Maturity models and tools for enabling Smart Manufacturing Systems: comparison and reflections for future developments

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Abstract. One of the most exciting new capabilities in Smart Manufacturing (SM) and Cyber-Physical Production Systems (CPPS) is the provisioning of manufacturing services as unbundled "apps or services", which could be significantly more flexible and less expensive to use than the current generation of monolithic manufacturing applications. However, bundling and integrating heterogeneous services in the form of such apps or composite services is not a trivial job. There is a need for service vendors, cloud vendors, manufacturers, and other stakeholders to work collaboratively to simplify the effort to "mix-and-match" and compose the apps or services. In this regard, a workshop was organized by the National Institute of Standards and Technology (NIST) and the Open Applications Group Inc. (OAGi), with the purpose to identify – through parallel sessions – technology and standard needs for improving interoperability and composability between services. The workshop was organized into five working session. This paper documents evidences gathered during the “Smart Manufacturing Systems Characterization” (SMSC) session, which aims at establishing a roadmap for a unify framework for assessing a manufacturer’s capability, maturity and readiness level to implement Smart Manufacturing. To that end, the technology maturity, information connectivity maturity, process maturity, organizational maturity, personnel capability and maturity, have been identified as critical aspects for Smart Manufacturing adoptions. The workshop was culminating at providing a coherent model and method for assisting manufacturing companies in their journey to smart manufacturing realizations. This paper shows three different maturity models and tools that, thanks to their complementarity, enable to reflect on the different perspectives required by SMSC. These models and tools are usable together for assessing a manufacturing company’s ability to initiate the digital transformation of its processes towards Smart Manufacturing. Therefore, based on their comparison, the ultimate purpose of the research is to come up with a set of coherent guidelines for assessing a manufacturing system and its management practices, for identifying improvement opportunities and for recommending SM technologies and standards for adoption by manufacturers.

adfa, p. 1, 2011.

Keywords: Smart Manufacturing Systems Characterization; maturity model; manufacturer's capabilities; Industry 4.0; Smart manufacturing readiness

1 Introduction

With the introduction of the Smart Manufacturing (SM) concept, manufacturers are faced with a plethora of technologies that envision different ways to improve their manufacturing systems. Thus, many stakeholders, such as governments, consulting companies or research institutes, have provided their own definitions of SM building on such technologies. Among the definitions, for example, PwC identifies eleven digital technologies that enable the SM or Industry 4.0 framework [1]: mobile devices, IoT platforms, location detection technologies, advanced human-machine interfaces, authentication and fraud detection, 3D printing, smart sensors, big data analytics and advanced algorithms, multilevel customer interaction and customer profiling, augmented reality/wearables and cloud computing. It is interesting to point out the wide scope of applications, i.e. value chains, business models, products and services: enabled by the technologies, SM focuses on the end-to-end digitization of all physical assets and integration into digital ecosystems with value chain partners [1]. It is in fact possible to state that manufacturers' adoptions of digital technologies will have three key impacts [2]: (i) the overall product and asset lifecycles, both within and outside the factory; (ii) the entire ecosystem manufacturing systems, thanks to the full interoperability of systems based on shared vision and standards and to their ability to defy rigid standardized hierarchies but create dynamic structures from their articulated functions; (iii) the ability to create new value-added services for customers and operators from the utilization, production and design processes.

However, this leads to the rise of many new complex enterprise challenges [3][4][5]. Indeed, the integration of so many different disciplines could lead to an increased complexity of the whole SM system, which might limit the obtainable advantages from the digital transformation. Therefore, a company should be ready to cope with this complexity. For this reason, we assume that the impact of the digitalization process on a manufacturing company in terms of obtainable opportunities may differ depending on the maturity level of that company's capabilities. This means that, before starting the transformation process towards SM or Industry 4.0, manufacturing companies should define their transformation roadmap according to the actual maturity level of their capabilities [6]. This requires proper methodologies for maturity assessment applied to SM, with the aim to support companies finding their own way towards the digital transformation, i.e. helping manufacturers in understanding their current capabilities and so their needs for undertaking the digital transformation. Even though such methodologies are emerging, there is no established approach or framework to this end. This paper describes three different but complementary tools for analyzing the maturity level of manufacturing systems and environments within a SM perspective, i.e. DREAMY (Digital REadiness Assessment MaturitY model), SMSRL (Smart manufacturing readiness level) and MOM (Manufacturing Operations Management). Based on their comparison, the future work of this research is to come up with a coherent guidelines for maturity assessment to support the transition towards SM.

