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Evolution of a Lean Smart Maintenance Maturity Model towards the new Age of Industry 4.0

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Abstract

Over the last few years, the complexity of asset and maintenance management of industrial plants and machinery in the producing industry has risen due to higher competition and volatile environments. Smart factories, Internet of Things (IoT) and the underlying digitisation of a significant number of processes are changing the way we have to think and work in terms of asset management. Existing Lean Smart Maintenance (LSM) philosophy, which focuses on the cost-efficient (lean) and the learning organisation (smart) perspectives enables a value-oriented, dynamic, and smart maintenance/asset management. The associated LSM maturity model is the evaluation tool that contains the normative, strategic, and operational aspects of industrial asset management, based on which numerous reorganisation projects have already been carried out in industrial companies. However, due to the ever-increasing development of Industry 4.0 (I4.0), it is necessary to extend the model by selected aspects of digitisation and digitalisation. Based on a structured literature review (SLR) of state of the art I4.0 maturity models, we were able to investigate the essential maturity items for I4.0. To restructure and expand the existing LSM maturity model, the principle of design science research (DSR) was used. The architecture of the LSM maturity model was based on the structure of the Capability Maturity Model Integration (CMMI). Further development of a Lean Smart Maintenance maturity model thus covers the future requirements of I4.0 and data science. It was possible to enhance existing categories with new artefacts from the I4.0 range to represent the influence of cyber-physical systems (CPS), (big) data and information management, condition monitoring (CM) and more. Furthermore, the originally defined LSM-Model was restructured for a more simplified application in industrial use cases.

Keywords

Capability Maturity Model; Industry 4.0; Smart Factory; Maintenance; Asset Management; Lean Smart Maintenance; Digitalisation; Digitisation

1. Introduction

'How do we adapt our production line and the associated maintenance strategy for the asset to the ever-increasing complexity of industrial plants and processes?' - 'How is it possible to achieve operational excellence with the help of the latest technological approaches of the fourth industrial revolution (Industry 4.0).' These are only examples of the most frequently discussed questions in the industry, regardless of the sector in which the company (steel, paper, mobility, etc.) is located. Practitioners and academics all over the world are discussing how to implement new technologies, e.g. big data analytics, IoT, machine learning and deep learning applications in predictive maintenance, and therefore, a scientifically founded and tested concept has to be developed. The LSM concept, which is discussed in detail in chapter

4, unites two approaches, the smart and the lean-approach. In the Lean Management concept, which is based on the Lean Production System by the Toyota Motor Company [1], a learning orientation, as well as risk and resource-oriented alignment, are crucial. The second part, smart maintenance management, attempts to put a focus on value-oriented, intelligent, and learning maintenance. In order to harmonise the LSM concept with the technical and organisational prerequisites of I4.0, the authors modify and expand the current LSM MM with selected categories and items from existing I4.0 MMs. In chapters two and three, the authors give a summary of I4.0, and its different key elements, as well as a systematic overview of MMs. Subsequently, the methodology of how this research was conducted is explained in chapter 5, which is followed by a deep dive into the Lean Smart Maintenance Maturity Model (LSM) and the main categories it contains, such as, e.g. 'Corporate Culture', 'Spare Parts Management', 'Process Organisation'. This work concludes with Chapter 7, where a summary is given, and further research needs are identified.

2. Industry 4.0

The term Industry 4.0 is based on the German wording 'Industrie 4.0', which first appeared at the Hannover Messe in 2011. A group of experts from Germany defined this term in order to achieve industry leadership and excellence. [2] Although it is a German expression, and it is not well-known outside of the DACH-countries (Germany, Austria, Switzerland) [3], there are several similar approaches. The concept of Industry 4.0 is comparable to the 'Industrial Internet' [4], 'Advanced Manufacturing' [5] and also 'Integrated Industry' [6] or 'Smart Manufacturing', and 'Smart Industry' [7],[8],[9]. Industry 4.0 is characterised by the ever-increasing complexity of technical systems as well as by the holistic view of production systems [10]. Through the use of cyber-physical systems (CPS), advanced data analytics applications, cloud storage and -computing and other technologies, the increasing connectivity between machines (Machine to Machines or M2M) or also known as the Internet of Things (IoT), Internet of Services (IoS) or machine to people (M2P) and technology-assisted people-to-people (P2P) interaction is resulting in the overall connectivity with unlimited data transfer and transparency on the Internet of Everything (IoE) [10],[11]. The company CISCO defines the IoE as 'the intelligent connection of people, process, data, and things' [12]. Related to the manufacturing and logistics industry, the term 'Smart Factory' combines all the aspects mentioned before [13].

3. Maturity Models

MMs are defined as artefacts with elements, that are arranged in an evolutionary scale with measurable transitions from one level to another and which are used for benchmarking, self-assessment and continuous improvement [14], [15]. MMs can be classified in different ways, one being the division of MMs into three different categories by Caralli [15]: (i) Capability Maturity Models, where the capabilities & processes of the organisation are the focus; (ii) Progression models, meaning a simple evolution of elements; and (iii) hybrid models, which combine the progression model architecture attributes, characteristics, patterns, etc., but the transitions between the maturity levels are defined by the capability maturity hierarchy. De Bruin describes that Maturity models can be descriptive, prescriptive, or comparative [16]. Fraser describes different possible components of MMs, which might be present in a model [17]: (i) a number of levels; (ii) a name of each level; (iii) a generic description of each level; (iv) a number of dimensions; (v) a number of elements for each dimension; (vi) a description for each of these elements. A maturity model architecture is defined as the fundamental organisation of a system embodied in its components, their relationships to each other, and to the environment, and the principles guiding its design and evolution [18]. The architecture shared by SW-CMM and CMMI is the most common MM architecture throughout the different domains, in which MMs are used [19]. Depending on the representation and CMMI version, CMMI uses five to six maturity levels, from Incomplete to Optimizing [20], [21]. Different authors have developed systematic approaches for developing maturity models [22]. Most notably, de Bruin has developed a generic MM development framework, consisting of six development phases: (i) Determining the Scope of the desired model; (ii) Choosing the Design, or architecture of the MM; (iii) Populating the model with different components, or sub-components of the domain; (iv) Testing for validity, reliability and generalisability; (v) Deploying the model and (vi) Maintaining the model. According to these definitions, the LSM MM is currently in a development loop from phase iv to phase vi.

