Climbing the Maturity Ladder in Industry 4.0: A Framework for Diagnosis and Action that Combines National and Sectorial Strategies

Full Paper

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Abstract

We present a framework to assist Industry 4.0 initiatives at countrywide and sector-specific levels. It was created using design-science research in the context of non-metal mineral industry - ceramic, glass, stone, and nanomaterials. Our findings suggest that (1) existing maturity models for Industry 4.0 do not fit all industrial contexts; (2) their use can be discouraging for small and medium-size enterprises planning digital strategies; (3) Industry 4.0 technologies should be considered as prescriptive solutions rather than descriptive dimensions, and (4) it is possible and desirable to consider Industry 4.0 maturity as a co-evolutionary growth of digital services and processes within supply chains. Our proposal provides staged and continuous representations of maturity that can be tailored for each industry. Maturity models can be a prime communication tool for managers and technology providers. Our contribution supports the European efforts to succeed in the Fourth Industrial Revolution, shared by millions of industries worldwide.

Keywords

Industry 4.0, Fourth industrial revolution, Maturity model, Design-reality gaps, Design-science research.

Introduction

A new industrial revolution has started. It is the fourth, according to the World Economic Forum, and promises drastic changes in organizations. Countries around the globe have this topic at the top of their political agendas (Acatech 2013; Smit et al. 2016), which involves technological innovations (Schwab 2015) and new challenges that emerge from the use and adaptation of information technologies (IT) and orientation to business processes (Paul 2007). We can find similar movements around the globe, for example, *Advanced Manufacturing* in the United States and *Made in China 2025* in Asia (Smit et al. 2016). According to Klaus Schwab, "*we are in the midst of the Fourth Industrial Revolution, which will affect governments, businesses and economies in very substantial ways. We should not underestimate the change ahead of us*" (Schwab 2015).

Industry 4.0 was initially proposed by the German government to foster industrial competitiveness with "*the organisation of production processes based on technology and devices autonomously communicating with each other along the value chain*" (Smit et al. 2016). There is a plethora of technological innovations in Industry 4.0 which involve Big data, Mobile devices, Cloud computing, Robotics, Smart sensors, Location technologies, 3D printing, Digital marketing, and Augmented reality (Oesterreich and Teuteberg 2016). Yet, major challenges and requirements for Industry 4.0 are not technological, but rather point to standardization, work organization, new business models, protection of intellectual property, availability of skilled workers, and the importance of design principles for the new scenarios offered by Industry 4.0 (Acatech 2013; Hermann et al. 2016; Lasi et al. 2014; Smit et al. 2016). It seems appropriate to reiterate: "*don't automate, obliterate*" (Hammer 1990), nevertheless, as we can realize in Bauer et al. (2016), the majority of organizations do not have a roadmap for Industry 4.0.

Maturity models describe current scenarios of the organizations and offer improvement guidelines (de Bruin et al. 2005; CMMI 2010; Röglinger et al. 2012). This type of tools can be positioned in-between models and methods or roadmaps (Menon et al. 2016; Mettler 2011). It is possible to find online self-assessment tools for Industry 4.0 (IMPULS 2017; PwC 2017) and new assessment models are emerging in academia (Ganzarain and Errasti 2016; Leyh et al. 2017). However, in our research, we gathered evidence that current maturity models for Industry 4.0 have limitations when applied in different sectors of the economy, and are, themselves, in initial stages of maturity. These limitations include the inflexibility to deal with change and an excessive focus on the organizational problems instead of providing solutions. Moreover, the high complexity of Industry 4.0, its emergent nature, and the need to improve models design and use (Mettler 2011) claims for additional research. We subscribe to the view of Oesterreich and Teuteberg (2016, p.136) about the "*urgent need for the development, understanding and assessment of frameworks, business models, reference models and maturity models for Industry 4.0 implementation with focus on technology, people and processes*".

