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Maturity Models in Industrial Internet: a Review

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Abstract

The introduction of assembly lines in industrial plants marked the beginning of the third industrial revolution. The support of information technology has enabled continuous progresses, up to the digitalisation of the processes. In this context, the further innovation characterised by the introduction of Cyber-Physical Systems and other enabling technologies has allowed the fourth industrial revolution. Proposed by the German government, Industry 4.0 appealed to both researchers and practitioners. Since the appearance of the term Industry 4.0, the linked-term Industrial Internet has been introduced to indicate the technology stack and knowledge management required by Industry 4.0. Industrial Internet makes a factory smart by applying advanced information and communication systems and future-oriented technologies, as well as new principles of knowledge management. Undeniably, such a system introduces greater complexity in terms of technologies, knowledge and socio-cultural aspects. Companies are often unprepared to deal with innovation issues, because they lack knowledge and competences and they are not culturally prepared for the relative novelties, but especially because they lack the necessary technological pre-requisites to develop the appropriate technology stack. From this perspective, different models of maturity have been developed, both in academic and technical environments, to support companies in understanding their position within the paradigm of the Industrial Internet. Starting from a quantitative review of the maturity models designed in the general literature, this article develops a qualitative review of the models applied in Industry 4.0, characterising all relevant models and proposing future perspectives to improve existing models and develop new ones.

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Keywords: Industry 4.0; Industrial Internet; Maturity Model; Literature Review

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1. Introduction

The term Industry 4.0 (I4.0) is related to an initiative of the German government, developed to promote and ensure the German leadership in industry, especially in the manufacturing sector [1]. It refers to the perception of the new industrial scenario as the fourth industrial revolution [2], which follows the third one that is characterized by technological innovations, such as change from analogue to digital, and had a huge impact, especially on the electronics industry [1]. The ongoing digitalization through electronics and Information Technologies (IT) has recently evolved in the development and implementation of Cyber-Physical Systems (CPS), Internet of Things (IoT) and Internet of Services [3]. Indeed, CPS, IoT, and Smart Factories are the three main components of I4.0 [2]. The IoT concept proposes to embed electronics, software, sensors and network connectivity into devices (i.e. things), to allow the collection and exchange of data through the internet. CPS are smart embedded and networked systems within production environment that operate both at virtual and physical levels, controlling and interacting with physical devices, sensing and acting on the real world [4]. In a nutshell: IoT allows communication between assets [5], CPS join the physical world to the virtual one [6]. Smart Factories are the dynamic organization characterized by (i) advanced automation in a flexible-boundaries supply chain, and (ii) the collaboration not only with their own industrial partners [7]. In the industrial environment, and especially in the manufacturing context, the aims of these three main components are (i) the smartification of the production system, i.e. the Smart Manufacturing as convergence of humans, technology and information [8], and (ii) the smartification of products, i.e. Smart Product, that is a product which regulates its own manufacturing and adds the concepts of related services to its features [9]. This disruptive scenario requires the evolution of the organizations, the market, and the business. Companies are likely to fail to recognize this evolution: very often they don't understand its implications [9], they do not have suitable technologies [10], and they are afraid of the huge investments to be done [11]. To avoid these issues, and to develop and manage appropriate development plans, companies need to understand their current level of maturity concerning the I4.0 in their specific context [12]; however, ofttimes industries cannot define what needs to be measured, since they are unprepared to grasp the I4.0 novelties and requirements [13]. Several researches have been proposed with the aim of measuring and addressing the development level of I4.0 in the organizations. There is a general consensus to use *maturity models* (MMs) to assess this maturity level [14]. The combination of the queries *Industry 4.0* and *Maturity Model* in the Scopus database (see *https://www.scopus.com/search/form.uri?display=basic*), which returns 108 results as of 2016, is however a measure of the gap in I4.0 literature since the combination of the search keys *Industry 4.0* and *Reference Architecture*, which is another trend research-topic in I4.0, returns 233 result in the same period. Moreover, the existing models depends on the subjective opinion of assessors, which means that the existing models do not allow to obtain accurate results and they rely on uncertainty and vagueness in real practice [15]. Nevertheless, there is confusion in general literature on maturity and only in recent years the research has begun to structure its modelling [16]. The present paper proposes to combine a review of the literature on MMs and on their application to I4.0, to understand the trends and topics of MM in general, as well as the specific subjects and the characteristics of MMs applied to I4.0.

