# Design of an Assessment Industry 4.0 Maturity Model: an application to manufacturing company

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## Abstract

The context of the fourth industrial revolution brings companies numerous challenges. Agility, flexibility, and responsiveness are necessary characteristics in this business ecosystem, with the deep insertion of digital technologies in manufacturing. Therefore, this work has the objective of developing a model of measurement of the maturity and readiness of the industry 4.0 so that companies can visualize their positioning in this new reality. Qualitative and quantitative methods were used for the development of the model that contemplates 6 (six) dimensions. It was applied in the Industrial Pole of Manaus (PIM), in a multinational manufacturing company. The results obtained are adherent to the reality of the company in relation to the industry 4.0.

## Keywords
Industry 4.0, Maturity Model, PIM

### 1. Introduction

Agility is a strategic feature that is becoming increasingly important to successful companies (Schuh et al. 2017). A large product variability, and reduce time product-life-cycles require agile and flexible production operation, which can be reconfigured rapidly for new demands (Weyer et al. 2015).
The industry is experiencing a major shift worldwide labelled as "The Fourth Industrial Revolution". This change, also known as Industry 4.0, is triggered by an whopping growth in new digital technologies (information and automation) (Colli et al. 2018). According with Canetta, Barni & Montini (2018), in this new digitised ecossystem, companies are facing significant challenges regarding the implementation of the concept, both at organisational and technological level. The development process implemented by these companies includes the definition of strategic plans to the updating of technology and products, and the creation of new skills.
In the context of informatization and industrialization, some developed and developing countries announced their national manufacturing strategies to support their economic transformation and national competitiveness, for example, Advanced Manufacturing in the United States and Made in China 2025 in Asia, "*La Nouvelle Industrielle*" iniative of France (Liao et al. 2017; Kagermann 2013; Li 2015).
Industry 4.0 should impact on supply chains, business models and processes. As started in Kagermann et al. (2013) these changes, which are likely to be enabled by the transformation to Industry 4.0, are as follows: custom customer requests; flexibility; efficient decision-making; resource productivity and efficiency; creation of new services; responding to change in the workplace and work-life-balance.

The requirements and concepts of Industry 4.0 are cited by many researchers. Since Industry 4.0 includes many technologies, in terms of the functionalities and capabilities they offer. The essential technologies that are applied within the context of Industry 4.0 are as follows: Cloud Computing (Khan et al. 2017) , Big Data (Schimdt et al. 2015), Internet of Things (IoT) (Bi, Xu & Wang 2014), Cyber-Physical Systems (Wang et al. 2016) , and Augmented Reality (Bottani and Vignalli 2019).

The benefits of promoting Industry 4.0 practice is to provide smart manufacturing from some dimensions and to improve the business performance. Despite the widely accepted benefits of Industry 4.0, there is a lack of content of literature regarding the implementation of smart manufacturing practices and their impacts on the efficiency (Lin et al.2018).

Looking at all of these concepts and the broad range of different requirements a question arises: *How is the industry 4.0 maturity being measured in companies?* In this ecosystem of uncertainty manufacturing companies in relation to the idea of Industry 4.0, need to develop new methods and tools capable of providing guidance and support to align strategies and business operations. Recognizing what features are needed, and in which way and for what purpose, still a challenge for industries. This is where the present paper comes and this results in the main research question:

**RQ1** – *What should a maturity model assess a industry in the context of industry 4.0* ?

The contribution of this paper, and answer the research question, consists for the development of an Industry 4.0 maturity assessment instrument. It is structured as follows: First, an explanation of the Industry 4.0 concept is given, followed by the systematic literature review and the review of existing maturity models. Finally, the Industry 4.0-Maturity Model and the conclusions are presented.

## 2. Theoretical background and literature review

### 2.1 Manufacturing and interoperability

Manufacturing is the process of creating a product out of raw materials. Smart manufacturing enables to take advantages of advanced information and manufacturing technologies to provide responsivity in physical processes to address a dynamic and global Market with increasing competition (Davis et al 2012).

As showed above, smart manufacturing is the convergence of technologies (information, manufacturing and management), and aims to take new capabilities and core competences to manufacturing enterprises (Li et al. 2018). IT is developing in different layers and directions. Industrial Manufacturing is also increasing quickly with new process techniques, and new materials. Management technology includes architectures, product life-cycle and supply chain.