Maturity models must be able to incorporate national policies and variants tailored for different economic sectors. This need is consistent with recent initiatives to promote synergies between the academia and the industry. One example, that included the development of a maturity model, was launched in Portugal on January 31st, 2017, with the active involvement of the highest instances of the government, universities, and companies such as Deloitte, Google, Microsoft, Siemens, Huawei, and Bosh. In that moment we started our cooperation with the national institution responsible for Industry 4.0 maturity model. Common guidelines to assist the development of maturity models for Industry 4.0 was identified as a priority. But *which structure can be adopted to develop national and sector-specific maturity models required by Industry 4.0?* It is necessary to consider the differences of economic sectors and align sectorial needs with national strategies. For example, the state of innovations in different components of the Industry 4.0 domain may be different, influencing the prescriptive utility of the maturity model: "*when focusing on the assessment of emerging innovations the levels of maturity may be extremely uncertain given that no dominant design is found already. Recommended improvement activities therefore probably will be estimated as speculation*" (Mettler 2011, p.85). These open challenges motivated our proposal of a framework for assessing and implementing the Fourth Industrial Revolution (Industry 4.0.) at national and sector specific levels.

The next section of this paper reviews existing maturity models for Industry 4.0. Then, we introduce our design-science research approach, which included field studies in ceramic industries and a workshop involving 120 participants. Subsequently, we propose a framework to assist governments and industries in the creation of maturity models for Industry 4.0. We conclude stating the study limitations and opportunities for future work.

Review of Maturity Models for Industry 4.0

The past two years are marked by the proposal of maturity models for Industry 4.0. In fact, some proposals are still under development, for example, FIR (2017), INTRO4.0 "Introduction strategies of Industry 4.0 methodology and technology for smes" to end in 2018 (KIT 2016), or IPH Hannover (IPH 2017). To identify and assess the existing models, we searched Google and academic papers in EBSCO, ScienceDirect, IEEE, Google Scholar, and Mendeley. Given the emergent nature of the topic, we searched for journals and conferences, without a time restriction. The combination of search terms included "*industrie 4.0*" + "*maturity model*" [yielding 81 results in Google Scholar, 18/02/2017], "*industry 4.0*" + "*maturity model*" [yielding 78 results], "*fourth industrial revolution*" + "*maturity model*" [yielding 35 results]. We followed the guidelines suggested by Webster and Watson (2002) that recommend concept-centric review. A total of fourteen models were identified, evaluated, and classified according to two categories: (1) practitioner models and (2) academic models. We found two prevalent sub-categories of papers for practitioner models, namely, (1.1) online assessment models – for third party use and (1.2) practitioners models – for own use. In academic models, the sub-categories are (2.1) for Industry 4.0 domain, and (2.2) for Industry 4.0 sub-domains – for example, Internet-of-Things (IoT). Next, we present a summary of the results according to the two focal categories of contributions.

Practitioners Models for Industry 4.0

Most of the tools found in this category were created by consulting companies, preferring online self-assessment, focusing on simplicity and a wide audience. The one from PwC (2017) has four stages (I-Digital Novice, II-Vertical Integrator, III-Horizontal Collaborator, and IV-Digital Champion) and six dimensions, namely, (1) Business Models, Product & Service Portfolio; (2) Market & Customer Access; (3) Value Chains & Processes; (4) IT Architecture; (5) Compliance, Legal, Risk, Security & Tax; and (6) Organization & Culture. The stages evolve according to the integration perspective (cross-departmental, partners network), a decision that is aligned with academic models such as Leyh et al. (2017) and Westermann et al. (2016). Other leading consulting companies, for example, Capgemini Consulting (Industry 4.0 Framework), McKinsey & Company (Bauer et al. 2016) and Deloitte are also key players in the development of strategies for Industry 4.0 in European countries.

There are examples of maturity models produced by technology providers, for example, the Rockwell Automation (2014) model, consisting of five stages (from 1-assessment to 6-collaboration). Hitachi created its own maturity model to assess maturity of production management systems (Isaka et al. 2016). A plant at level 1 uses data for visualization of their site. Level 2-connection, allows product traceability and level 3-analysis, work automation and process optimization. The following stages are 4-measurement, to identify and solve production bottlenecks, 5-prediction, and the most advanced 6-symbiosis, where resources are optimized and production plans coordinated with company stakeholders. The five stage model presented by Westermann et al. (2016) also highlights the transition from mere data monitoring (level 1) to network cooperation (level 5), involving communication and analysis (level 2), interpretation (level 3), and adaptation to specific contexts (level 4). Other models were proposed by private associations, for example IMPULS (2017), which includes six dimensions that address social, organizational, and technological aspects.