4. Lean Smart Maintenance

Smart factories, as part of I4.0, are getting more complex in the way of technological equipment, maintenance, and controlling of the overall manufacturing processes. The dynamic environment leads to an adaption of the maintenance processes and an adaptation of nearly every organisational aspect. As a result, the Lean Smart Maintenance (LSM) concept, a holistic management concept which increases the effectiveness and improves the efficiency of asset management was developed. Its foundation contains all aspects of planning, controlling and implementing of maintenance with strategic tools like performance measurement systems (KPI's), Management by Objectives (MbO as target system), and also physical tools, e.g., IT-Systems, IoT-Applications, etc.[23] Each of the two pillars has its main focus, whereby one concentrates on the concept of the LEAN – cost-efficient and no waste, and the other one on the SMART – intelligent concept. Key concepts of the lean part are the efficiency perspective, where continuous reduction of waste, minimising non-value adding processes, and an overall sustainable resource orientation. Characteristic for the smart segment are the fundamental methods of problem-solving and performance enhancement, and the change from cost-controlled, input-oriented, across to output control, which focuses on reliability, availability, maintainability, and safety (RAMS).[23]–[25] As a result of the combination of the lean philosophy, and the smart maintenance approach, the LSM concept represents a holistic, sustainable smart, dynamic, and value-orientated maintenance management system [24].

5. Methodology

The methodological basis for the creation of the new MM is Design Science Research (DSR), as proposed by Hevner [26]. A further basis for this scientific work is formed by a structured literature review (SLR), as described by Tranfield [27]. The three stages and nine phases of an SLR are shown in Figure 1. The following sections outline the creation process of the new artefact, proposed by this scientific paper, following the three stages of a systematic review.

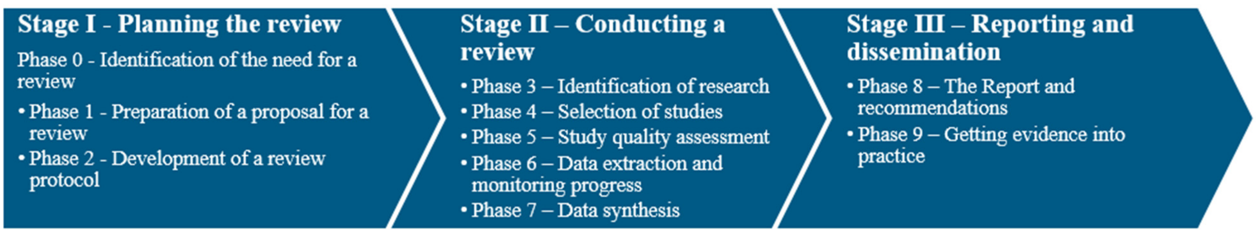

Figure 1: Stages and phases of a Systematic Literature Review [27]

The impetus for this scientific contribution was the identification of a gap between the application of the LSM concept and the integration of I4.0 aspects. This gap was confirmed by LSM integration projects carried out by the Chair of Economics and Business Administration at the Montanuniversitaet Leoben. Therefore, it was decided to conduct a literature review on the basis of past literature reviews of I4.0 MMs and merge the collected data with LSM. Throughout this process, a review protocol was used to document all necessary information around the review. In a first step, literature searches were conducted using the abstract and citation data banks Scopus and Web of Science to identify past literature reviews on I4.0 and digitalisation. This turned up 230 results in Scopus and 93 in Web of Science. After the elimination of duplicates and a title and abstract screening, six reviews on I4.0 MMs using Scopus and one further review using Web of Science were identified. A list of the seven review papers can be found in Table 2 in the Appendix. Next, a list of I4.0 MMs was created using the MMs reviewed in the aforementioned papers. After a title screening for relevance, this process resulted in 47 and 36 papers after an abstract screening. During the quality assessment, inclusion criteria were an industry focus of the paper, which eliminated a number of papers around software development, the presence of maturity levels and either a general description of the levels, or descriptions of the category levels and a number of maturity dimensions, or categories. The quality assessment resulted in a final number of 17 MMs for further investigation. A list of those 17 I4.0 MMs can be found in Table 1 in the Appendix. On this basis, the extracted I4.0 MM categories were compared to the 18 LSM categories. A few categories could not be allocated to LSM categories; these can be found under the category 'Business Model and Service Strategy'. For this reason and because past projects have shown that a too high number of MM categories can result in problems when presenting the results and deriving measures, it was decided to restructure the maturity model into nine categories with a number of sub-categories each.

6. Lean Smart Maintenance Maturity Model

In this chapter, the new LSM categories are defined, and selected digitalisation and digitisation aspects are presented. The number of maturity levels, the names and generic descriptions for the levels are based on the CMMI architecture, it can, however, be classified as a hybrid and prescriptive model.

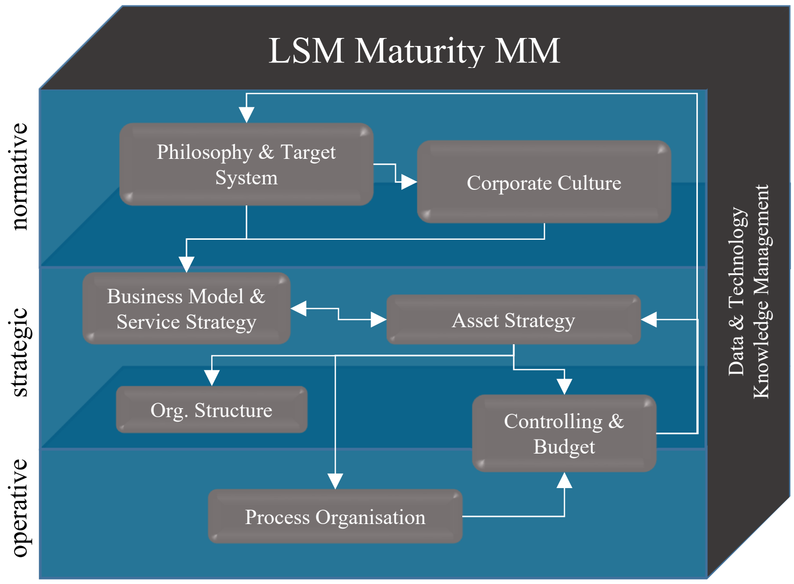

Figure 2: LSM MM & the three levels of the St. Gallen Management Modell (own presentation)