2 Smart Manufacturing Systems Characterization and Maturity models and tools

2.1 Smart Manufacturing Systems Characterization as a new concept

SM means many things in terms of applications, e.g. new info technologies in supply chains, in product development, in business to shop floor integration, in the development of smart products, in production equipment [7]. Then, SM is really a convergence of technologies and related capabilities brought from multiple areas and multiple business lifecycles. In order to help and guide manufacturers coping with such a complex system, the Smart Manufacturing Systems Characterization (SMSC) was introduced as a new concept. Indeed, based on the work carried out during NIST/OAGi Workshop 2016 [8], it can be stated that SMSC is defined as the enabler of unbiased models, tools, norms or guidelines to understand and analyze manufacturing systems and environment with an Industry 4.0 perspective, to the final aim of prioritizing the investments in the new technologies manufacturers might launch. This, in turn, helps building an approach whose purpose is to support the identification of opportunities for improvement of the manufacturing systems through SM technologies [8]. In other words, SMSC serve for assessing a manufacturing system and its management practices, for identifying improvement opportunities and for recommending SM technologies and standards for adoption by manufacturers [8].

As overall assumption, the manufacturers need to adopt a progressive introduction of the SM applications, systems, and hardware based on a composition of different technologies [6]. Thus, the SMSC is an essential driver: we consider that the introduction of new technologies depends on understanding the actual readiness of the manufacturer to deploy the new technologies in its manufacturing system(s); this should be assessed/re-assessed to master the maturation process towards SM. In particular, SMSC methods are focused on the assessment of manufacturer's capabilities, and readiness level to implement SM technologies and applications. To this aim, a maturity model appears a relevant "tool".

2.2 Overview on maturity models and tools

In order to understand what maturity models are, here the basics concepts of maturity models are given. To this aim, it is appropriate to provide some definitions since the concept of maturity adopted varied, even within one field of expertise [9].

Maturity can be defined as "*the state of being complete, perfect or ready*" [10][11][12]. Another slightly different perspective on the concept of maturity is the one given by Maier et al. [9], who stated that the process of bringing something to maturity means bringing it to a state of full growth. In other words, maturity implies an evolutionary progress from an initial to a desired or normally occurring end stage

[13]. This last definition, which stresses the process toward maturity, introduces another important concept, which is the one of *stages of growth* or *maturity levels.*

Before reaching a state of "full growth", an entity (an organization as well as a human being) has to encounter different stages of growth or maturity levels. In particular, the stages an organization passes through have three main distinctive elements [14]: (i) they are sequential in nature; (2) they occur in a hierarchical progression that is not easily reversible; (3) they involve a broad range of organizational activities and structures. To this end, we can state that maturity models can be used as tools for determining manufacturers' readiness level and capabilities also within a SM perspective.

Maturity models in literature have different characteristics: they can be of moderate or high complexity, maturity levels can be described in simple or complex terms, and so on. To this end, Fraser et al. (2002) [16] presented a first clear classification per typology of maturity models. In particular, they distinguish three types of maturity models [16]: (1) Maturity grids; (2) Likert-like questionnaires; (3) CMM-like models.

The maturity grids typically illustrate maturity levels in a simple and textual manner, structured in a matrix or a grid. As Fraser et al. (2002) stated, they are of a moderate complexity and they do not specify what a particular process should look like; they only identify some characteristics that any process and every enterprise should have in order to reach high performance processes [9]. On the other hand, the Likert-like questionnaires are constructed by "questions", which are no more than statements of good practices. The responder to the questionnaire has to score the related performance on a scale from 1 to n. A hybrid model can be defined as a combination of the questionnaire approach with the maturity grid definition[16]. Finally, the CMM-like models (Capability Maturity Model) identifies the best practices for specific processes and measures the maturity of organizations in terms of how many practices are implemented [9]. Their architecture is more formal and complex compared to the first twos. They are composed of process areas organized by common features, which specify a number of key practices to address a series of goals. Typically, the CMM-like models exploit Likert questionnaires to assess the maturity. These models have been improved successively by the Capability Maturity Model Integration (CMMI) [17].