On the one hand, practitioner models provide simplicity and highlight the main topics of Industry 4.0 – which has an educational value. On the other hand, it is not totally clear how they were designed, and they can be difficult to use for prescriptive (what to do next) purposes because, comprehensibly, their main purpose is to assess, not to provide detailed answers to the industry. Nevertheless, the existence of these models confirms that the industry is actively involved in this revolution and the importance of integration and cooperation within supply chains.

Academic Models for Industry 4.0

We can find academic models with a technological focus, a social focus, and a combination of both. The System Integration Maturity Model Industry 4.0 (SIMMI 4.0) is a recent proposal that considers four dimensions – vertical integration, horizontal integration, digital product development, and cross-sectional technology criteria (Leyh et al. 2017). The authors suggest key activities to guide companies in stage climbing, with a technological focus (e.g. enterprise systems, mobile applications, big data solutions, and cloud-based platforms). Other authors propose models with a behavioral focus, for example Bärenfänger and Otto (2015) that identified capabilities for digital business models and Knoke et al. (2017), who propose the Collaborative Innovation Capability Maturity for virtual manufacturing enterprises. Schumacher et al. (2016) included social, technical, and organizational dimensions to assess Industry 4.0 readiness in manufacturing. These authors considered a total of nine dimensions, each one calculated as a weighted average of different items (62 in total). It is a comprehensive model with radar charts to visualize data and identify improvement priorities. However, we could not find guidance / roadmap for progressing through stages.

The three stage maturity model proposed by Ganzarain and Errasti (2016) focuses on the process of change in diversification strategies. It is necessary to (1) define a vision, (2) establish a roadmap, and (3) implement Industry 4.0 projects ensuring training and risk management. This sequence is aligned with consulting models that highlight the strategic analysis and the creation of pilot projects. Nevertheless, a study promoted by the European Parliament also recognizes that one obstacle to the participation of SMEs in the supply chain of Industry 4.0 is the "*capacity to run pilot projects to test out Industry 4.0 mechanisms and potentially limited access to facilities to test advanced solutions*" (Smit et al. 2016). Other barriers to develop Industry 4.0 projects in SMEs include the lack of awareness about technologies, high investments required, the need for specialized IT staff, and the dependency from big companies

(Smit et al. 2016). Other studies address specific technologies involved in Industry 4.0 (sub-domains), for example, a reference model and roadmap for Internet-of-Things (IoT) in manufacturing (Soldatos et al. 2016), industrial internet (Menon et al. 2016), and cyber-physical systems (Westermann et al. 2016). We see potential in integrating the more specific technological models in existing high level maturity models. However, we also note that these are less accessible to managers of SMEs and more directed to technological experts as their main audience.

The Capability Maturity Model Integration (CMMI) developed by the Carnegie Mellon University includes a maturity scale that inspired many researchers, for example, in Ganzarain and Errasti (2016) and Knoke et al. (2015), while in Schumacher et al. (2016, p.164), there are "*five maturity levels where level 1 describes a complete lack of attributes supporting the concepts of Industry 4.0 and level 5 represents the state-of-the-art of required attributes*". Other authors, such as Donovan et al. (2016) consider ten levels for industrial analytics, while Isaka et al. (2016) established six levels for sensing and analysis technology. In spite of the evident inspiration in CMMI and the capability of providing staged assessment, we could not find a continuous assessment proposal in the revised models. Additionally, existing proposals (1) do not provide sector-specific guidance to create Industry 4.0 roadmaps and (2) may be difficult to adapt to some sectors of the economy, for example, the traditional sectors with low level of digitalization but potential participants in decentralized supply chains suggested by Industry 4.0.