The reminder of the paper is organised as follows: in section 2 we provide a review on issues about MM and I4.0. Section 3 reports the method used to collect the document list from the Scopus database, and the model used for analyzing, both quantitatively and qualitatively, the collected documents on MM and I4.0. Section 4 presents the results of the analysis. Finally, in section 5 we provide the conclusions and the future outlooks.

2. The context

2.1. Maturity Models

Maturity represents a theory of stage-based evolution and its basic purpose consists in describing stages and maturation paths through a scale of maturity [17]. In this field, a MM defines a basis for assessing and benchmarking an organisation, and in addition it provides a basis for 'strategic planning' of investments, so as to ensure continuous improvement and to move towards corporate objectives [18]. Since MMs grant insights into how to advance along the maturity plan [19] they differ much from techniques such as *Gap Analysis* and *Benchmarking*. These are, however, very reliable methods to compare and assess judgements on the subject under analysis, but they cannot be used as stand-alone solutions when assessing maturity. On the contrary, these are ancillary techniques to MMs that can be used, for instance, to understand the ultimate goal of an organization to be aimed at once the maturity level has been defined [20].

Despite the huge amount of literature on maturity, maturity models (MMs) cannot be defined unambiguously: the root of this issue is in the MM design, whose frameworks are often too specific to the application and the subject to be measured [21]. Useful attempts to organize the MM design have just been made in recent years, aiming at (i) providing the main phases of generic model development [22], and (ii) defining a structured method to develop a specific MM [12]. Since the design method proposed by Becker et *al.* [12] appeared in literature, it has been very used (i.e. cited 563 times in Google Scholar, until 01 March 2019). Authors propose a general procedure model in eight phases and seven requirements: each phase meets one or more requirements, and all phases need for the main requirement "scientific documentation". On the other hand, De Bruin et *al.* [22] can be considered as pioneers of the definition of MM design: they propose a six-step framework whose first and second steps determine the *scope* and the *design* or architecture of the model. The former allows to set the outlying boundaries for model application and use: it requires to define the focus of the model and the development stakeholders. The latter forms the basis for further development and application. It requires to define five criteria: (i) the audience, (ii) the method and the (iii) the driver of application, (iv) the respondents and finally (v) the end application. The other core step is the *population* of the model, i.e. how to gather the content. Finally, follows the *test*, the *deployment* and the ongoing updating of the model (i.e. *maintain* phase).

2.2. Vocabulary in Industry 4.0

Although the research community, comprehending both academics and practitioners, has shown a huge interest in I4.0 [23], there still is much confusion on vocabulary and topics. For instance, the terms *Industrie 4.0* and *Industry 4.0* are often used alternately; the former, however, refers to the German government initiative within a national program that has been followed by other subjects in the world, e.g. *Factories of the Future* within the program *Horizon2020* of the European Commission. The term *Industry 4.0*, instead, was introduced in research and it has become widespread in society because, even if the individual changes in the manufacturing sector can be interpreted as an evolution of the current third industrial revolution, there is a general consensus that the speed and impact of these development led to the fourth industrial revolution [24]. Furthermore, there is still confusion between the term *Industry 4.0* and the term *Industrial Internet*, i.e. it is not clearly defined which term has a more holistic vision, and sometimes they are used alternately (see [23], [25] and [26]). An interesting contribution comes from Thoben et *al.* [27]: the authors of that study distinguish between the two terms by identifying in *Industrial Internet* the technology stack required by the innovative system designed to respond to the *Industry 4.0* revolution, and extend this concept to the whole industry making use of the term *Industrial Internet of Things* (IIoT), which especially focuses on the interconnectivity of industrial assets. Its main aim is to strengthen modern industries with three pillars: (i) the process optimisation, the (ii) optimised resource consumption, and (iii) the creation of complex autonomous system [28].