Although a number of different types of maturity models have been proposed in literature, they share some common proprieties, which are shown below [6] [16]: (i) Maturity levels (typically from three to six); (ii) A "descriptor" for each level, which gives a meaningful name to each level; (iii) A generic description of the characteristics of each level; (iv) A number of dimensions or "process areas"; (v) A number of elements or activities for each process areas; (vi) A description of each activity, that has to be performed at each maturity level.

The terms 'readiness' and 'maturity' are relative and related. To this end, we define the term 'smart manufacturing readiness' as the capability or maturity of a manufacturing company 'to' deploy smart manufacturing concepts, and the term 'smart manufacturing maturity' as how well a manufacturing company has employed smart manufacturing concepts or its smart manufacturing capability. To that respect, some maturity models can be viewed as part of smart manufacturing readiness assessment such as the manufacturing operation management (MOM) maturity; and an example of a smart manufacturing maturity model is the Industrie 4.0 Readiness [25] (although calling itself readiness, it is more of a smart manufacturing maturity). In the following chapter, three different tools for assessing manufacturers' readiness or maturity levels 'to' implement SM concepts are described.

2.3 DREAMY (Digital REadiness Assessment MaturitY model)

The Digital REadiness Assessment MaturitY model is a tool with two main objectives. Firstly, it is aimed to assess a manufacturing company readiness level for starting the digital transformation process, which is an aspect of smart manufacturing concepts. For this reason, according to their main objective [10–12], it has the form of a maturity model based on the inspiring principles of the CMMI framework [18,19]. Secondly, it is a tool for identifying manufacturing companies strengths and weaknesses and related opportunities they can gather from the digital transformation, with the final aim to help manufacturers in defining a roadmap for prioritizing investments [6].

Table 1. DREAMY Maturity levels' definition (taken from [20])

ML 1 Initial	The process is poorly controlled or not controlled at all, process management is reactive and does not have the proper organizational and technological "tools" for building an infrastructure that will allow repeatability / usability / extensibility of the utilized solutions.
ML2 Managed	The process is partially planned and implemented. Process management is weak due to lacks in the organization and/or enabling technologies. The choices are driven by specific objectives of single projects of integration and/or by the experience of the planner, which demonstrates a partial maturity in managing the infrastructure development.
ML3 Defined	The process is defined with the planning and the implementation of good practices and management procedures. The management of the process is limited by some constraints on the organizational responsibilities and / or on the enabling technologies. Therefore, the planning and the implementation of the process highlights some gaps/lacks of integration, information exchange, and ultimately interoperability between applications.
ML4 Integrated and interoperable	The process is built on information exchange, integration, and interoperability across applications; and it is fully planned and implemented. The integration and the interoperability are based on common and shared standards within the company, borrowed from intra- and/or cross-industry de facto standards, with respect to the best practices in industry in both perspectives of the organization and enabling technologies.
ML5 Digital-oriented	The process is digital oriented and is based on a solid technology infrastructure and on a high potential growth organization, which supports – through pervasive integration and interoperability – speed, robustness and security in information exchange, in collaboration among the company functions and in the decision making.

To define the DREAMY architecture, it was fundamental to identify the manufacturing relevant processes, within which value-added activities are performed, and that are strategic for the digital transformation [20]. In order to make the architecture as general as possible, manufacturing company's processes were grouped in five main areas: 1) Design and Engineering; 2) Production Management; 3) Quality Management; 4) Maintenance Management; 5) Logistics Management. Each process area can be considered as a self-contained module and therefore it is possible to add or remove one or more areas in case they are not meaningful in certain industrial situations. Cutting-across to these process areas is the Digital Backbone, within which all the information exchange processes across the process areas are considered [20]. The digital readiness of a manufacturing company is then defined through a scale of maturity levels. These levels describe a proper set of company capabilities, to provide a snapshot of their current abilities. The levels have been based on the inspiring principles from the CMMI framework [19] [18]. In this way, as the five-scale CMMI maturity levels provided a generic model to start from, they have been re-adapted in order to gather the definitions, and so the semantic, of the digital readiness levels [20] (see **Table 1**).