Method

Design-science (Hevner et al. 2004) is our research approach, having its foundations in the work of Simon (1996). Our main purpose is to create an artifact in the form of a framework that must account for the main components of the Industry 4.0 domain, with the possibility of being tailored for different industrial sectors. Presently, the maturity of the application domain is low, but the maturity of solutions is high, motivating us to extend existing work such as the maturity models for the new problems raised by Industry 4.0 in distinct sectors of the economy (Gregor and Hevner 2013). We follow the steps proposed by Peffers et al. (2008), namely (1) problem identification and motivation, (2) definition of the objectives for a solution, (3) design and development, (4) demonstration, (5) evaluation, and (6) communication.

The problem at the core of our work was identified by a technological center in Portugal, with the mission to assist non-metal mineral industries. They needed a solution to diagnose Industry 4.0 maturity but the models initially tested by them, while interesting for preliminary diagnosis, were considered insufficient to guide company plans to adopt Industry 4.0. Moreover, the creation of maturity models became central in the Portuguese policies for Industry 4.0, requiring to align the sectorial efforts with national initiatives. It was critical to evaluate existing maturity models, focus on future user needs (Becker et al. 2009) and then identify the maturity model domain, the domain components – independent aspects that are important for the domain maturity, and the sub-components (de Bruin et al. 2005). Maturity models can provide a solution for assessing and implementing Industry 4.0, but it is necessary to provide a structure of components and sub-components that adheres to the differences of multiple sectors, technologies, and social characteristics. These models allow self-assessment, but recent studies point to the risk of overestimate digitalization level and IT proficiency in the production sector, especially in SMEs (Leyh et al. 2016), representing near 99% of all businesses in the European Union. So, sanity checks are required in the models to mitigate this problem.

The design process (Peffers et al. 2007) of the framework to guide the design of maturity models for national and sector-specific levels included field interventions to design, demonstrate, evaluate, and communicate the artifact. First, we made a qualitative study (Myers 1997) in three medium-sized ceramic companies (two of them in the sub-group of ornamental and tableware; while the other producing floor & wall tiles) to evaluate existing maturity models. Data collection included interviews with top managers and observation. Complementarily, one of the authors discussed the topic of Industry 4.0 and tested two online assessment models identified by the technological institute (IMPULS 2017; PwC 2017). The literature review and the insights gathered in these two initial field interventions provided the basis to prepare a national workshop for industry. A first draft of domain components of the maturity model was presented in a full day workshop with 120 participants from industrial manufacturing companies using non-metallic materials (ceramic, glass, stone, and nanomaterials). The workshop conclusions and debate allowed us to propose a refined framework for assessing and improving Industry 4.0. The next section presents the insights that we gathered from the field studies.

Results

Examining the Craft

According to the three companies studied, existing online maturity models are vague and its results can be frustrating. According to one of the managers that were interviewed "*to know that we are at level 0 it was not necessary to answer so many questions; thank you for nothing*". Another issue is that Industry 4.0 combines diverse topics, ranging from social (e.g. digital competences) to technical aspects (e.g. robotics, Internet-of-Things), raising difficulties for single respondents. In all three case companies, we needed to assist the managers in "decoding" the questions of the existing models. For example, one of the managers asked "*to which department are they referring to with this question? In some we use smart sensors, others don't even know what a sensor looks like*". The main benefit that the companies found was to understand a little better what is Industry 4.0 and related technologies. Yet, these companies did not consider that the model was useful (maturity zero was the prevailing result) or that they would be more prepared to deal with the challenge after the diagnosis. We highlight the need to consider multiple respondents in the complex context of Industry 4.0, and to focus more on concrete processes of the organization. One of the managers agreed that the models did not seem to be made for SMEs but rather for technological suppliers, automotive, aerospace or other advanced industries (more mature in technological terms). Existing tools must consider the case of SMEs in "traditional sectors".