3. Materials and Methods

3.1. Selecting and analyzing the suitable literature

The list of literature concerning MM in I4.0 was obtained from the largest abstract and citation database of peer-reviewed literature, i.e. Scopus. We made use of a query string fulfilling the following three requirements. First, the string must disregard the declension of the word and the vocabulary inconsistency, we thus use the asterisk symbol *, which in Scopus allows to not consider the suffix of the term (e.g. *Industr*4.0* stands for both *Industrie 4.0* and *Industry 4.0* as well). Second, the string must disregard typos (e.g. *Industry 40*). Third, it must consider just engineering and computer science literature on production systems. Hence, considering that the Scopus search tool is case sensitive, the final string was the following: (TITLE-ABS-KEY ("industr* 4.0" OR "industr* 40" OR "industr* 4/0")) AND ((manufacturing OR production OR operation)) AND ("Maturity Model*") AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "COMP")). It considers just the main term *Industry 4.0* since it has been ascertained that, by adding further terms such as *Industrial Internet of Things* or *Smart*

Manufacturing to the query string, the number of extracted papers was not changing significantly. Such query string, which returned 108 results, was therefore inserted in a machine-learning program at our University, written in Python 3.7 and running in the IDE "Jupiter Notebook". The program queries the Scopus database, by using the user' API key, and provided a full database of the document on MM in I4.0 (i.e. 108 docs from the query string) and all the document cited by these (i.e. 3,318 documents). Nevertheless, Scopus database contains several inconsistencies, and just a small subset of all the 3,426 documents (i.e. 108 + 3,318) had all the records filled in (e.g. article title, doi, authors, abstract, year of publication). Hence, to define the final lists for the quali-quantitative analysis we selected just the documents whose records were complete. The *cleaned* database gathered 66 SOURCE documents (i.e. literature on MM in I4.0) and 697 TARGET documents (e.g. literature on MM, I4.0, Project Management, IT and so on). After this step we made use of an algorithm for *automatically reading* the *title*, the *abstract* and the *keywords* of the documents from the SOURCE list, with the aim of identifying the SOURCE documents just concerning MM. It was implemented by authors in VBA and its design simulate the basic rules of the text-mining design. Since the present study does not focus on mathematics and computer science rules, we avoid describing the algorithm to help readers to focus on the answering of the research questions. The algorithm provides a literature selection of just 65 consistent documents. The literature on MM and the literature on MM in I4.0 suitable for the quantitative analysis consisted of two lists, s-SOURCE and TARGET respectively. Finally, the reading of title and abstract of the TARGET documents provided the final lists of suitable documents (i.e. s-TARGET) to be analyzed qualitatively. The s-TARGET list includes 9 documents: we disregarded (i) literature reviews, which do not provide a model, (ii) studies preparatory to a further presentation of a model, (iii) models concerning a single application, e.g. assessing the maturity of product-as-a-service. The framework to select the suitable literature is depicted in Fig. 1 according to the pattern for the literature selection provided by Webster et *al.* [29].

3.2. Research Methods

The review of the suitable literature on MM in I4.0 follows a quali-quantitative approach. The quantitative review comply with the method designed by Pickering et *al.* [30]. The qualitative approach conforms to the document review requirements defined by Curry et *al.* [31], even if more focused on a basic outline of the material analyzed, rather than a holistic vision as proposed by the author of the adopted qualitative method.

The review of the general-literature on MM was less structured and is here described. We first grouped into year of publication the documents listed in the s-SOURCE list and then we determined the frequency of publications per year. Than we read the *title* and *abstract* of each single record in the list, and we identified 19 *research areas* and 8 *subject categories* clustering them. Both was identified through the contents of the *titles* and *abstracts* themselves. Hence, we grouped the documents with regard to the *subject categories* and the *research areas*. Finally, we determined the frequencies of each *subject category* and *research area*. For space requirements, we provide both *subject categories* and *research areas* in section 4, together with results (see Fig. 4).