One of the key points of Industry 4.0 is interoperability. According to Chen et al. (2008), interoperability is "the ability of two systems to understand each other and to use functionality of one another." It represents the capability of two systems sharing data, information, and knowledge (Vernadat 2010). The interoperability of Industry 4.0 will includes software components, applications, business processes, and diversified business context.

The Interoperability of Industry 4.0 needs specific principles to guarantee the complete process of accuracy and efficiency. Eight principles are appropriate for Industry 4.0 to be interoperable: accessibility, multilingualism, security, privacy, subsidiarity, the use of open standards, opensource software, and multilateral solutions (Panetto and Molina 2008).

Smart manufacturing stands at the merge of industrialization and informatization (Li et al. 2018). New skills and competencies will be created in companies, and their countries, in this new context of smart manufacturing. Therefore, smart manufacturing needs systematic solutions and methodologies, and its standardization.

### 2.2 Maturity models

A systematic literature review was applied to find existing maturity models in the context of Industry 4.0. Maturity model for Industry 4.0 assessment/readiness were selected as the starting point for research. The literature review considered the following Keywords and searched terms: "Industry 4.0", "Smart Manufacturing", "Advanced Manufacturing", "Fourth Industrial Revolution", "Digital Manufacturing", "Cyber-Physical System", and "Maturity Model" were used. The databases of Scopus, Web of Science, and Sciencedirect were searched. From the obtained results, the authors selected only the results considered relevant for the purpose of this study, focused only on those contributions referring to methodologies to assess maturity of companies under digital or Industry 4.0 features. To ensure academic rigor, only publications from peer-reviewed journals and conference proceedings were considered.

285 articles were identified with the search terms. Duplicate articles were initially deleted. As part of the first filter, the studies were evaluated of their adherence by examining their keywords, titles, and abstracts, before reading the papers fully. The figure 1 shows the portfolio development process considers the criteria of filters.

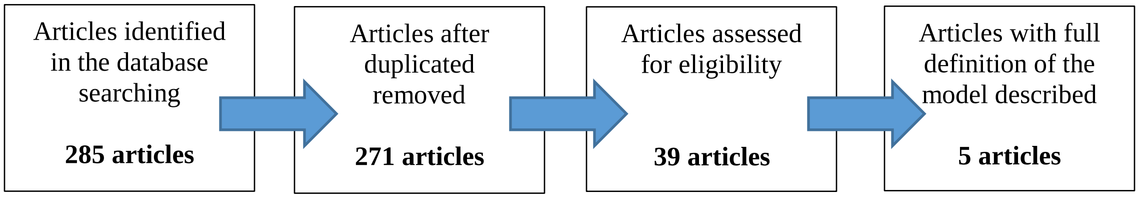


Figure 1: Article Portfolio Development Process

The first manifestations of maturity models date back to the 1970s and are rooted in software engineering (Nolan, 1973; Van Iooyet al. 2013). Since then, the concept of maturity has evolved into an important tool in business practice. The concept of maturity can be used for descriptive, prescriptive and/or comparative purposes (Röglingeret al. 2012). It serves a descriptive purpose if applied for as-is assessments, a prescriptive purpose if used to establish a desirable path of development and a purpose if used for internal or external benchmarking.
Maturity models are usually used as an instrument to conceptualize and measure maturity (process, organization, or objective). Also called readiness models with the goal to capture the starting-point and allow for initializing the development process (Schumacher et al. 2016).
Both researchers and practioners have published several digital maturity models (Lanza et al. 2016; Leyh et al. 2017; Lichtblau et al. 2015; Schuemacher et al. 2016), e.g. Fraunhofer IFF (Schenk et al., 2015) and Acatech (Schu et al. 2017). In order to do that, all of these models are based on the hypothesis that the digital transformation towards Industry 4.0 is an evolutionary journey (Kagermann et al. 2013) across a number of sequential digital stages, characterized by an increasing digital integration complexity. Accordingly, as a key point principle, they build on a cumulative capability perspective (Miller et al. 1994).
In the past, methodologies have been developed in order to assess the technological impact on companies. One of the most accepted one is the so called Technology-Organization-Environment Framework (Di Pietro, Wiarda & Fleischer (1990). The theory behind this framework states that “The process by which a firm adopts and implements technological innovations is influenced by the technological context, the organizational context, and the environmental context”. The technological context includes the internal and external technologies that are important to the firm. The organizational context refers to the characteristics and resources of the firm. The environmental context includes the size and structure of the industry, the firm’s competitors, the macroeconomic context, and the regulatory environment (Tidd, 2001).
Assessment tools have been developed both by academia and firms, with the aim of providing analytical frameworks that companies could adopt to self-assess their conditions or colaboratively analyse them a guided interaction with the developers of the framework (Chanias and Hess 2016).
A comparison of the models reveals publication streams developed by firms and academia (Table I). The groups are concentrates on IT architecture and/or capabilities, specifically with regard to the IoT (Katsma et al. 2011; Weber et al. 2017; Jæger and Halse 2017), on the CPS (Westermann et al.,2016). The authors align their models to the Industry 4.0 phenomenon and acknowledge that digitization radically affects current business models in a unique and unprecedented way –especially the models of manufacturing companies (Leyh et al. 2016; Ganzarain and Errasti 2016; Schumacher et al. 2016; Gökalp et al. 2017; Klötzer and Pflaum 2017; De Carolis et al. 2017).
There are many types and range of maturity models is already available, supporting companies on defining their maturity and improving potentials. Created to companies themselves apply the tools and cooperative instruments. These maturity models share to objectify the roadmap towards future production systems (Schuh et al. 2017).