The discussion of existing maturity models with graduate students in IS, although not representative of the future maturity model users and merely accessory to our research, provided two main insights. It was an opportunity to contrast the opinions of informatics engineers and industry experts about the same model. All students confirmed the utility of the models to identify Industry 4.0 priorities, but also found the questions too vague themselves. According to one of the students – a graduate in industrial engineering – "*questions should have concrete scenarios for each sector, for example, do you have real-time data in process X that is used to adjust process Y? That would be really useful because it would include concrete guidance to each company* [business cases] *inside the model*".

Finally, a sector-specific workshop was scheduled to February 2nd, three days after the announcement of Industry 4.0 strategy by the national government. The morning session had presentations from governmental entities, Industry 4.0 experts, and industry associations. The afternoon session was moderated by one of the authors and aimed to (1) evaluate the perception of maturity in specific dimensions of Industry 4.0 (e.g. vertical integration, competencies) and (2) understand priorities for key processes of the industry (e.g. energy management involving IoT and predictive algorithms). A mobile app was created to allow interaction between researchers and the 120 participants, as presented in Figure 1.

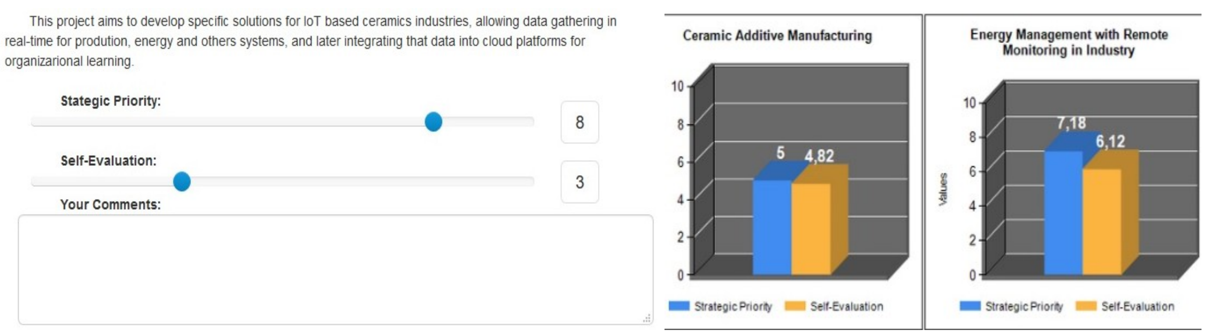

Figure 1. Industry 4.0 Workshop – Mobile App and Reports (extract).

The mobile app included the possibility to evaluate company maturity on the topics presented (on the left) and to define the strategic priority of the organization, as well as comments and the expression of interest to develop projects related to each component. Key processes were selected (e.g. energy management, marketing) and a discussion about possible solutions occurred (e.g. IoT for energy management, Big data for marketing). The results of voting were used for the debate, as presented on the right of Figure 1.

Interestingly, the most disrupting topics of robotization and additive manufacturing were not considered as top strategic priorities for the industry. The participants were more enthusiastic about the creation of a digital services cloud, energy management solutions, new marketing strategies using big data (e.g. design trends for ceramic products). Only 20% of the participants voted, so the results must be carefully weighed. Nevertheless, the workshop discussion confirmed that (1) not all (hyped) technological components associated with Industry 4.0 are relevant for their digital strategy, (2) a higher maturity stage does not mean that the component has low priority (e.g. the participants considered to be well prepared in terms of energy management, but this topic is so important for ceramic and glass industries that they still consider it a top priority for all Industry 4.0 actions), (3) the majority of respondents considered themselves in a positive stage (above 5 in a scale ranging from 0 to 10) but our field studies shows a less developed scenario. An important conclusion was the need to include existing suppliers in Industry 4.0 initiatives, in parallel with new competitors and startups. New sector-specific models are essential, yet, aligned with national models to ensure that the sectors can be included in global supply chains.

Framework Proposal

Our proposal adopts the staged and a continuous representations also used in CMMI (2010) and ISO/IEC 15504. The staged representation assesses the evolutionary stage of the organization in its digital ecosystem (Barrett et al. 2015), while the continuous representation address the specificities of each industry sector and competitive context (scenarios). The use of the model in practice is inspired in Heeks (2006) design-reality gaps of information; technology; processes; objectives and values (through which factors such as culture and politics are manifest); staffing and skills (competences); management systems and structures; and other resources (e.g., time and money). Figure 2 depicts the framework.