From what defined in the maturity levels, it is clear that, when evaluating the capabilities of a company, not only the technologies used to support the processes have to be considered [20]. From these evidences and considering the objective of the maturity model itself, it was decided to evaluate the digital readiness of manufacturing companies through four analysis dimensions (equivalent to four aspects of analysis): *Process*, *Monitoring and Control*, *Technology*, and *Organization* [20].

The DREAMY model is synthesized in **Fig. 1**.

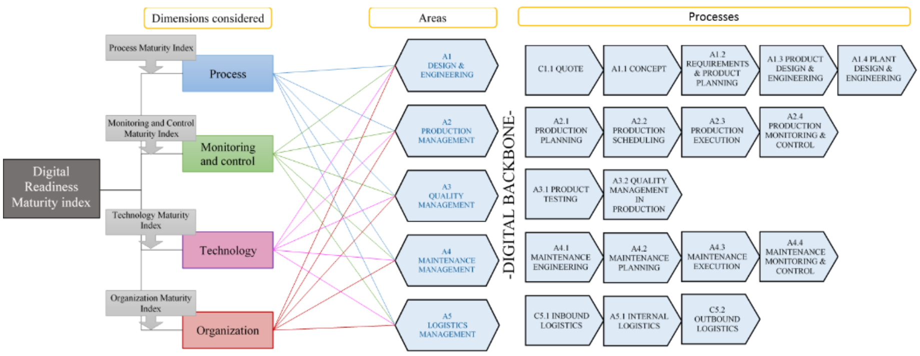

Fig. 1. DREAMY (Adapted from [20])

The model in its current form can be used for descriptive purposes. That is maturity indexes for each process can be calculated to reflect the as-is situation of a manufacturing company [20]. With further analysis, strengths, weaknesses, and opportunities (prescription [6]) for smart manufacturing concept adoptions can be derived. Going forward the model can be enhanced such that such information can be automatically generated form the model To date, the "factory" is the unit of the analysis considered by the model. However, thanks to its modular structure, future works will be done to include other value-added process areas such as Supply Chain

Management, Sales, Marketing, Customer care, Human Resource Management, etc. in order to extend the scope of the analysis. In addition, due to the high relevance of the topic, which is also seen as one of the enabler of manufacturing companies' digital transformation, also *Skills of Personnel* should be considered as analysis dimension when assessing company capabilities.

2.4 SMSRL

Smart manufacturing readiness level (SMSRL) is an index that measure a manufacturing company's readiness for employing smart manufacturing concepts with the assumption that smart manufacturing is an intensive use of information and communication technologies to improve performances [21]. For this reason, SMSRL bases its readiness model on the factory design and improvement (FDI) processes, i.e., an IDEF0 activity model [22,23]. FDI consists of four high-level activities as shown in **Fig. 2**. Each activity has one more level of decomposition consisting of tasks/processes that should be regularly performed for continuously improving factory operational performances. Information flowed between activities and software functions supporting each activity are captured in the activity model.

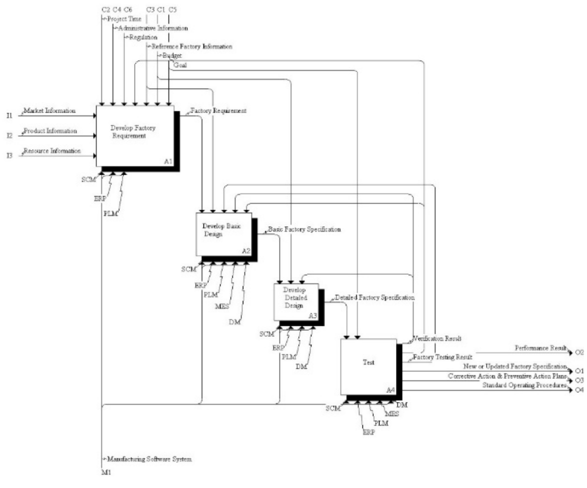

Fig. 2. Factory Design and Improvement Activity Model (from [23])

The figure shows software functions grouped into five categories entering the bottom of each activity box SCM for supply chain management, ERP for enterprise resource planning, DM for digital manufacturing, PLM for product life cycle management, and MES for manufacturing execution system. The more tasks performed and managed, software functions deployed, and information digitally flowed, the more ready a factory is for the deployment of smart manufacturing concepts. The contribution of these aspects and dimensions to the smart manufacturing readiness is illustrated as shown in **Fig 3**. Differing ways of computing readiness index are used for C1 to C4. C1 uses the CMMI index qualification. C2 and C3 uses counting measures, while C4 uses incidence matrix-based similarity measure along with an incidence scoring scheme based on the technology used to enable the information flow. They are viewed independently or averaged into a single SMSRL index.