3.3. Quantitative review of literature on Maturity Model in I4.0

The quantitative analysis of the documents from the TARGET list relies on the authors' keywords. In doing it, we first normalized these 210 keywords, e.g. by arranging in *CPS* keywords as Cyber-Physical System, CPSs and CPS. This process gathered 165 normalized-keywords, whose reading allowed us to identify 27 main headings (i.e. *headers*) to label them. The further step consists in clustering *headers* by making use of an algorithm, less complicated than the literature selection one but however relying on the same text-mining basic-rules, which enters in the TARGET list, and automatically reads the *headers* and attributes a *cluster*. The *clusters* were identified by reading 10% of documents in the list as suggested by Pickering et *al.* [30] with the aim of searching frequent words and topics concerning I4.0 (i.e. three clusters), MM (i.e. two clusters), and applications (a single *cluster*). The six *clusters* we deemed appropriate to use are: (i) Business Innovation, which refers to innovation in knowledge management and business intelligence in I4.0; (ii) ICT which refers to information technologies required for I4.0; and (iii) IIoT, within the meaning of definition provided in section 2.2; (iv) Maturity, which is relative to the main theme of *maturity* i.e. *(reference) architecture framework* and *maturity*; (v) Method, which is relative to the *method application* to assess the maturity level (e.g.

assessment and KPI); and finally (vi) Users, identifying the end applications to which the model is addressed or the account executive of the relative study (e.g. SME, EU Projects).

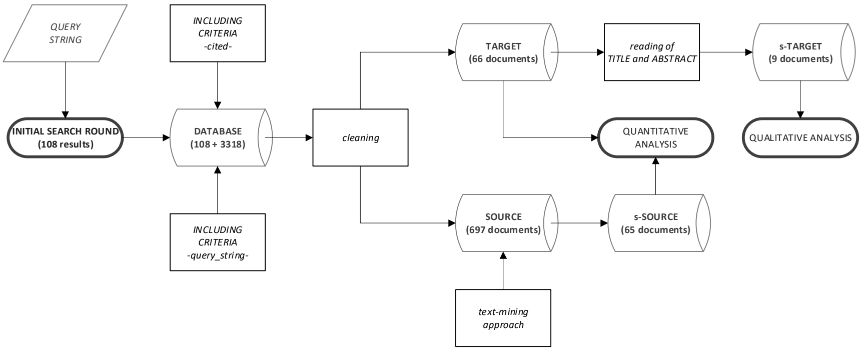

Fig. 1. Method for the literature selection adapted by Webster et al. [36].

Since both the *headers* and the *clusters* were defined, we measured the frequency of each *header* and their amount in the relative *cluster*. Here again, for space requirements, we provide the full list of *headers* in section 4, together with results (see Table 1).

3.4. Qualitative review of literature on Maturity Model in I4.0

The qualitative review that we propose is a description of the MM in I4.0 in the form of a *document outline*, meaning that it follow the main rules of a document review [31] but focused just on core characteristics of the model. To identify the core characteristics we refers to the two main steps to design a MM as defined by De Bruin et *al.* [22], i.e. *design* and *populate*. Through the five criteria of the *design* step, we identified the following core features of a model to assess maturity: (i) the *dimensions* to measure, related to the *diver of application* and the *application*; (ii) the *measurement of the maturity*, related to the *audience*, the *respondents*, and the *method application*; the last one addresses also (iii) the *calculation tool*, and (iv) the way to express the *results*; finally, the *maturity stages*, related to the *audience*. The map of the relation between core steps in De Bruin et *al.* [22] and the identified core features to outline the MM is provided in Fig. 2.

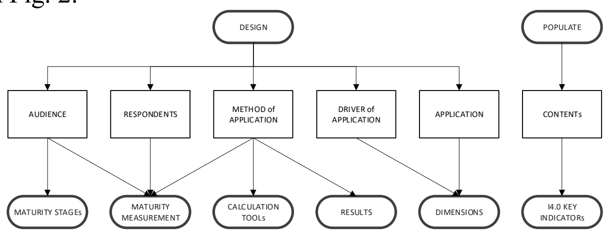

Fig. 2. Map of relation between core steps in De Bruin et *al.* [22] and core features to outline MM in I4.0.