The St. Gallen Management model differentiates between three managerial levels: normative, strategic and operative management. While the goal of normative management is to develop a mutual understanding and reach social acceptance and societal legitimation, strategic management refers to the development of a sustainable and competitive advantage and operative management strives to control efficient processes for daily problem solving and the day-to-day business.[28] Figure 2 depicts the different maturity categories ordered according to the managerial levels as presented in the St. Gallen Management Model from normative to operative management. Furthermore, the dependencies between the different categories are represented via white arrows. At the top of this LSM cube, the category 'Philosophy & Target System' can be found, which forms the basis for the categories 'Corporate Culture' and 'Business Model & Service Strategy', the latter also being influenced by the former. 'Asset Strategy' interacts with 'Business Model & Service

Strategy', and forms the basis for 'Organisational Structure', 'Controlling & Budget' and 'Process Organisation'. 'Controlling & Budget' represents the basis for an adjustment of 'Philosophy & Target System' as well as 'Asset Strategy'. 'Data & Technology' and 'Knowledge Management' form a second dimension that affects all LSM maturity categories. In total, the maturity model consists of nine main categories, where each of these main categories has a distinct number of sub-categories. Figure 3 is the graphical representation of the model and represents the 'keyboard' of the LSM concept, with the respective digital level of extension.

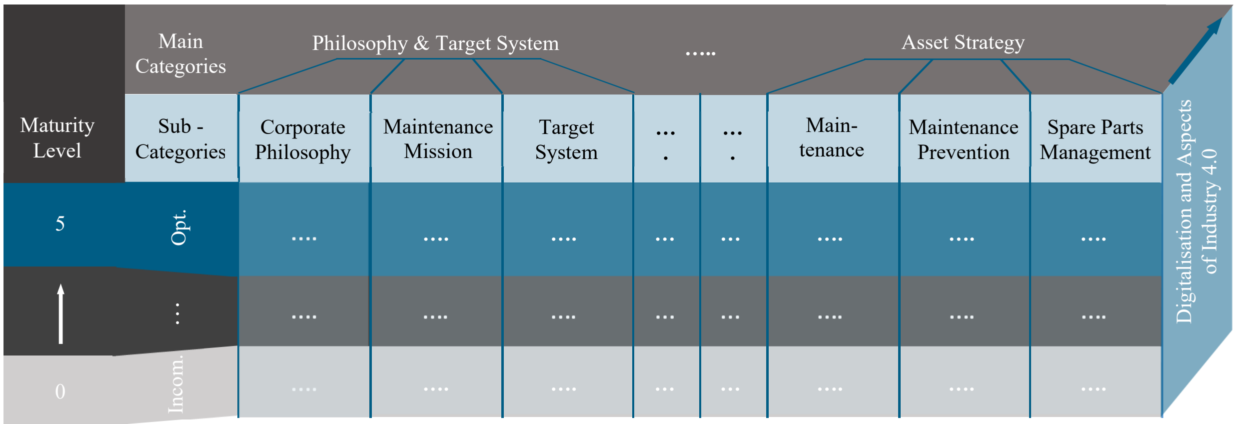

Figure 3: Lean Smart Maintenance Maturity Model (own presentation)

In the following sections, the LSM maturity categories will be described starting with the normative categories and ending with the second dimension depicted in Figure 2.

6.1 Philosophy & Target System

A defined corporate philosophy and the management philosophy derived from it, provide all employees with a direction for their behaviour, which is concretised by a vision **[29]**. A maintenance mission statement is used to communicate one's requirements internally and to present and appreciate the importance of maintenance in the company **[30]**. The target system of the asset management, the maintenance and asset goals and their relationships are brought together and structured according to their target dimension **[31]**. For effective I4.0 implementation, maturity items like recognising digital challenges, addressing legal risk with collaboration partners and optimising the value chain network for legal & tax, security and compliance have to be considered **[32]**. Furthermore, a quality management system needs to be implemented throughout the organisation, including asset management [33].

6.2 Corporate Culture

One of the most critical aspects of management systems is how they handle corporate culture [34]. In the new LSM MM, corporate culture is composed of three sub-categories, 'Culture & Motivation', 'Leadership & Change Management', and 'Communication'. Corporate culture is a very complex and multidimensional property of a group of people who learned to work together and achieve common goals [35]. To understand organisational behaviour, and transform it in a sustainable manner, it is necessary to know how to analyse, assess and change each element of its corporate culture [34]. Therefore, every category of the LSM concept is designed in such a way that it is deposited with the three cultural levels: artefacts, exposed values, and underlying assumptions. To increase the efficiency of transforming an organisation from a lower level of maturity to a higher one, the developed MM helps by identifying the right points to start the change process from top-down and bottom-up. Industry 4.0 and the digitalisation changes corporate culture in a way that the 'willingness to change' and also 'social collaboration' via the Internet becomes crucial for companies to survive. [36] The capability of each organisation to handle the data can be classified as 'Innovation Culture' whereas Klötzer & Pflaum stagger this type of culture from the lowest level, ‘openness for service’ up to the highest level, which is represented by ‘digital enterprise thinking established’. [37]

6.3 Business Model and Service Strategy

Nowadays, companies are challenged with an increasingly complex environment and most business models, and service strategies have to undergo a radical change. Therefore, management has to become aware of new technologies, methods, and possibilities for this constant change through I4.0. [38] Geissbauer et al. identify the influence of I4.0 as disruptive for the whole supply chain, due to the change from mass production to single-item production. Through digitalisation and digitisation, a tremendous improvement of processes is possible and changes business as manufacturers become more and more permanent product owners who sell a service and not a product.[32], [39] The newly introduced LSM category ‘Business Model and Service Strategy’ extends the MM and enables enlargement of the understanding and analysis of maintenance as a service inside of companies.