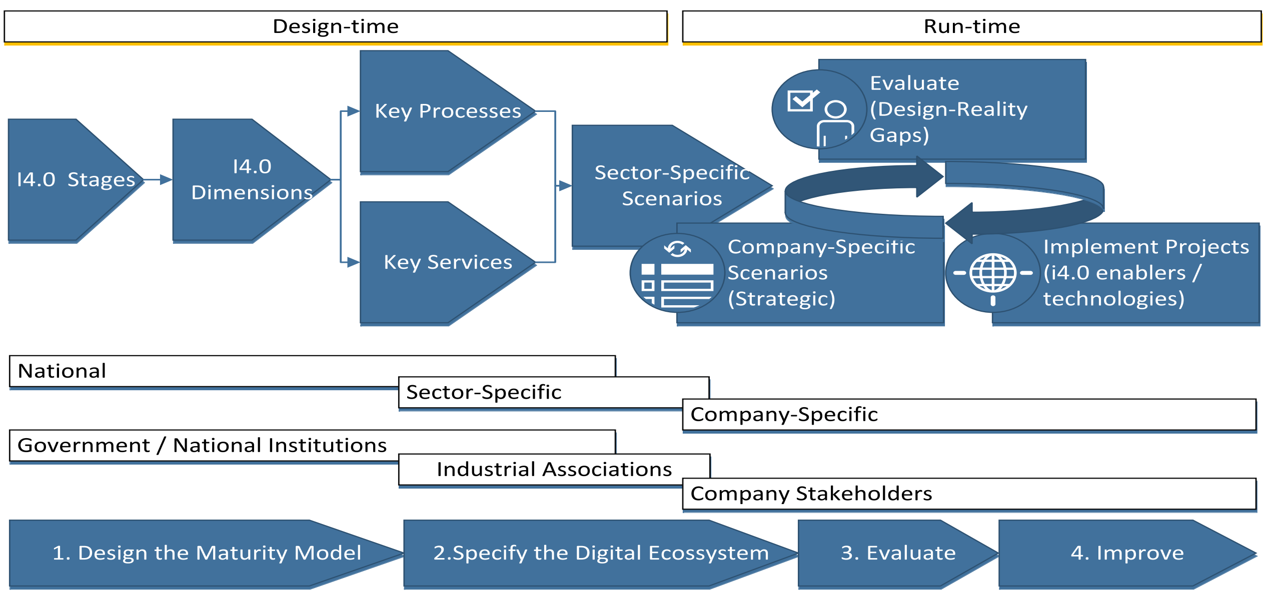

Figure 2. Industry 4.0 NS Framework

Our NS framework considers the design-time of the maturity model and the run-time phase of using it as a tool for communication and improvement. On the left of Figure 2, I4.0 Stages provide the overall maturity level of the organization, ranging from level 1-initial to 5-optimizing. Each stage is assessed according to I4.0 dimensions defined by the national strategy. The NS framework is not prescriptive about the dimensions to consider, for example SIMMI considers vertical integration, horizontal integration, digital product development, and cross-sectional technology criteria (Leyh et al. 2017). We propose to detail each dimension for the most relevant processes and services of the digital ecosystem (e.g. production, marketing, digital commerce). At this phase it is necessary to take into consideration that key processes and services may vary in each sector (for example, an after sales service may be crucial for some industries such as automotive but not determinant for some mineral extraction industries that operate in early stages of the supply chain). On the right of Figure 2 we extend the development and application cycle proposed by Mettler (2011) to the run-time phase of adopting the Industry 4.0 initiatives and associated projects (Ganzarain and Errasti 2016). Bellow, we express the scope of model components (e.g. sector-specific), required participants to develop the model components (e.g. industrial associations,) and the four main steps of model design.