Table I: Industry 4.0 maturity assessment models developed by Source

| Maturity model | Authors | Source |
|---|---|---|
| Digital Transformation – How to Become Digital Leader | Arthur D. Little (2015) | Firms |
| IMPULS – Industry 4.0 Readiness | Lichtblau et al. (2015) | Firms |
| Raising your digital quotient | McKinsey & Company (2015) | Firms |
| An industry 4 readiness assessment tool | WMG (2015) | Firms |

| | | |
|---|---|---|
| Industry 4.0 Maturity Model | Schumacher et al. (2016) | Academia |
| European Financial Services Digital Readiness Report | Accenture (2016) | Firms |
| The Industry 4.0 / Digital Operations Self Assessment | PWC (2016) | Firms |
| SIMMI 4.0 | Leyh et al. (2016) | Academia |
| DREAMY | De Carolis et al. (2017) | Academia |
| VTT Model of Digimaturity | Leino et al. (2017) | Academia |
| ACATECH | Schuh et al. (2017) | Academia |

Such maturity models offer a good starting point to assess the current achievements, to set strategy-specific goals and, in case of the presented Fraunhofer Austria maturity model, to provide further guidance towards best-practice scenarios (Schumacher et al. 2016; Schuh et al. 2017). Still, a disadvantage of most maturity models is the restricted applicability regarding the impact assessment related within the Industry 4.0. While showing best practices and proposing areas of activity, others only show the financial effect of Industry 4.0-related decisions. the problem is the missing link between maturity levels and quantitative performance measures to track effective improvements. The same author aforementioned shows these maturity models are used in the evaluation process, which are often based on good practices and success factors derived from projects that have demonstrated favorable results to an organization or an industry sector.
In order to analyze existing maturity models objectively, a set of assessment criteria which have been employed in similar studies is identified based on the literature. The level of detail explanations of the attributes in the corresponding dimensions was examined in the article portfolio resulted in 5 maturity models (Table II).

Table II: Industry 4.0 maturity models

| Maturity model | Authors | Dimensions |
|---|---|---|
| IMPULS – Industry 4.0 Readiness | Lichtblau et al. (2015) | Strategy and organization, Smart Factory, Smart Operations, Smart Products, Data-driven services and employees |
| The Industry 4.0 / Digital Operations Self Assessment | PWC (2016) | Business Models, Product and Service, Portfolio Market and Customer Access, Value Chains and Processes, IT Architecture, Compliance, Legal. Risk, Security and Tax, Organization and Culture |
| Industry 4.0 Maturity Model | Schumacher et al. (2016) | Strategy, Leadership, Customer, Products, Operations, Culture, People, Governance, Technology |
| SIMMI – System Integration Maturity Model Industry 4.0 | Leyh et al. (2016) | Vertical integration, Horizontal integration, Cross-sectional technology criteria |
| ACATECH | Schuh et al. (2017) | Resources, Information systems, Organisational structure, Culture, classified by stages |

## 3. Research model and variables

In this section, the focus is on the dimensions of the maturity model developed, highlighting how these features can show the maturity level.
Previous researchers have developed maturity models to capture and define the features of industry 4.0 in the organization. Their common goal is to assess the digital maturity level of an organization and provide an indication of activities needed to increase this level. To define the framework behind the assessment instrument was started from the identification of the gaps (Figure 2) currently showed by descriptive and comparative tools, to develop a methodology that, following an incremental approach, was able to analyses some functional areas. In combining the results from the mathematical models and the cluster analyses, there is support for the maturity model.

