The procedure just described is subject to some subjectivity, so the descriptions of the dimensions were permanently invoked in the judgment on what is the best alignment for each one. In this sense, the more information each author added to the definition of their dimensions, the greater the level of objectivity is. The column granularity, in Table 1 records the level of detail and information about each MM.

Simultaneously, to deal with the most ambiguous decisions regarding the definition and placement of dimensions, a symmetric matrix was created to annotate the proximity relations between dimensions. A table where all dimensions appear both as rows and as columns, to be able to point out the eventual closest relationships between them. For example, there is some overlap between the *Data Collection* dimension of the *Smart Factory* category and the *Product Data* dimension of the *Smart Products* category, which leads to highlight this relationship in that table.

4.2 Phase 2

The previous procedure resulted in a very extensive spreadsheet with some complexity that does not facilitate reasoning and decision making. Several spreadsheets were then created to deal with each category of dimensions separately, and an additional spreadsheet to deal with the dimensions that were left out of these categories.

Categories of dimensions were analysed separately, even if some decisions taken in phase 1 concerning the placement of the dimensions have been reverted. In these cases, all spreadsheets were kept consistent, with the Phase 1 spreadsheet being altered and the dimensions moved between different Phase 2 spreadsheets. The symmetric matrix played a key role in helping to maintain consistency. The dimensions that were left out of the categories, because didn't fit into any, began to form what we designated as *Market & Network* category, containing the dimensions *Cooperation within the network* [17], *Pricing/Promotion* [8], *Integrated marketing channels* [25], etc.

In each category sheet, the dimensions were rearranged. Firstly, the dimensions with IMPULS twin-dimensions. Secondly, the generic dimensions. Those, that were identified in situation 2 of phase 1 as being generic to the category itself. In the description of these dimensions, information can be found to help better characterize any of the more specific dimensions of the same category. Thirdly, the dimensions that IMPULS does not contemplate and that are replicated more than once in the various models. For example, in *Strategy & Organisation* there are 13 dimensions related to the topic of *Leadership/Structure.*

Finally, the dimensions with singular instances that do not have within the category, a similar or equivalent dimension, are left apart. For instance, *Organizational Structure: Agile management* [17] in category *Smart Factory.*

This way, some new dimensions for our MM have been drawn, particularly those that have a high cardinality. As for the aforementioned dimension *Leadership/Structure* it became clear that there would have to be a new dimension regarding the aspects of *knowledge creation and management* since among the selected models were realized the alignment of eight dimensions with this subject.

Altogether, eleven new dimensions were created. Table 2 shows the final roll of dimensions established at the end of the process for the MM we are proposing. Shaded are the new dimensions.

- Three new dimensions included in Strategy & Organization: Leadership & structure, Business Models, Compliance & Legal;
- One new dimension comprised in Smart Operations: Control and Monitoring;
- Two new dimensions built-in Smart Products: Products' digital connectivity, Customization/Individualisation;

Table 2. The final cast of dimensions that resulted from the study.

Strategy & organization	Employees	Market & network	Smart operations	Smart factory	Smart products & services
Strategy Investments Innovation Leadership & structure Business model Compliance & Legal	Skills Skill Acquisition Knowledge Autonomy/ Flexibility	Digital Channels Sales Communication & Collaboration	Integration Autonomous Processes Control & Monitoring IT Security Cloud usage	Equipment Infrastructure Digital Model Data Collection and Usage IT Systems	ICT Add-Ons Products' digital connectivity Product Data Customisation/Individualisation Data-driven Services DDS Share

- Two new dimensions included in Employees: Knowledge, Autonomy/Flexibility
- Three new dimensions for the new Market & Network category: Digital Channels, Sales Services, Communication.

4.3 Phase 3

This phase aimed to verify the feasibility of the new dimensions that emerged from the previous phase. The maturity levels were added to the discussion and it was decided to choose five different levels, although IMPULS, the starting model, defines six. There is great variability in the number of levels proposed by the MMs, as can be seen in Table 1. It was understood that five is the ideal number of levels, based mostly on the CMMI [5] inspiring maturity model. Efforts were made to transform the IMPULS requirements defined to six levels, into only five. In some dimensions, it even seemed to make more sense than the original.