4. Results and discussions

The frequency of publications per years of the documents on MM (see Fig. 3) provides the trend of the general-literature. The number of publications is basically increasing since 2002, i.e. the year of the first publication of the s-SOURCE list, and since 2015 a considerable interest in it has been arising. The single publication in 2018, instead, could be a singularity due to how defined the s-SOURCE list, i.e. the cited literature in this case is too recent. Furthermore, in Fig. 4 we provide the number of publications with respect to the identified *subject categories* (a) and *research areas* (b). The most of publications belongs to the *manufacturing area*, and they aim at defining a MM for the *digitalization of business* and the development of *products* and *services*. Other *research area* interested in MM belongs to the *business design,* and the *information systems*: the likely cause of this result is the relation between these *research areas, which* are concurrent because of their multi-disciplinary. It is important to note that 20 of 65 documents are Literature Reviews and just provide insights on the maturity model of the specific research topic.

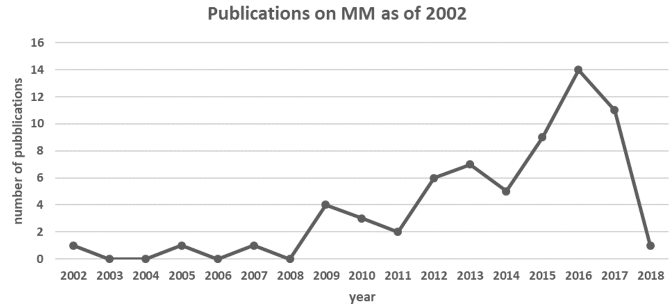

Fig. 3. Publications per year on Maturity Model since 2002. In this year appears the first publication of the database.

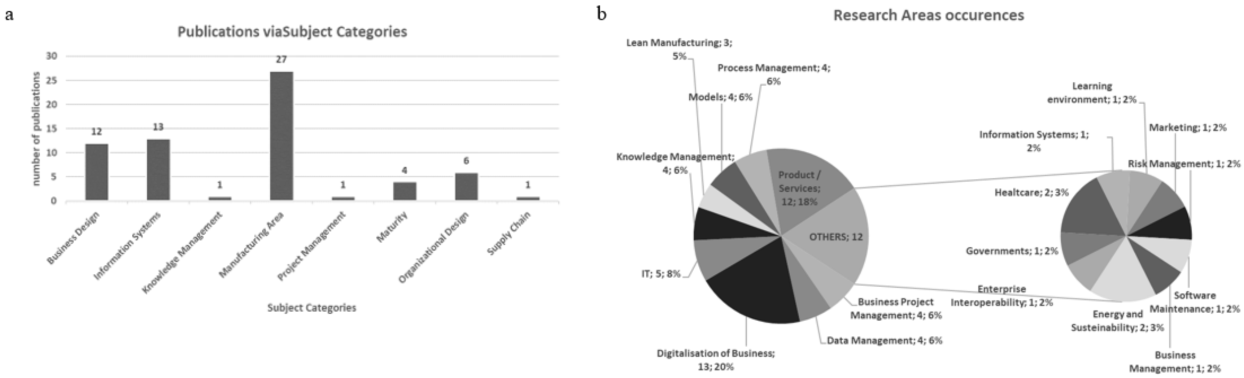

Fig. 4. Publications on MM general literature: (a) Subject Categories and (b) Research Areas (percentages rounded to the closest integer).

We further present the result of the quantitative analysis on the literature on MMs in I4.0 performed on the authors' keywords (see Table 1). The frequency of the *headers*, within a same cluster, is almost comparable except for some singularity, e.g. Gap Analysis and Holistic Approach Method within Method, Project within Users. On the contrary, it is interesting that in this literature as few as 25% of keywords are related to the themes of *maturity*.

Table 1. Headers and cluster of the authors' keywords used in the MM in I4.0 literature.

Cluster	# of occurrences	Headers	# of occurrences
IIoT	(78)	CPS; Digital Twin; Industry 4.0; IoT; Revolution 4.0; Servitization; Smart Factory (Mfg)	(11); (12); (14); (18); (7); (6); (10)
ICT	(27)	Agility; Algorithms; IC; Interoperability	(11); (4); (8); (8)
Business Innovation	(12)	Business Intelligence; Knowledge Management	(8); (4)
Maturity	(20)	Architecture Framework; Maturity Model	(7); (13)
Methods	(32)	Assessment Method; Gap Analysis Method; Holistic Approach Method; Key Performance Indicators (KPI) Method; Literature Review; MCDM Method	(7); (1); (1); (12) (4); (7)
Users	(41)	Energy&Environment; Engineering; Industry (Geo/Sector); Projects; SMEs; Use Case	(6); (16); (8); (1); (5); (5)

Table 2. Outline the core characteristics of the MM in I4.0. The symbol "-" stands for not provided.