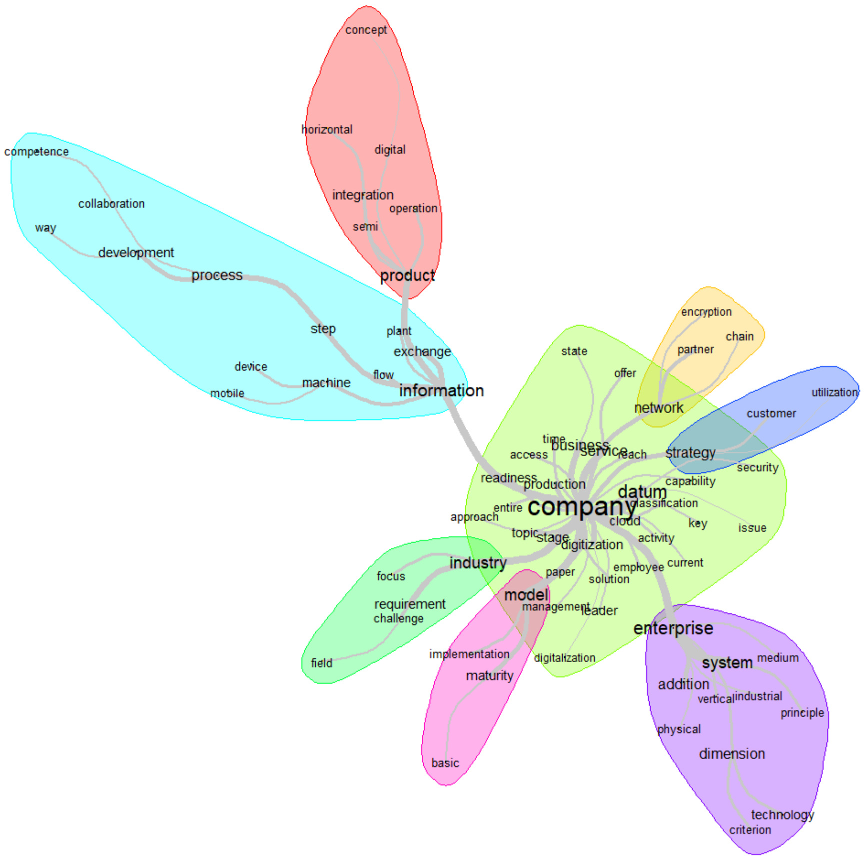


Figure 2: Gaps of the industry 4.0 maturity models

The model is based on a group of dimensions, combined transversely with stages, i.e. value-based increase levels that help companies to identify their way through every dimension/stage. From what already defined in the maturity levels, it is clear that, when evaluating the digital capabilities of a company, not only the Technologies used to support the processes have to be considered. Therefore, from these considerations, from the evidences presented in the literature and considering the objective of the maturity model itself, it was decided to evaluate the industry 4.0 maturity model through six dimensions: Products and services, Manufacturing, Strategy, Supply chain and Interoperability. Which dimensions and their respective attributes, each one classified in stages of maturity intended to offer a growing vision regarding the complexities inherent in the multiplicity of factors that combine at the industry 4.0 features.
The table III offer details regarding the dimensions, features, and stages applied to assessment-methodology. Other models and tools we found do not offer any details regarding structure and contents, for example Lichtblau et al. (2015), Schumacher et al. (2016), Leyh et al. (2016) and De Carolis et al. (2017).
According to Schuh et al. (2017) the companies are still confronting the challenge of creating the basic conditions for Industry 4.0. Although computerization and connectivity are parts of the 4.0 industry, such internships are basic requirements for its implementation.