The next step was to evaluate if these requirements could be improved by the contributions of the other models that were understood to have equivalent dimensions. The adjustments were performed with punctual amendments and it was concluded that for the dimensions already defined by the IMPULS, the requirements of the various levels are relatively consensual. Adjustments were made to *Smart Factory: Digital modelling*; *Smart Operations: IT Security*; *Smart Operations: Cloud usage*; *Smart Product: Product data*. Table 3 shows the requirements for the five maturity levels of *Smart Operations: IT Security*, complemented with the help of the following dimensions: *Manufacturing and operations: IT and data security* (WMG [25]), *Information Systems: IT security* (Acatech [17]), *Cybersecurity* (ManuTech [9]), *Technology: Security* (Deloitte [14]), *Technology: IT & data security* (Almamalik [26]).

Table 3. Requirements for the five maturity levels of the dimension Smart Operations: IT Security.

Level 1	Level 2	Level 3	Level 4	Level 5
No, or initial IT security solutions planned (IMPULS [7]). No base practice is performed. Ad-hoc reactively application and implementation of IT (Schumacher et al. [10], WMG [25], Acatech [17])	Multiple IT security solutions are planned or initial solutions are in development (IMPULS [7]). Although there is a concern to normalize IT governance activities, they are erratic (Schumacher et al. [10], WMG [25], Acatech [17])	IT security solutions have been partially implemented (IMPULS [7]). There is a written standard for IT governance activities currently being internalized (Schumacher et al. [10], WMG [25], Acatech [17])	Comprehensive IT security solutions have been implemented, existing gaps are being closed (IMPULS [7]). There are performance targets for every IT application (Schumacher et al. [10], WMG [25], Acatech [17])	IT security solutions have been implemented for all relevant areas (IMPULS [7]) and are reviewed frequently to ensure compliance (WMG [25]). IT governance is fully implemented (Schumacher [10], Acatech [17])

For the new dimensions that were intended to be created, the requirements had to be completely defined and for that it was useful to understand where better contributions could be sought. Once again, we reported the degree of detail (column granularity) of each MM in Table 1. Then, the requirements of the new dimensions were built using the MMs best described.

Table 4 shows the requirements for the five maturity levels of the *Digital Channels* dimension, from the new category *Market & Network*, built based on the following dimensions: *Market & Customer Access* (PWC [12]), *Business model: Integrated marketing channels* (WMG [25]), *Smart marketing and Sales operations*, and *Sales and Distribution channels - Campaign systems and sales channels* (Akdil et al. [8]), *Customers: Customer's Digital media competence* (Schumacher et al. [10]).

The symmetric matrix signalized that the dimensions *Data-driven Services: Share of data used* and *Smart Products: Data usage* are deeply related. As such, it was intended to merge the two dimensions and position the resulting dimension under *Smart Products* which is more representative. Consequently, we also incorporated the remaining two dimensions of *Data-Driven Services* into the *Smart Products* category, establishing a unique category named *Smart Products and Services.*

Table 4. Requirements for the 5 maturity levels of Market & Network: Digital Channels.

Level 1	Level 2	Level 3	Level 4	Level 5
Online presence, if present, is separated from offline channels (WMG [25])	At least one channel beside the classical sales force is used for customer interaction (typically a website and shop). First steps are done to increase customer insight (PWC [12]). Online presence is separated from offline channels (WMG [25])	There is already a multi or omnichannel approach for customer access (PWC [12]). Integration within the online and offline channels but not between them (WMG [25]). Campaign systems and sales channels have low-level integration and data analytics tools are not in use to measure campaign performances (Akdil et al. [8])	Multiple channels are used for customer interaction. Data is used extensively to increase customer insight (PWC [12]). Integrated channels and individualised customer approach (WMG [25]). Campaign systems and sales channels have medium level integration and data analytics tools are in use to measure campaign performances (Akdil et al. [8])	Multiple channels (site, social, mobile devices) are leveraged to sell products and services (PWC [12]). Integrated customer experience management across all channels (WMG [25]). Campaign systems and sales channels have high integration and data analytics are in use to measure campaign performances (Akdil et al. [8])