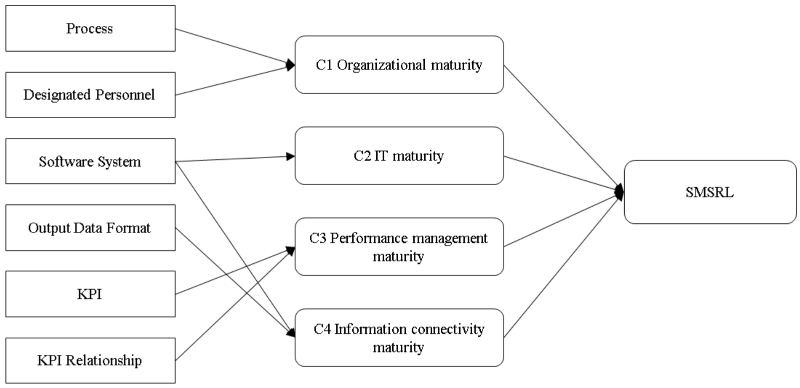

Fig. 3. SMSRL measurements (from [[21])

Like other models SMSL is largely descriptive. After an assessment, a company can use the model to prescribe goals to improve the readiness, but the model has not yet included guidelines for achieving those goals. The FDI activity model underlying the assessment also focuses on within-factory improvement tasks, not day-to-day factory operation tasks, and has weaknesses on supply chain and logistics operations. The model will also need to be revisited to clearly bound the assessment as smart manufacturing readiness as opposed to smart manufacturing maturity because some of the software functions included may already step into the smart manufacturing arena. For these reasons, SMSRL will benefit from alignment and harmonization with other assessment methods described in this paper.

2.5 MOM Maturity

MESA (Manufacturing Enterprise Systems Association) created the MOM/CMM (Manufacturing Operations Management/ Capability Maturity Model) to evaluate the maturity of manufacturing enterprises' manufacturing facilities [24].The objective is to determine the policy, procedure, and execution of a manufacturing operation management to be organized, robust, and repeatable. In other words, MOM/CMM does not provide a measure of sophistication of the physical production, but a measure of the capability to streamline operations, particularly in the abnormal events. The MOM/CMM focuses on four main process areas: 1) Production Operations Management, 2) Inventory Management, 3) Quality Test Operations Management, and 4) Maintenance Operations Management. Each process area consists of multiple activities: 1) Scheduling, 2) Dispatching, 3) Execution Management, 4) Resource Management, 5) Definition Management, 6) Data Collection, 7) Tracking, 8) Performance Analysis [24]. Each activity can have a maturity level from level 0 to level 5, which are briefly characterized in Table 2.

The higher the level of maturity, the more likely an efficient organization and fewer problems at the manufacturing operations management level. The maturity levels can be also applied across different aspects, such as 1) roles and responsibilities, 2) succession plans and backups, 3) policies and procedures, 4) technology and tools, 5) training, 6) information integration, and 7) KPIs. The model, in its raw form, can be time and resource consuming to complete with 832 questions and lacks improvement strategies based on the results. However, the model can provide a benchmark for comparison to others in their industry and can aid in understanding where to make improvements. Future work will simplify the questionnaire and map improvement strategies to the results.

Table 2. MOM Maturity level definitions

Level 0	There has been no evaluation performed.
Level 1	Procedures for activities and their executions are at initial stage and not documented or formally managed.
Level 2	Procedures of some activities are documented and executed with possibly repeatable results in the normal situation.
Level 3	Procedures for activities are defined with documented standards for all activities whose executions are possibly supported by software tools and better handling of abnormal situations.
Level 4	Procedures for activities are defined and documented across all organizational groups; and their executions are repeatable and monitored with software tools supports.
Level 5	Procedures for activities are focused on continuous improvement and optimization.