6.4 Asset Strategy

The asset strategy is defined as the framework for how the operations around the asset are designed to reach a specific target and encompasses the sub-categories ‘maintenance strategy’, ‘maintenance prevention’, ‘outsourcing’ and ‘spare parts management’. The aspects of Maintenance Strategy is defined as a set of procedures (rules) that specify, in relation to the asset, which individual maintenance measures are to be carried out in terms of content, method and scope in a specific chronological sequence [40]. To guarantee the necessary agility in the future, a more frequent adjustment of the maintenance strategy is necessary. In order to be able to react to changes as quickly and flexibly as possible, processes for maintenance strategy adjustment must be defined [41]**.** Within the category ‘maintenance prevention’, continuous improvement and the extensive analysis of failures and occurring problems are used to transfer the gained knowledge into the acquisition of new equipment and assets. Through high connectivity between different types of assets, more in-depth insight into the behaviour of industrial facilities is possible.[42] This sub-category entails the influence of the present technological innovations on the lowest maturity level, where no maintenance prevention is given, up to the highest level, where a holistic life cycle assessment and life cycle thinking are implemented.[43]–[45] In the category ‘asset strategy’, ‘outsourcing’ refers to the procurement or outsourcing of maintenance services [46]**.** An overall outsourcing strategy has to be defined, and it is essential, that no core competencies are outsourced. The profitability has to be considered when outsourcing and service bundles should be outsourced together. Outsourcing should be used to cushion peak loads on the one hand while striving for long-term partnerships on the other. One-sided economic dependencies in external service relationships should be avoided, and continuous improvement in maintenance achieved**.** [47] The primary task of spare parts management is to provide the required quantity, type and quality of spare parts for the maintenance of plant and equipment to the appropriate user at the right time at minimum cost [48]. Modern spare parts management systems call for the use of tools for analysis of spare parts and a dynamic spare parts management strategy. New technologies, like mobile devices and 3D printing, have a high potential to revolutionise spare parts management [41]**.**

6.5 Maintenance Budget & Controlling

Maintenance Controlling is used for planning, controlling and monitoring activities within Plant Maintenance as well as for coordinating and reconciling activities with Production, Materials Management and Cost Accounting [49]**.** In relation to plant maintenance, the budget is the cost-oriented limit within which plant maintenance has performance-related leeway [44]**.** A risk and decision-oriented budgeting approach is seen as the optimum for maintenance budgeting since it meets the requirement for dynamic and future-oriented budgeting and adjustment in the current period [50]**.** In addition, LSM calls for a key performance indicator system derived from the various success factors, and a cause-related recording of maintenance costs [41], [46], [51]. In the I4.0 MMs factors like productivity, quality, cost, lead-time, safety, environment and the connectivity between Key Performance Indicators are mentioned [52], [53].

6.6 Organisational Structure

The formal division of job tasks, how they are grouped and coordinated is defined by the organisational structure [54]. In maintenance and asset management, design of the organisational structure is substantially influenced by choice of the organisational structural principle, the definition of the structuring option and the degree of decentralisation [46]. The LSM category includes ‘autonomous maintenance’, ‘object orientation’, the ‘location of workshops’ and ‘information around the organisational structure’. For successful digitisation and digitalisation of the company, flexible communities and decision rights management are identified as integral to the development of a company [36]. Collaboration is seen as necessary to become a digital champion [32]. Promoters, the adaption of the R&D department and the internal IT organisation, the implementation of an internal smart service organisation and a service ecosystem and finally (Big) data analytics are further aspects that have to be considered when adapting the organisational structure [37].

6.7 Process Organisation

Process organisation in asset management encompasses the combination of individual work steps to complex processes as well as the harmonisation within and across processes in terms of time and space [55]. The category focuses on ‘planning’, ‘information in process organisation’, ‘continuous improvement’ and ‘weak-point-analysis’. In the context of I4.0, an evolution to agile & networked optimisation of processes is necessary [56]. The goal of digitalisation is autonomous process planning and control [39], while an integration across the vertical and horizontal dimensions of the value chains, which includes real-time availability of all data, support by augmented reality and optimisation in an integrated network, is promoted [32], [42]. Real-time planning, the level of automation operation process traceability and simulation visualisation technologies are further aspects to be considered [57]. The overall digitalisation of business processes and if service system management and data lifecycle management processes are defined and established are other aspects to consider when assessing maturity [37].

6.8 Knowledge Management

As digitalisation increases, a tremendous amount of data and information are gathered, and therefore the management aspect of data, information and the resulting knowledge has to store and be accessible. To create a highly efficient maintenance organisation, processed knowledge has to be highly accurate, interdisciplinary and above all; it must be seen as a key production factor [58]. Klötzer and Pflaum have created a new perspective on knowledge by bringing together innovation and knowledge in the single category ‘cooperation’. For the future implementation of the digitalisation in the industry, the LSM concept entails knowledge management as a central component of employee training, qualifications, continuous improvement and in particular the accompanying error culture as several other authors have already mentioned in their publications.[37], [59]

6.9 Data & Technology

Since the LSM concept is based on the targeted use of technologies and the reasonable use of data, it is necessary to identify the intersections of technology, data and knowledge as well as the particular management aspects [41]. As it comes to the use of new technologies as handheld devices, wearables, Internet of Things (IoT), (Big) Data Analytics (BDA), to mention a few examples, aspects of LSM are useful for integration and acceptance in the company. In a management model, as it is represented by the LSM MM, every level of each category is influenced by the appearance of new technologies. For example, the qualification and training of employees will massively change due to the availability and use of virtual reality, blended-learning concepts and the permanent availability of Information and Communication Technology (ICT).[60]