At sector-specific planes, the competences, services, and processes vary. For example, governments may be interested in creating supplier networks for key strategic objectives (e.g. improve the exports of the fashion cluster to Asia), while sectors may be concerned in more specific issues, such as energy costs. A maturity model that is viable for all sectors of the industrial economy and allows to assess Industry 4.0 maturity at a national level does not seem viable. Yet, it is necessary to align Industry 4.0 initiatives at both plans and it is desirable to create a national level framework that supports tailoring the maturity levels for each sector. After defining the key processes and services it is suggested to establish the scenarios (features of the digital ecosystem) that will allow the organization to mature its stage according to their priorities and necessity. We stress the possibility to include company-specific quantitative/qualitative scenarios emerging from the company strategy (e.g. achieve a response time of 2 hours to critical requests). Along the cycle of evaluation and deployment of Industry 4.0 projects we can identify different stakeholders starting with the national institutions, sector associations, and finally, at the company level, involving company stakeholders. We suggest a scenario-based assessment (e.g. "does the company know the number of product defects in sector X at real time?"), not a technology based assessment (e.g. "does the company use smart sensors?"). The responsible (specialist) for each key process/service should assess their list of specific scenarios, making the model shared by different stakeholders, inside and outside the organization. Example of key process/service are: Energy management; Quality; Maintenance; Marketing; Production; Provisioning; Export. An example of the artifact developed to detail scenarios for key process/service of the organization is presented in Figure 3.

Key Process/Service	managerial	input-based	transformational	output-based
Level 1	Scenarios (may differ for each industry sector)			
Level N				

Figure 3. Industry 4.0 Scenarios: Matrix for Key Process/Service

The matrix in Figure 3 is developed for each key process/service, explaining sector-specific scenarios for competencies (columns in the matrix) that the organization should develop. Accomplishing the scenarios will allow the company to reach a specific maturity level (first column on the left). We gather inspiration in the work of Lado and Wilson (1994) to propose four main types of competences that organizations should develop to participate in the digital ecosystem of Industry 4.0: (1) managerial, (2) input-based, (3) transformational, and (4) output-based competences. Managerial competences include the articulation of strategic vision, empowerment of the firm members, and enacting organizational environment (Lado and Wilson 1994; Mithas et al. 2013). Input-based competences include the investment in human capital, IT and cyber-physical systems. Transformational competences exploit innovation and entrepreneurship, fostering a culture that encourages Industry 4.0 scenarios (Hermann et al. 2016), organizational learning, and a shared view of IS role within the organization (Chen et al. 2010). Finally, the output-based competences include reputation and assets such as quality, and customer loyalty (Lado and Wilson 1994).

The company can use the maturity model for self-assessments and as a roadmap, but also to discuss design-reality gaps (Heeks 2006) with the technology providers. For example, the company can ask the suppliers to evaluate their company with the matrix to identify discrepancies. This contrast will improve project discussion and minimizing the risk of the company overestimate their maturity (Leyh et al. 2016).

Discussion

Maturity models have been criticized by their (1) inflexibility to deal with change, (2) focus on identifying problems instead of providing solutions – the so-called "knowledge-doing gap" as presented by Mettler (2011), (3) lack of sufficient granularity to measure progress over time, and (4) excessive emphasis on work processes when comparing to social and organizational issues (Jugdev and Thomas 2002). Rigor and relevance in the development of maturity models can mitigate the risks of being "*reduced to the status of a mere marketing tool for business consultants*" (Becker et al. 2009, p.221). Our framework addresses these problems suggesting sector-specific scenarios that guide the improvement initiatives of the organization. Moreover, we also advise to include company-specific scenarios that emerge from the organizational strategy. Then, the company can assess the gaps between their reality and the sector-specific/company-specific scenarios, establishing Industry 4.0 projects, and using the same maturity model to revaluate their gaps, after implementation (represented on the right of Figure 2 – Run-time).

Existing maturity models for Industry 4.0 have the advantage of providing initial guidance to managers and of being pedagogical to a wide audience. Yet, some of those models are vague, "do not speak the language of industrial SMEs" that sometimes lack technological know-how and need prescriptive guidance. Existing models could also be tailored for specific sectors of industry, some of them traditional, not adhering to the stereotype of high-tech industries. However, SMEs are the majority of European companies and will play a major role in global supply chains.