Authors (Year of Publication)	Dimensions	I4.0 Key Indicators	Maturity Measurement	Calculation Tool	Presentation of Results	Maturity Stages
Andreas Schumacher, Selim Erol, Wilfried Sihn [14] (2016)	9 dimensions related to the company organizational units, 62 items	practitioners' assessment on I4.0 topic	assessment by questionnaire to be answered by users	weighted average on KPI	radar-chart graphics	5 stages
Vladimir Modrak, Zuzana Soltysova, Robert Poklemba [32] (2019)	3 areas related to smartification and business development	literature review + multi-case study on SMEs	assessment by questionnaire to be answered by users	weighted average on KPI (dimension and measured item)	spider-graph graphics	5 stages
Jaione Ganzarain, Nekane Errasti [33] (2016)	-	literature review + survey on reference architecture	-	-	-	5 stages
Lee Bibby, Benjamin Dehe[34] (2018)	13 key attributes related to technologies and business and knowledge management	literature review	assessment by questionnaire on focal firm and supply network	weighted average on KPI (dimension and measured item)	ranking	4 stages
Luca Canetta, Andrea Barni, Elias Montini [35] (2018)	5 sections related to company departments	literature review	assessment by dynamic questionnaire	weighted average on KPI (dimension and measured item)	radar-chart	3 stages + overall level
Christian Leyh, Thomas Schäffer, Katja Bley, Sven Forstenhäusler [36] (2017)	4 dimensions related to the concept of integration	literature review	-	-	stage representation	5 stages
Sameer Mittal, David Romero, Thorsten Wuest [37] (2018)	5 organizational dimensions	literature review	domain-mapping matrix relying on toolboxes	Toolboxes (combination rules not provided)	3D-chart graphic	5 stages
Anna De Carolis, Marco Macchi, Elisa Negri, Sergio Terzi [38] (2017)	4 dimensions to be met by the manufacturing backbone, i,e, 5 process ares	literature review	assessment by questionnaire	linear combination of dynamic weights and indexes	-	5 stages
Ebru Gökalp, Umut Şener, P. Erhan Eren [39] (2017)	5 aspects dimensions related to assets, data, process and organizational management	literature review	as in ISO/IEC 15504 (former spice)	as in ISO/IEC 15504 (former spice)	as in ISO/IEC 15504 (former spice)	5 stages
Leineweber Stefan, Wienbruch Thom, Lins Dominik, Kreimeier Dieter, Kuhlenkötter Bernd [40] (2018)	3 dimensions, i.e. technology, organizational and personnel, and 44 criteria to meet	analyzed by the chair of production systems at the Ruhr-University of Bochum	-	weighted average on KPI (dimension and measured item)	stage representation	4/7-stages depending on the meeting criteria

Finally, we provide the result of the document outline. Generally, the models are structured in dimensions, each one characterized by a different number of items. Dimensions are judged on their relevance in I4.0 and items are the measurement point to grasp the state-of-the-art of the organization. The maturity assessment relies on a *static* linear combination (weighted average on KPI) between element of dimensions and measured items. Particular attention deserve the model proposed by De Carolis et *al.* [38], which proposes a *dynamic* calculation depending on the dimensions enabled to the assessment and their role addressing the maturity, and the model by Canetta et al. [35], which proposes a *dynamic* questionnaire, meaning that the measurement point in a specific dimension (i.e. section) depend on the gathered previous answers. The outline of the all models is provided in Table 2.