7. Summary & Outlook

In this research paper, the authors aimed to identify I4.0 elements to expand the LSM MM. The goal was to fill the gaps between the LSM concept and state of the art I4.0 MMs concerning maturity items and categories for digitalisation and digitisation. The methodology used is based on a structured literature review and design science research. After analysing literature reviews on MMs for I4.0 and Smart Factory, a comprehensive list of research papers regarding the aforementioned domain was created, the different maturity models were compared, and maturity categories and items extracted. Based on this analysis, missing digitalisation and digitisation properties of each maturity category and level were integrated into the LSM MM. In the course of this process, the need to restructure the LSM MM was identified, and the number of categories was restructured from eighteen to nine categories with several sub-categories and maturity items. The review of the I4.0 MMs has shown that the authors of the MMs do not consider 'Outsourcing' and 'Asset Strategy' sufficiently in their models. However, due to the rising integration of IT systems around aspects of these LSM categories, they were checked for I4.0 readiness. One reason for the lack of these maturity dimensions in the I4.0 MMs is that the reviewed MMs take a general perspective on the topic of I4.0 and do not focus on the domain of industrial asset management. This research only considered MM papers found in the review papers published from 2017 to 2019, listed Table 2 in the Appendix, which means, that I4.0 MMs published after the newest review paper were not considered. Furthermore, all MMs focused on software development were excluded after the abstract screening. The following steps include a field test, further development and improvement based on the newly structured LSM MM. The critical point is to prove the practical applicability of the new model. Due to the complexity and the advancement of technical developments, the need for further research in the different categories has been identified. Furthermore, further research is needed to identify the dependencies between the different sub-categories and maturity items of the model.

Appendix

Table 1: I4.0 MMs

	Author	Year	Title	Categories	Levels	Annotations
[57]	**Akdil et al.**	2018	Maturity and Readiness Model for Industry 4.0 Strategy	3 categories, one of the categories has 3 sub-categories, 13 items	4 levels: Absence - Existence - Survival - Maturity	Detailed level descriptions for each category, questionnaire
[39]	**Anderl et al.**	2016	Guideline Industrie 4.0 - Guiding principles for the implementation of Industrie 4.0 in small and medium sized businesses	6 categories each for production and products	5 levels for each category	Description for each category and the implementation process
[61]–[63]	**Berghaus et al.**	2017	Digital Maturity & Transformation Report 2017	9 categories	5 levels which are defined according to the difficulty levels of indicators	A comprehensive survey among Swiss companies
[33], [67], [71]	**De Carolis et al.**	2017	A Maturity Model for Assessing the Digital Readiness of Manufacturing Companies	5 categories, 18 sub-categories	5 levels: Initial - Managed - Defined - Integrated and Interoperable - Digital-Oriented	3 case studies in a second publication with potentials for improvements
[66]	**Ganzarain & Errasti**	2016	Three stage maturity model in SME's towards Industry 4.0	3 categories	5 levels	process model
[32]	**Geissbauer et al.**	2016	Industry 4.0: Building the digital enterprise	7 categories	4 levels: Digital novice - Vertical integrator - Horizontal collaborator - Digital champion	List of possible pilot projects given
[67]	**Gökalp et al.**	2017	Development of an assessment model for industry 4.0: Industry 4.0-MM	17 items, that are assigned to the different maturity levels	6 levels: Incomplete - Performed - Managed - Established - Predictable - Optimizing	-
[68], [69]	**Halse et al.**	2016	IoT Technological Maturity Model and assessment of Norwegian manufacturing companies	No categories, but 25 items, that are assigned to the different maturity levels	8 levels: 3.0 Maturity - Initial - Connected - Enhanced - Innovating - Integrated - Extensive - 4.0 Maturity	Assessment of four companies, very detailed level descriptions
[53]	**Jung et al.**	2016	An Overview of a Smart Manufacturing System Readiness Assessment	4 categories, 6 sub-categories	5 levels: Initial - Managed - Defined - Qualitative - Optimizing	-
[56]	**Katsma et al.**	2011	Supply Chain Systems Maturing Towards the Internet-of-Things: A Framework	4 categories	4 levels: ERP - ERP 2.0 - SOA/SAAS - Internet of Things	4 case studies and cross-case analysis
[37]	**Klötzer & Pflaum**	2017	Toward the Development of a Maturity Model for Digitalization within the Manufacturing Industry's Supply Chain	9 categories each for 'Smart product realization' and 'Smart product application.'	5 levels: Digitalization awareness - Smart networked products - The service-oriented enterprise - Thinking in service systems - The data-driven enterprise	-
[52]	**Lee et al.**	2017	A Smartness Assessment Framework for Smart Factories Using Analytic Network Process	4 categories, 10 sub-categories, 46 assessment items	5 levels: Checking - Monitoring - Control - Optimization - Autonomy	A case study with 20 SMEs
[42], [70]	**Leyh et al.**	2017	Assessing the IT and Software Landscapes of Industry 4.0-Enterprises: The Maturity Model SIMMI 4.0	4 categories	5 levels: Basic digitization level - Cross-departmental digitization - Horizontal and vertical digitization - Full digitization - Optimized full digitization	Activities for each level defined
[71]	**Lichtblau et al.**	2015	Industrie 4.0-Readiness	6 categories, 18 sub-categories	6 levels: Outsider - Beginner - Advanced - Experienced - Expert - Excellence	Study on I4.0 readiness of German companies
[36]	**Schuh et al.**	2017	Industrie 4.0 Maturity Index	4 categories	5 levels: Computerisation - Connectivity - Visibility - Transparency - Adaptability	Investigation of capabilities in different functional areas
[72], [73]	**Westermann et al.**	2016	Reference Architecture and Maturity Levels for Cyber-Physical Systems in the Mechanical Engineering Industry	7 categories, 12 sub-categories	5 levels: Monitoring - Communication and Analysis - Interpretation and Services - Adaption and Optimization - Cooperation	Morphological Box for evaluation