Table III: Dimensions and Industry 4.0 impact features

| Dimensions | Industry 4.0 Impact feature | Related Stage of ACATECH | Variable |
|---|---|---|---|
| Products and Services | Product customisation, Data-driven services, Level of product data usage | Visibility | Latent |
| Manufacturing | Automation, M2M, Equipment readiness for industry 4.0, | Transparency Predictive capacity | Latent |

| | | | |
|---|---|---|---|
| | Autonomously guided workpieces, Self-optimizing process, IT, data security | Adaptability | |
| Business Model | Data driven decisions, Tracking, Real-Time Scheduling, Interoperable marketing partners, IT support business | Transparency | Latent |
| Strategy | Degree of implementation, KPI, People Capabilities, Leadership, Finance | Visibility<br>Transparency<br>Adaptability | Latent |
| Supply Chain | Inventory control using real-time, integration, visibility and flexibility | Transparency<br>Predictive capacity | Latent |
| Interoperability | Data sharing, high-integration level, system integration, and Risk | Visibility<br>Transparency | Mediator |

### 3.1 Analysis dimensions

The number of variables under analysis to the sample size was a limitation of this work, since the research was based on surveys. As two groups of variables were used, making possible the methods Multiple correlation (Cohen, 1988) and Factor analysis (Mundfrom et al. 2005) to analyze cross-dependence between these variables. There are other methods, such multivariate methods typically require more samples than the number of analyzed variables order to obtain accurate results (Cohen 1988; Mundfrom et al. 2005). The bivariate correlation analysis (Cohen, 1988) does not require large data sets, as only two variables at the time are analyzed, was chosen for the modelling.
In theory statistics, a bivariate correlation indicates the strength and direction of a linear relationship between two random variables. The correlation refers to the behavior of two variables by independence. Thus, before identifying a correlation, it needs to be determined whether the data set is normally distributed.
If the data set under analysis does not compliance to a normal distribution, a non-parametrical methods can be used Point biserial correlation, Spearman or Kendall (Cohen & Cohen, 1983). On the other hand, in case of normal distribution, the parametrical Pearson correlation coefficient, *r*, is the most accurate measure for correlation strength (Cohen & Cohen, 1983; Siegel, 1957). This coefficient is reached by dividing the covariance by standard deviations (two variables).
For each of described dimensions of analysis, a numerical result is obtained using the concept of Pearson correlation and Cohen's taxonomy in order to analyze the relationship of dimensions and how impacts industry 4.0 features (parameters). Nonetheless, Cohen himself suggests a taxonomy for the determination of correlation strength (small – 0.1 to 0.3; medium – 0.3 to 0.5; large – 0.5 to 1).

### 3.2 Adapted Index of Agreement

Willmott et al. (2012) examines various statistics that have been proposed in a variety of environmental fields to provide model evaluation. Model evaluation techniques are useful in several models, for example development, verification, and model calibration (Pappenberger and Beven 2006). Moreover, values of the various statistics of model efficacy cannot be cross-compared and even those who often report such measures may not know what a value´s index of model performance really means (Legates and McCabe 2013)
Thus, according to (Willmott et al. 2012) these approach is important to demonstrate a large number of statistics of model evaluation available shows undermost relationship across disparate measures. It is necessary to map this criterion to understand more about each of these statistics and examine their behaviour behavior of the calculated values.
The original form of index of agreement (Willmott and Wicks 1980; Willmott 1981) was described in Equation (1). They used letter "d" to represent the index and in this work follows their convention here. It (d) was a sums-of-squares-based measure, within which $\delta$ was the sum of the squared errors while $\mu$ was the overall sum of the squares of sums of the absolute values of two partial differences from the observed mean. The form of the original index is commonly written as

$$d = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|P_i - \overline{O}| + |O_i - \overline{O}|)^2}$$ Equation (1)

The value of *d* indicates the sum of the magnitudes of the differences between the predicted and observed deviations about the observed mean relative to the sum of the magnitudes of the perfect-model (Pi =Oi, for all i) and observed deviations about the observed mean. This index occurs from 0 to 1, with 1 being the smaller amplitude of the errors, that is, greater adherence to the parameters (Ji and Gallo 2006).

## 4. Pilot Case Study

The Industrial Pole of Manaus has more than 1100 companies of small, medium and large size, involving seven subsectors of different branches of activities, which can be seen in Figure 3. The emphasis of the companies to be researched will focus in the electronics sector that is the 16.77% of the PIM billing. The research will be developed in companies of medium, large and small size.