As presented by Prof. Jeanne Ross in ICIS 2016, to become digital, a digital services platform must complement the operational backbone of company processes (Andersen and Ross 2016). Industry 4.0 maturity should be evaluated at a process and service level of detail. Companies can have high maturity, for example, in e-commerce and not in product traceability – a possible scenario for production process. The detail of dimensions for each process/service can vary according the industrial sector and has the potential to use inputs from other maturity models. For example, in energy management where existing maturity models can be a valuable source to identify sector-specific scenarios.

Maturity models can be useful at run-time of Industry 4.0 projects. For example, as a communication tool between organizations and stakeholders (Röglinger et al. 2012) to identify design-reality gaps (e.g. comparing self-evaluation and evaluation by technology providers). Moreover, maturity models require flexibility to discard non-relevant items in specific sectors. If an item is not relevant for the company strategy, how relevant is its maturity? A weighted solution can be used (Schumacher et al. 2016), providing different weights to scenarios in its impact of the process/service capability over time, helping in the identification of priorities (higher weights) for Industry 4.0 projects. It is out of the scope of our research to suggest scenarios for specific industries or to associate dimensions (like process areas in CMMI) to stages of the maturity model, which are opportunities for future research.

Industry 4.0 maturity cannot be seen as a "one size fits all" and the so-called "Industry 4.0-ready" solutions are not advised. Therefore, each organization needs to assess its stage of maturity to compete and create a tailored roadmap for Industry 4.0. Otherwise, companies face high risks by limiting their decisions to the vision of technology suppliers and supply chain leaders. "*The challenge for management, then, is to establish the conditions for the business process ecosystem – a mix of human and non-human actors – to operate and maintain itself in a region of emergent complexity, a region bounded by stasis and chaos. Further, managers must recognize that they are embedded within the ecosystem and that they are themselves shaped by, as well as shaping, the ecosystem*" (Vidgen and Wang 2006, p.272).

Conclusion

We presented a framework for assessing and implementing the Industry 4.0 initiatives at national and sector-specific levels. It was build using a design-science research process. We conducted field work and challenged our ideas in a workshop that included 120 participants from industrial manufacturing. Existing maturity models can be integrated in the NS framework and improved to the context of SMEs in traditional sectors. Our proposal can assist governments and other institutions in the development of nationwide and sector-specific maturity models, useful for assessment, but also to create an Industry 4.0 roadmap and foster the discussion of best solutions for each scenario with technology providers. Industry 4.0 consultants may find our model useful to propose solutions to their customers based on sector-specific scenarios created by industry associations and the solutions presented as suggested in Figure 3.

The NS framework can guide researchers in the development of Industry 4.0 maturity models for different sectors of the economy. On the one hand, it considers differences in each sector and in each organization (specific strategic scenarios). On the other hand, it suggests potential alignment of sector-specific maturity models for each dimension and key process/service (e.g. production).

Our research has limitations that need to be stated. First, we focused in the non-metal mineral industry (ceramic, glass, stone, and nanomaterials) cluster, so it is necessary to conduct additional studies in other industries, which is an ongoing process in different European countries. Second, the framework adheres to the CMMI structure but also suggests sector-specific and company specific scenarios, not yet detailed at this stage. Third, in spite of the care taken in our literature review, maturity models in Industry 4.0 is a vibrant research area and other models may emerge and be important to consider.

Our next steps are to cooperate with the development of the national maturity model and the related sector-specific models. The project will provide Portuguese industries with a new tool to compete in global industrial supply chains. Complementarily, we plan to identify sector-specific scenarios for the non-metal mineral industry cluster and test the first sector-specific model in five ceramic companies, interested in investing in Industry 4.0. The design-reality gaps will be detailed for different interfaces, namely, contrasting the perspectives of company managers, suppliers, key customers, and the specialists of each key process/service of the digital ecosystem. Industry 4.0 is not restricted to the company borders. In fact, the decentralization and the need to create new value networks involving multiple partners will make the tools that we propose essential for the success of the Fourth Industrial Revolution.

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