Table 2: I4.0 MM Reviews

	Author	Year	Title	Focus	#MMs
[74]	Felch et al.	2019	Maturity Models in the Age of Industry 4.0 – Do the Available Models Correspond to the Needs of Business Practice?	Scientific and consultancy I4.0 MMs	20
[75]	Unterhofer et al.	2018	Investigation of Assessment and Maturity Stage Models for Assessing the Implementation of Industry 4.0	Broad-spectrum of I4.0 MMs from different domains	60
[76]	Blatz et al.	2018	Maturity model of digitization for SMEs	Focus on a few MMs for the as-is analysis of the level of digitisation of SMEs	4
[77]	Mittal et al.	2018	A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs)	Analysis of I4.0 and smart manufacturing MMs with a focus on their categories and items, on research gaps and the adaption for SMEs	15
[57]	Akdil et al.	2018	Maturity and Readiness Model for Industry 4.0 Strategy	Industry 4.0 MMs	4
[67]	Gökalp et al.	2017	Development of an Assessment Model for Industry 4.0: Industry 4.0-MM	Industry 4.0 MMs	7
[64]	De Carolis et al.	2017	Maturity Models and Tools for Enabling Smart Manufacturing Systems: Comparison and Reflections for Future Developments	Smart manufacturing MMs	3

References

[1] J. P. Womack, D. T. Jones, and D. Roos, The machine that changed the world: how Japan’s secret weapon in the global auto wars will revolutionize western industry, 1st HarperPerennial ed. New York, NY: HarperPerennial, 1991.

[2] S. Pfeiffer, ‘The Vision of “Industrie 4.0” in the Making—a Case of Future Told, Tamed, and Traded’, NanoEthics, vol. 11, no. 1, pp. 107–121, Apr. 2017.

[3] H. Lasi, P. Fettke, H.-G. Kemper, T. Feld, and M. Hoffmann, ‘Industrie 4.0’, Wirtschaftsinformatik, vol. 56, no. 4, pp. 261–264, Aug. 2014.

[4] P. Evans, ‘Industrial Internet: Pushing the boundaries of minds and machines’, Gen. Electr., Jan. 2012.

[5] President’s Council of Advisors on Science and Technology, ‘Accelerating U.S. Advanced Manufacturing’. Report to the President, 2014.

[6] T. Bürger and K. Tragl, ‘SPS-Automatisierung mit den Technologien der IT-Welt verbinden’, in Industrie 4.0 in Produktion, Automatisierung und Logistik, T. Bauernhansl, M. ten Hompel, and B. Vogel-Heuser, Eds. Wiesbaden: Springer Fachmedien Wiesbaden, 2014, pp. 559–569.

[7] T. Bauernhansl, M. ten Hompel, and B. Vogel-Heuser, Eds., Industrie 4.0 in Produktion, Automatisierung und Logistik. Wiesbaden: Springer Fachmedien Wiesbaden, 2014.

[8] J. Davis, T. Edgar, J. Porter, J. Bernaden, and M. Sarli, ‘Smart manufacturing, manufacturing intelligence and demand-dynamic performance’, Comput. Chem. Eng., vol. 47, pp. 145–156, Dec. 2012.

[9] M. Wiesmüller, ‘Industrie 4.0: surfing the wave?’, E Elektrotechnik Informationstechnik, vol. 131, no. 7, pp. 197–197, Oct. 2014.

[10] E. Blunck, ‘Industry 4.0 – An Opportunity to realize Sustainable Manufacturing and its Potential for a Circular Economy’, 2017.

[11] M. H. Miraz, M. Ali, P. S. Excell, and R. Picking, ‘A review on Internet of Things (IoT), Internet of Everything (IoE) and Internet of Nano Things (IoNT)’, in 2015 Internet Technologies and Applications (ITA), Wrexham, United Kingdom, 2015, pp. 219–224.

[12] D. Evans, ‘The Internet of Everything - How More Relevant and Valuable Connections Will Change the World’, p. 9, 2012.

[13] M. Hermann, T. Pentek, and B. Otto, ‘Design Principles for Industrie 4.0 Scenarios’, in 2016 49th Hawaii International Conference on System Sciences (HICSS), Koloa, HI, USA, 2016, pp. 3928–3937.

[14] T. Mettler, P. Rohner, and R. Winter, 'Towards a Classification of Maturity Models in Information Systems', in Management of the Interconnected World, 2010, pp. 333–340.

[15] R. Caralli, 'Discerning the Intent of Maturity Models from Characterizations of Security Posture', Softw. Eng. Inst. Carnegie Mellon Univ., p. 6, 2012.

[16] T. de Bruin, M. Rosemann, R. Freeze, and U. Kulkarni, 'Understanding the main phases of developing a maturity assessment model', presented at the ACIS 2005 Proceedings - 16th Australasian Conference on Information Systems, 2005.

[17] P. Fraser, J. Moultrie, and M. Gregory, 'The use of maturity models/grids as a tool in assessing product development capability', presented at the IEEE International Engineering Management Conference, 2002, vol. 1, pp. 244–249.

[18] IEEE, 'IEEE Recommended Practice for Architectural Description for Software-Intensive Systems', IEEE Std 1471-2000, pp. 1–30, Oct. 2000.

[19] V. Saavedra, A. Dávila, K. Melendez, and M. Pessoa, 'Organizational maturity models architectures: A systematic literature review', Adv. Intell. Syst. Comput., vol. 537, pp. 33–46, 2017.

[20] CMMI Institute, 'CMMI® for Development, Version 1.3 CMMI-DEV, V1.3', CMMI Dev., p. 482, 2010.

[21] CMMI Institute, 'How is CMMI V2.0 different from V1.3?', CMMI Institute Help Center. [Online]. Available: http://cmmiinstitute.zendesk.com/hc/en-us/articles/360000175667-How-is-CMMI-V2-0-different-from-V1-3-. [Accessed: 29-Aug-2019].

[22] G. A. García-Mireles, Ma. Á. Moraga, and F. García, 'Development of maturity models: A systematic literature review', presented at the IET Seminar Digest, 2012, vol. 2012, pp. 279–283.

[23] H. Biedermann and A. Kinz, 'Lean Smart Maintenance—Value Adding, Flexible, and Intelligent Asset Management', BHM Berg- Hüttenmänn. Monatshefte, vol. 164, no. 1, pp. 13–18, Jan. 2019.