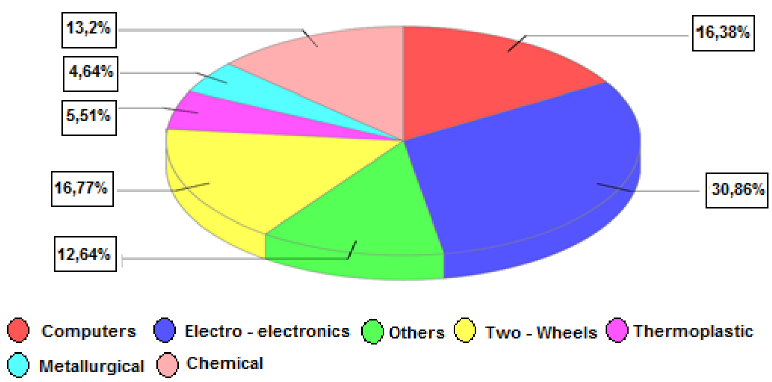


Figure 3: Share of activities of sub-sectors in sales of the Industrial Pole of Manaus)

In order to calibrate the assessment model, one pilot case study was conducted with an electronic manufacturing enterprise with around 500 employees which manufactures wireless Embedded Multimedia Terminal. To ensure accuracy of results, we have chosen an organization that already is engaged in Industry 4.0 and understanding about its basic concepts.
A questionnaire was sent to the organization to obtain the current situation. Although self-assessment of the maturity items is a easy method to conduct. In the following of the assessment procedures, the response then was inserted into the software tool do measure the maturity.
From the expert interviews we found the weighting-factor for each dimension, then calculating the weighted average. Figure 2 displays the index of agreement d of these six dimensions for four-point responses scales, and the average of the indexes reached 0.7 that indicates the maturity of the company.

| Results/ Dimensions | Products and Services | Manufacturing and Operations | Business Model | Supply Chain | Strategy and organization | Interoperability |
|---|---|---|---|---|---|---|
| *d* (index of agreement) | 0,83 | 0,65 | 0,87 | 0,74 | 0,32 | 0,84 |

Figure 2. Industry 4.0 maturity in six dimensions – adapted index of agreement

To demonstrate the model´s systemic, the assessment calculation of the dimension “supply chain”. The company self-assessed the five features maturity items (see Table IV).

Table IV: Supply chain dimension

| *Features* | *Oi* | $\sum_{i=1}^{n}(P_i - O_i)^2$ | $\sum_{i=1}^{n}(\lvert P_i - \overline{O}\rvert + \lvert O_i - \overline{O}\rvert)^2$ | *Weighting-factor* | *d* | $d_{adjust}$ |
|---|---|---|---|---|---|---|
| Real-time inventory control | 2 | 4 | 4 | | | |
| Integration | 2 | 5 | 5 | | | |
| End-to-end visibility | 1 | 9 | 9 | 2 | 0.37 | 0.74 |
| Agility | 3 | 10 | 10 | | | |
| Lead Times | 4 | 10 | 15.86 | | | |

**5. Conclusions**

The current research was conducted assessing Industrial Pole of Manaus (manufacturing companies) , but our findings may apply to a wider sample. This study has important implications for both academia and firms.

This research presents some important theoretical contributions to the state-of-the-art on assessment and readiness industry 4.0 maturity models. The goal of this research is to provide a maturity model for the classification of a company's roadmap in the context of the Industry 4.0 requirements. As it was conducted as a pilot case study, including a surveyed companies, the analysis, focusing on the Industrial Pole of Manaus.

Our approach identifies how the association of Industry 4.0 requirements according to different contextual variables (dimensions) may contribute to increase the assessment and readiness maturity level.

Beyond the development of model was based on the literature review (the comparison of existing maturity models), a mapping of these maturity models would be important to merge their different points of assignments and dimensions between these models to enable companies to classify themselves in concepts of Industry 4.0 in all levels of their enterprise.

The model has been developed using a qualitative and quantitative methods for empirical validation. Thus, in contrast to other approaches the contribution of this paper effort is the inclusion of mathematical methods to measure the maturity level.

This work contains empirical evidences on assessment and readiness Industry 4.0 maturity model. Within this paper we present the first version of our maturity model PIM4.0. The model provides a mapping of key business dimensions and maturity improvement points.

## References

Bi, Z., Da Xu, L., & Wang, C. (2014). Internet of things for enterprise systems of modern manufacturing. IEEE Transactions on industrial informatics, 10(2), 1537-1546.

Biegler, C., Steinwender, A., Sala, A., Sihn, W., & Rocchi, V. (2018, June). Adoption of Factory of the Future Technologies. In 2018 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC) (pp. 1-8). IEEE.