3 Models comparison: building a framework for SMSC and road-mapping its development

From the review of the different methods described in the previous chapters (DREAMY, SMSRL, MOM maturity models), it is possible to state that they provide complementarity in the overall scope of Smart Manufacturing. In fact, MOM maturity model focuses on day-to-day factory operation tasks. Therefore, it can be complemented by SMSRL, which focuses more on assessing the maturity of factory improvement tasks. Both MOM and SMSRL do not include product life cycle and business processes in their scope of analysis, so they can be complemented by DREAMY, which offer a business processes-oriented view also on product life cycles phases. According to their *different but complementary* objectives, DREAMY, SMSRL, and MOM models might be used by manufacturing companies with *different but complementary* purposes, i.e. descriptive and prescriptive and descriptive and comparative respectively.

In the table below summarizes the three models showing their objectives, clarifying their focus, and describing their structures.

Table 3. Comparison of DREAMY, SMSRL and MOM models

Element	DREAMY	SMSRL	MOM
Objective(s)	1. To assess a manufacturing company readiness level for starting the digital transformation process 2. To identify strengths and weaknesses and related opportunities manufacturers can gather from the digital transformation, with the final aim to help them in defining a roadmap for prioritizing investments	To assess a manufacturing company's readiness to employ data-intensive technologies for its performance management.	To determine level of an organization's capability to have mature, robust, and repeatable manufacturing operations [24].
Focus	Manufacturing company / Product and Factory Life Cycles	Maturity of performance improvement tasks/processes, availability of software supports, maturity of information sharing capability, and availability of responsible personnel	Manufacturing Operations Management (MOM) processes
Analysis Dimensions	Process / Execution, Monitoring and control, Organization, Technology	Organization, IT, Performance Management (process execution), and Information Connectivity	Process / Execution
Process Areas	Product and asset design and engineering, Production management, Quality management, Maintenance management, Logistics management, Digital Backbone	(Change) Requirement developments, Basic (rough) design of a new or a change requirement, Detail design, and Test	Production Operations Management, Inventory Management, Quality Test Operations Management, Maintenance Operations Management
Maturity levels	5 (1-5)	6 (0-5)	6 (0-5)
Inspiring framework	CMMI	Factory Design and Improvement Activity model	ISA-95 Enterprise Control Activities
Assessment methods	Interview / case study	Self-assessment	Self-assessment
Model purpose	Descriptive and prescriptive	Descriptive and comparative	Descriptive and comparative
Questions / Answers' type	Questions with normative answers	Yes/No Question, Scoring Question	Yes/No Questions
Number of questions	About 200 scoring questions	242 scoring and at least ~123 Yes/No questions	832 Yes/No Questions

4 Conclusions

Smart Manufacturing (SM) “recipe” requires enterprises to merge together different “ingredients” to obtain the best results in terms of performance improvements. In particular, due to the high-complexity of the digital transformation process, companies aiming at building SM systems have to be ready for starting the journey and need to be endowed with several capabilities. What are these capabilities and how can they be measured? This paper carries out some reflections of this smart manufacturing system characterization (SMSC), showing three different tools for assessing manufacturing companies their ability to start the digitalization process. Thanks to their comparison, it is now possible to reflect on the different perspectives required by SMSC, and future developments expected for such types of “tools”.

First of all, the evidences from the literature, and from the considerations emerged during the workshop organized by NIST and OAGi [8], show that several capabilities are required in terms of organization, process execution and technology. To this aim, models and tools for assessing enterprises’ readiness to start the digitalization process to embrace SM should consider all these different aspects and analysis dimensions in order to be effective. For this purpose, we may expect that many, current, and emerging models and tools could be used by the manufacturers, in different aspects and dimensions. Furthermore, it is worth remarking that these models and tools should not support solely at the assessment phase. Instead, they should be enhanced to support the prescription phase of improvements. In addition, with sufficient improvement data, benchmarking can be developed providing the evidence of return-on-investment for the smart manufacturing adoption. This could accelerate the industry adoption. Finally, further studies should deal more with principles, providing an abstract view on the founding concepts, and adequately addressing the differences between other “readiness” and “maturity” models, in order to suggest the most appropriate tool to use in each of the digital roadmap building phase, i.e. for maturity assessment and/or for digital readiness identification.

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