[24] A. Kinz, R. Bernerstaetter, and H. Biedermann, 'LEAN SMART MAINTENANCE – EFFICIENT AND EFFECTIVE ASSET MANAGEMENT FOR SMART FACTORIES', p. 9.

[25] H. Biedermann, 'Lean Smart Maintenance', in Industrial Engineering und Management, H. Biedermann, Ed. Wiesbaden: Springer Fachmedien Wiesbaden, 2016, pp. 119–141.

[26] A. R. Hevner, S. T. March, J. Park, and S. Ram, 'Design science in information systems research', MIS Q. Manag. Inf. Syst., vol. 28, no. 1, pp. 75–105, 2004.

[27] D. Tranfield, D. Denyer, and P. Smart, 'Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review', Br. J. Manag., vol. 14, no. 3, pp. 207–222, 2003.

[28] J. Rüegg-Stürm, The New St. Gallen Management Model: Basic Categories of an Approach to Integrated Management. Palgrave Macmillan UK, 2005.

[29] K. Bleicher and C. Abegglen, Das Konzept integriertes Management: Visionen - Missionen - Programme, 9., aktualisierte und erweiterte Auflage des Standardwerks. Frankfurt New York: Campus Verlag, 2017.

[30] A. Alcalde Rasch, Erfolgspotential Instandhaltung: theoretische Untersuchung und Entwurf eines ganzheitlichen Instandshaltungmanagements. Berlin: E. Schmidt, 2000.

[31] Knowledge Based Maintenance: Strategien, Konzepte und Lösungen für eine wissensbasierte Instandhaltung: 15. Instandhaltungs-Forum. Köln: TÜV-Verlag, 2001.

[32] R. Geissbauer, J. Vedso, and S. Schrauf, 'Industry 4.0: Building the digital enterprise', Glob. Ind. 40 Surv. Build. Digit. Enterp., p. 36, 2016.

[33] A. De Carolis, M. Macchi, E. Negri, and S. Terzi, 'A Maturity Model for Assessing the Digital Readiness of Manufacturing Companies', in Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing, vol. 513, H. Lödding, R. Riedel, K.-D. Thoben, G. von Cieminski, and D. Kiritsis, Eds. Cham: Springer International Publishing, 2017, pp. 13–20.

[34] E. H. Schein, ‘Organizational Culture and Leadership’, p. 458.

[35] E. H. Schein, The corporate culture survival guide, New and rev. Ed. San Francisco, CA: Jossey-Bass, 2009.

[36] G. Schuh, R. Anderl, J. Gausemeier, and W. Wahlster, ‘Industrie 4.0 Maturity Index. Managing the Digital Transformation of Companies (acatech STUDY)’, Herbert Utz Verl., p. 60, 2017.

[37] C. Klötzer and A. Pflaum, ‘Toward the Development of a Maturity Model for Digitalization within the Manufacturing Industry’s Supply Chain’, p. 10.

[38] S. Rübel, A. Emrich, S. Klein, and P. Loos, ‘A Maturity Model for Business Model Management in Industry 4.0’, p. 12.

[39] R. Anderl et al., ‘Guideline Industrie 4.0 – Guiding principles for the implementation of Industrie 4.0 in small and medium sized businesses’, VDMA Forum Ind. 40, 2016.

[40] H. Biedermann, Anlagenmanagement: Managementinstrumente zur Wertsteigerung, 2., vollst. überarb. und aktualisierte Aufl. Köln: TÜV Media, 2008.

[41] A. Kinz, ‘Ausgestaltung einer dynamischen, lern- und wertschöpfungsorientierten Instandhaltung’, Monografie, Montanuniversität Leoben, Leoben, 2017.

[42] C. Leyh, T. Schäffer, K. Bley, and S. Forstenhäusler, ‘Assessing the IT and Software Landscapes of Industry 4.0-Enterprises: The Maturity Model SIMMI 4.0’, in Information Technology for Management: New Ideas and Real Solutions, vol. 277, E. Ziemba, Ed. Cham: Springer International Publishing, 2017, pp. 103–119.

[43] M. al-Radhi and J. Heuer, Total productive maintenance: Konzept, Umsetzung, Erfahrung. München: Hanser, 1995.

[44] W. Männel and K. Aman, Eds., Integrierte Anlagenwirtschaft. Köln: Verl. TÜV Rheinland, 1988.

[45] A. Beeck, Systemorientierte Untersuchungen zur Problematik einer instandhaltungsgerechten Anlagenplanung, Als Ms. gedr. Düsseldorf: VDI-Verl, 1987.

[46] W. Schröder, Ganzheitliches Instandhaltungsmanagement: Aufbau, Ausgestaltung und Bewertung. Gabler Verlag, 2010.

[47] W. Keplinger, ‘Erfolgreiches Outsourcing von Instandhaltungstätigkeiten’, in Risikominimierung im Anlagenmanagement: Risiken beim Planen, Errichten und Betreiben von Anlagen, Köln, 2003, pp. 201–208.

[48] H. Biedermann, Ersatzteilmanagement: effiziente Ersatzteillogistik für Industrieunternehmen, 2., erw. Und aktualisierte Aufl. Berlin: Springer, 2008.

[49] H. Biedermann, ‘Instandhaltungs-Controlling mittels Kennzahlen - Kennzahlen als Führungsinstrumentarium für Analyse, Planung, Steuerung und Kontrolle’, pp. 305–329, 1988.

[50] H. Biedermann and O. Esfandeyari, ‘Instandhaltungsbudgetierung: Verfahren und Methoden zur Planung von Budgets der Anlageninstandhaltung, not yet published’.

[51] B. Kleindienst and H. Biedermann, Performance Measurement und Management: Gestaltung und Einführung von Kennzahlen- und Steuerungssystemen. Wiesbaden: Springer Gabler, 2017.

[52] J. Lee, S. Jun, T.-W. Chang, and J. Park, ‘A Smartness Assessment Framework for Smart Factories Using Analytic Network Process’, Sustainability, vol. 9, no. 5, p. 794, May 2017.