4.4 Phase 4

Although the big majority of the MMs studied have a self-assessment questionnaire and have been designed to be used without the intervention of an appraiser, it was understood that the role of such a facilitator is not negligible. The appraiser can disambiguate any question, translating the spirit of the question into terms closer to the company's culture, can ensure that the questions are understood and the answers are given full awareness and can validate responses by collecting pieces of evidence.

We chose to extend the questionnaire that accompanies the model with the suggestion of some artefacts that can be collected to gather evidence about the company's real state of maturity.

The model was completed with the alteration of the IMPULS questions for the dimensions being adjusted and with the creation of new questions for the new dimensions introduced. As the model is intended to be used to assess the digital maturity of the Portuguese companies, the questions were simultaneously translated into Portuguese. Each question was complemented with an indication of the artefacts that can confirm a rigorous answer. Case of modelling artefacts like technical documentation as functional diagrams, plant diagrams, product descriptions, procedural descriptions; and operative plans as production plans and project plans. Physical artefacts like products, resources, production systems like equipment, sensors, actuators, and IT systems and control systems, may constitute the desired evidence to confirm the situations reported in the responses to the questionnaire.

Table 5 shows the questions that allow assessing the level of maturity regarding dimension *Knowledge*, as well as the type of evidence that can confirm the responses.

Table 5. Compound question to assess the dimension Knowledge of the category Employees.

E.3 How do People deal with the Information System, processes and transmission of knowledge?		
☐ Distrust the Information System	☐ Distrust processes	☐ Mouth to mouth
☐ Trust the core Information Systems	☐ Follow unstructured paper based processes	☐ In meetings
☐ Trust less conventional IS applications	☐ Follow structured paper based processes	☐ Using a Knowledge MIS
	☐ Follow digital structured workflows	☐ Using a Knowledge MIS integrated on corporate's IS
Hypothetical evidence:		
– Affirmations – Example of non-mainstream IS application – Example of a structured process workflow sheet		– Knowledge Management Information System – Workflow Software Application

5 Conclusion

Companies need assistance in the path to digital transformation. The overall idea of I4.0 is not completely understood by many companies. The implementation and gradual adoption of the industrial internet, accompanying disruptive technologies and related business models can be a very complex and extensive process of change. MMs are useful instruments to assist organizations by providing comprehensive guidance, paving the way towards I4.0 technologies/practices fulfilment.

This study aims to adjust and extend the MM that seems to be more used by the Portuguese companies, with components and requirements which can overcome its pointed-out breeches, thus suggesting ways for it completion and enrichment. Twenty-one MMs in the context of I4.0 were analysed, compared and reconciled to build an embracing perspective of digital transformation. The result is a MM with the appraisal of 28 dimensions organized in six categories. The framework to assess the maturity concerning I4.0 practices involves also a questionnaire that evaluates the fulfilment of the requirements of each dimension by maturity level, types of evidence that can confirm the evaluation, and a set of maturity requirements whose incremental satisfaction can serve as a roadmap for companies towards higher compliance with I4.0.

This work has some limitations. The first constraint concerns the fact that this study started from an existing MM without questioning it completely, although it has refined it in some aspects, changed the number of maturity levels, re-arranged dimensions in different categories, and even extending it with new categories and dimensions. The second limitation will be the subject of future work: the absence of an exploratory case study to validate the usefulness and applicability of the proposed MM. In the immediate future, we will conduct a set of test cases in industrial partner companies of a major Portuguese Interface Centre that develops and fosters research and innovation processes. Finally, how the company's overall maturity level is calculated stills a matter not properly addressed. Data from the exploratory test cases will play an important role in the definition of a weighted average that adjusts and quantifies the importance of each dimension according to the industrial sector, size and scope of the organizations.

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