5. Conclusion and Future Outlook

The number of MM for organizations has increased significantly in the last two decades, and it has been applied to several different aspects of organizations, such as project management, lean manufacturing, IT or business digitization, amongst others. As expected, a field in which the application of MM has raised a great deal of attention is I4.0. Since the concept of I4.0 has become of public interest, organizations and companies of any dimension and sector have started asking themselves 'how far have I evolved in the I4.0 scale?' In this study, we reviewed the general literature on MMs (i.e. SOURCE literature), as well as the literature on the application of MMs to I4.0 (i.e. TARGET literature). The TARGET literature was gathered from the Scopus database by means of an opportune search query, and it was reviewed in a quali-quantitative way. The SOURCE literature, instead, was obtained from the list of documents cited by the TARGET, and it was approached with a quali-quantitative review method.

In recent years, the concept of *maturity* and MMs have attracted a great deal of attention from the research community; this is proven from the fact that more than the 70% of the literature on this topic, ranging from 2002 to 2019, was published in the last seven years (2012–2019). Since the SOURCE literature was obtained by considering references cited by the TARGET literature, and due to the fact that the concept of I4.0 was presented in 2012, this result may look biased. We stress, however, as it can be seen in the opportune Fig. 4b, that the sole *research areas* that are directly related to I4.0 are *Digitalization of Business* and, probably, *Product / Services*, even if the latter is likely to be unrelated to the concept of the product-as-a-service. However, considering those both *research areas*, they comprehend less than 40% of the SOURCE literature. All the other *research areas*, on the contrary, are not directly related to I4.0. Thus, these results do not look biased by the method used to collect the documents we analyzed. Similarly, if we consider *subject categories*, more than the 60% of the SOURCE literature concerns the *subject categories Manufacturing* and *Information systems,* which are often related to the fourth industrial revolution. Hence, it might be deduced that, although recent literature on MM was not directly applied to the I4.0 *research area*, the recent interest in maturity might still depend upon or be driven by I4.0, at least to some extent.

We also note that a great number of studies was dedicated to reviewing existing literature, both in the SOURCE (30%) and in the TARGET (50%) literature. This fact suggests that the studies on MMs, and on their application to I4.0, have been significantly aimed at categorizing and comprehending existing knowledge, thus subtracting time and effort to the development of new knowledge. Furthermore, the percentage of literature reviews in the TARGET literature is curiously high. This data seems to suggest that literature on *maturity* and MMs is somehow late in keeping the pace of innovation of I4.0.

Moving the analysis to TARGET literature, we note that just 25% of keywords of the TARGET literature clearly concerns MMs (see the opportune Table 1), and this seems to suggest that the I4.0 literature approach concerns more the discussion on *maturity* rather than the design of MMs. It looks like if an innovative approach is still missing from MM literature, which is quite surprising because literature on *maturity* is far from well-established. The occurrences of keywords in the TARGET literature (see the opportune Table 1) also highlights the lateness of *maturity assessment* in I4.0. Not considering the expected results (i.e. *IoT, Industry 4.0, maturity model*), as well as those depending on the query string (i.e. *engineering*), the literature on *maturity* in I4.0 tries to understand how to measure maturity (i.e. *KPI* and *assessment methods*) and what to measure (i.e. *digital twin* and *CPS*). However, it generally forgets to address how to define the benchmark (i.e. *Architecture Framework*), and what are the effects of the industrial revolution (i.e. *servitization, business intelligence* and *interoperability*).

Furthermore, we note that all models we reviewed rely on surveys of users' opinion through assessment and questionnaires, hence the current maturity levels depend more on socio-cognitive basis (e.g. perception and acceptance to use), rather than on the objectively measurement of technology and knowledge stack.

In the opinion of the authors, the current study presents three main limitations described in the following.

First, the SOURCE literature on MMs was extracted from the references of the TARGET literature on the application of MMs to I4.0. Although this choice has been made to avoid inconsistency in the data for the quantitative analysis, this could be a conservative approach, and exclude interesting documents from the literature under analysis. A different approach could be that of generating a specific string to query the online database on the specific topic of *maturity*. Also, other databases could be queried, instead of the sole Scopus (e.g. EBSCO, ISI WoS) by adding synonyms or alternative for *Industry 4.0* too, like *Smart Manufacturing* and *Industrial Internet* which do not change significantly the query results in Scopus, but can provide a different TARGET literature by querying other databases. Finally, we did not perform any advanced statistical analysis on the results of our literature review, but we only limit this work to descriptive statistics.

At present, however, the authors are working on some of these limitations for future research.

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