[53] K. Jung, B. Kulvatunyou, S. Choi, and M. P. Brundage, ‘An Overview of a Smart Manufacturing System Readiness Assessment’, in Advances in Production Management Systems. Initiatives for a Sustainable World, vol. 488, I. Nääs, O. Vendrametto, J. Mendes Reis, R. F. Gonçalves, M. T. Silva, G. von Cieminski, and D. Kiritsis, Eds. Cham: Springer International Publishing, 2016, pp. 705–712.

[54] S. P. Robbins and T. A. Judge, Organizational behavior, Edition 17, Global edition. Boston: Pearson, 2017.

[55] E. Frese, Grundlagen der Organisation Konzept - Prinzipien - Strukturen. Wiesbaden: Gabler Verlag, 2000.

[56] C. P. Katsma, H. M. Moonen, and J. Van Hillegersberg, ‘Supply chain systems maturing towards the internet-of-things: A framework’, presented at the 24th Bled eConference - eFuture: Creating Solutions for the Individual, Organisations and Society, Proceedings, 2011, pp. 478–494.

[57] K. Y. Akdil, A. Ustundag, and E. Cevikcan, ‘Maturity and Readiness Model for Industry 4.0 Strategy’, in Industry 4.0: Managing the Digital Transformation, Godalming: Springer-Verlag London Ltd, 2018, pp. 61–94.

[58] M. Schnell and A. Kuhn, Wissensmanagement in der Instandhaltung: Probleme, Methoden, Lösungs- und Gestaltungsansätze beim Aufbau eines Wissensmanagementsystems in der Instandhaltung. Dortmund: Verl. Praxiswissen, 2002.

[59] E. Schmitz and M. Schröter, ‘Industrie 4.0 - Readiness’, p. 77, 2015.

[60] University of Information Technology and Communications, J. Stephan, A. S. Ahmed, University of Information Technology and Communications, A. H. Omran, and University of Information Technology and Communications, ‘Blended Learning Using Virtual RealityEnvironments’, Iraqi J. Comput. Inform., vol. 43, no. 1, pp. 6–13, May 2017.

[61] S. Berghaus, A. Back, and B. Kaltenrieder, ‘Digital Maturity & Transformation Report 2017’, 2017.

[62] S. Berghaus, A. Back, and B. Kaltenrieder, ‘Digital Maturity & Transformation Report 2016’, 2016.

[63] S. Berghaus, A. Back, and B. Kaltenrieder, ‘Digital Maturity & Transformation Report 2015’, 2016.

[64] A. De Carolis, M. Macchi, B. Kulvatunyou, M. P. Brundage, and S. Terzi, ‘Maturity Models and Tools for Enabling Smart Manufacturing Systems: Comparison and Reflections for Future Developments’, in Product Lifecycle Management and the Industry of the Future, vol. 517, J. Ríos, A. Bernard, A. Bouras, and S. Foufou, Eds. Cham: Springer International Publishing, 2017, pp. 23–35.

[65] A. De Carolis, M. MacChi, E. Negri, and S. Terzi, ‘Guiding manufacturing companies towards digitalization - A methodology for supporting manufacturing companies in defining their digitalization roadmap’, presented at the 2017 International Conference on Engineering, Technology and Innovation: Engineering, Technology and Innovation Management Beyond 2020: New Challenges, New Approaches, ICE/ITMC 2017 - Proceedings, 2018, vol. 2018-January, pp. 487–495.

[66] J. Ganzarain and N. Errasti, ‘Three stage maturity model in SME’s toward industry 4.0’, J. Ind. Eng. Manag., vol. 9, no. 5, p. 1119, Dec. 2016.

[67] E. Gökalp, U. Şener, and P. E. Eren, ‘Development of an assessment model for industry 4.0: Industry 4.0-MM’, Commun. Comput. Inf. Sci., vol. 770, pp. 128–142, 2017.

[68] L. L. Halse, H. Wiig, and A. H. Bø, ‘IoT Technological Maturity Model and assessment of Norwegian manufacturing companies’, p. 11, 2016.

[69] B. Jæger and L. L. Halse, ‘The IoT technological maturity assessment scorecard: A case study of norwegian manufacturing companies’, IFIP Adv. Inf. Commun. Technol., vol. 513, pp. 143–150, 2017.

[70] C. Leyh, T. Schäffer, and S. Forstenhäusler, ‘SIMMI 4.0 – Vorschlag eines Reifegradmodells zur Klassifikation der unternehmensweiten Anwendungssystemlandschaft mit Fokus Industrie 4.0’, 2016.

[71] K. Lichtblau et al., ‘Industrie 4.0 - Readiness’, p. 77, 2015.

[72] T. Westermann, H. Anacker, R. Dumitrescu, and A. Czaja, ‘Reference architecture and maturity levels for cyber-physical systems in the mechanical engineering industry’, in 2016 IEEE International Symposium on Systems Engineering (ISSE), Edinburgh, United Kingdom, 2016, pp. 1–6.

[73] T. Westermann and R. Dumitrescu, ‘Maturity model-based planning of cyber-physical systems in the machinery and plant engineering industry’, presented at the 15th International Design Conference, 2018, pp. 3041–3052.

[74] V. Felch, B. Asdecker, and E. Sucky, ‘Maturity Models in the Age of Industry 4.0 – Do the Available Models Correspond to the Needs of Business Practice?’, p. 10.

[75] M. Unterhofer, E. Rauch, D. T. Matt, and S. Santiteerakul, 'Investigation of Assessment and Maturity Stage Models for Assessing the Implementation of Industry 4.0', in 2018 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Bangkok, 2018, pp. 720–725.

[76] F. Blatz, R. Bulander, and M. Dietel, 'Maturity Model of Digitization for SMEs', in 2018 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC), Stuttgart, 2018, pp. 1–9.

[77] S. Mittal, M. A. Khan, D. Romero, and T. Wuest, 'A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs)', J. Manuf. Syst., vol. 49, pp. 194–214, 2018.

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