Bottani, E., & Vignali, G. (2019). Augmented reality technology in the manufacturing industry: a review of the last decade. IISE Transactions, 51(3), 284-310.

Canetta, L., Barni, A., & Montini, E. (2018, June). Development of a Digitalization Maturity Model for the manufacturing sector. In 2018 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC) (pp. 1-7). IEEE.

Chanias, S., & Hess, T. (2016). How digital are we? Maturity models for the assessment of a company's status in the digital transformation. Management Report/Institut für Wirtschaftsinformatik und Neue Medien, (2), 1-14.

Chen, D., Doumeingts, G., & Vernadat, F. (2008). Architectures for enterprise integration and interoperability: Past, present and future. Computers in industry, 59(7), 647-659.

Colli, M., Madsen, O., Berger, U., Møller, C., Wæhrens, B. V., & Bockholt, M. (2018). Contextualizing the outcome of a maturity assessment for Industry 4.0. Ifac-papersonline, 51(11), 1347-1352.

Davis, J., Edgar, T., Porter, J., Bernaden, J., & Sarli, M. (2012). Smart manufacturing, manufacturing intelligence and demand-dynamic performance. Computers & Chemical Engineering, 47, 145-156.

De Carolis, A., Macchi, M., Negri, E., & Terzi, S. (2017, June). Guiding manufacturing companies towards digitalization a methodology for supporting manufacturing companies in defining their digitalization roadmap. In 2017 International Conference on Engineering, Technology and Innovation (ICE/ITMC) (pp. 487-495). IEEE.

Depietro, R., Wiarda, E., & Fleischer, M. (1990). The context for change: Organization, technology and environment. The processes of technological innovation, 199(0), 151-175.

Ganzarain, J., & Errasti, N. (2016). Three stage maturity model in SME's toward industry 4.0. Journal of Industrial Engineering and Management (JIEM), 9(5), 1119-1128.

Hermann, M., Pentek, T., & Otto, B. (2016, January). Design principles for industrie 4.0 scenarios. In 2016 49th Hawaii international conference on system sciences (HICSS) (pp. 3928-3937). IEEE.

Jæger, B., & Halse, L. L. (2017, September). The IoT technological maturity assessment scorecard: a case study of norwegian manufacturing companies. In IFIP International Conference on Advances in Production Management Systems (pp. 143-150). Springer, Cham.

Ji, L., & Gallo, K. (2006). An agreement coefficient for image comparison. Photogrammetric Engineering & Remote Sensing, 72(7), 823-833.

Leyh, C., Bley, K., Schäffer, T., & Forstenhäusler, S. (2016, September). SIMMI 4.0-a maturity model for classifying the enterprise-wide it and software landscape focusing on Industry 4.0. In 2016 Federated Conference on Computer Science and Information Systems (FedCSIS) (pp. 1297-1302). IEEE.

Legates, D. R., & McCabe, G. J. (2013). A refined index of model performance: a rejoinder. International Journal of Climatology, 33(4), 1053-1056

Leino, S. P., Kuusisto, O., Paasi, J., & Tihinen, M. (2017). VTT Model of Digimaturity. In Towards a new era in manufacturing: Final report of VTT's For Industry spearhead programme (pp. 41-46). VTT.

Lichtblau, K., Stich, V., Bertenrath, R., Blum, M., Bleider, M., Millack, A., ... & Schröter, M. (2015). IMPULS-industrie 4.0-readiness. Impuls-Stiftung des VDMA, Aachen-Köln.

Katsma, C. P., Moonen, H. M., & van Hillegersberg, J. (2011, June). Supply Chain Systems Maturing Towards the Internet-of-Things: A Framework. In Bled eConference (p. 34).

Kagermann, H., Helbig, J., Hellinger, A., & Wahlster, W. (2013). Recommendations for implementing the strategic initiative INDUSTRIE 4.0: Securing the future of German manufacturing industry; final report of the Industrie 4.0 Working Group. Forschungsunion.

Khan, W. A., Wisniewski, L., Lang, D., & Jasperneite, J. (2017, June). Analysis of the requirements for offering industrie 4.0 applications as a cloud service. In 2017 IEEE 26th International Symposium on Industrial Electronics (ISIE) (pp. 1181-1188). IEEE.

Li, Q., Tang, Q., Chan, I., Wei, H., Pu, Y., Jiang, H., ... & Zhou, J. (2018). Smart anufacturing standardization: Architectures, reference models and standards framework. Computers in Industry, 101, 91-106.

Lin, D., Lee, C. K. M., Lau, H., & Yang, Y. (2018). Strategic response to Industry 4.0: an empirical investigation on the Chinese automotive industry. Industrial Management & Data Systems, 118(3), 589-605.

Nolan, R. L. (1973). Managing the computer resource: a stage hypothesis. Communications of the ACM, 16(7), 399-405.

Panetto, H., & Molina, A. (2008). Enterprise integration and interoperability in manufacturing systems: Trends and issues. Computers in industry, 59(7), 641-646.

Pappenberger, F., & Beven, K. J. (2006). Ignorance is bliss: Or seven reasons not to use uncertainty analysis. Water resources research, 42(5).

Van Looy, A., De Backer, M., Poels, G., & Snoeck, M. (2013). Choosing the right business process maturity model. Information & Management, 50(7), 466-488.

Röglinger, M., Pöppelbuß, J., & Becker, J. (2012). Maturity models in business process management. Business process management journal.18(2), 328-346.

Schmidt, R., Möhring, M., Härting, R. C., Reichstein, C., Neumaier, P., & Jozinović, P. (2015, June). Industry 4.0-potentials for creating smart products: empirical research results. In International Conference on Business Information Systems (pp. 16-27). Springer, Cham.

Schumacher, A., Erol, S., & Sihn, W. (2016). A maturity model for assessing Industry 4.0 readiness and maturity of manufacturing enterprises. Procedia Cirp, 52, 161-166.

Schuh, G., Anderl, R., Gausemeier, J., ten Hompel, M., & Wahlster, W. (2017). Industrie 4.0 Maturity Index. Managing the Digital Transformation of Companies. Munich: Herbert Utz.

Tidd, J. (2001). Innovation management in context: environment, organization and performance. International Journal of Management Reviews, 3(3), 169-183.

Unit, E. I. (2013). The Internet of Things business index: a quiet revolution gathers pace. The Economist.

Vernadat, F. B. (2010). Technical.semantic and organizational issues of enterprise interoperability and networking. Annual Reviews in Control, 34(1), 139-144.
Wang, S., Wan, J., Zhang, D., Li, D., & Zhang, C. (2016). Towards smart factory for industry 4.0: a self-organized multi-agent system with big data based feedback and coordination. Computer Networks, 101, 158-168.
Weyer, S., Schmitt, M., Ohmer, M., & Gorecky, D. (2015). Towards Industry 4.0-Standardization as the crucial challenge for highly modular, multi-vendor production systems. Ifac-Papersonline, 48(3), 579-584.
Weber, C., Königsberger, J., Kassner, L., & Mitschang, B. (2017). M2DDM–a maturity model for data-driven manufacturing. Procedia CIRP, 63, 173-178.

Westermann, T., Anacker, H., Dumitrescu, R., & Czaja, A. (2016, October). Reference architecture and maturity levels for cyber-physical systems in the mechanical engineering industry. In 2016 IEEE International Symposium on Systems Engineering (ISSE) (pp. 1-6). IEEE.
Willmott, C. J. (1981). On the validation of models. Physical geography, 2(2), 184-194.
Willmott, C. J., Robeson, S. M., & Matsuura, K. (2012). A refined index of model performance. International Journal of Climatology, 32(13), 2088-2094.

## Biographies

**Américo Azevedo** Associate Professor at University of Porto and Research Project Manager at Inesc Porto (one of the main research and technology transfer institutes in Portugal). I have been involved in several R&D project contract with European Union and Portuguese public institutions and enterprises and also, I have been reviewer and evaluator of several international R&D Industrial projects and member of several scientific programmes committees. undergraduate studies at the Faculty of Engineering of University of Porto (FEUP) in Electrical and Computers Engineering, graduating in 1988. I received a PhD in the area of collaborative planning systems in the context of networking enterprises from University of Porto in 2000. Author of many articles in international journals and technical publications and also I have been active in preparing and participating in R&D projects involving industrial companies as well as I have been supervising several PhD and M.Sc research thesis. Areas of research interest include topics in the domain of Business Process Engineering, Inter-firms Networks (Collaborative Operations Management, Alignment and Collaborative Business Process Management), Digital Manufacturing and industrial and Operations Management.

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