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Industry 4.0 Maturity Models to Support Smart Manufacturing Transformation: A Systematic Literature Review

Akhmad Hadi Susanto[1], Togar M. Simatupang[2], Meditya Wasesa[3]
[1,2,3]School of Business and Management, Institut Teknologi Bandung
[1]akhmad_susanto@sbm-itb.ac.id, [2]togar@sbm-itb.ac.id, [3]meditya.wasesa@sbm-itb.ac.id

Abstract

With increasing pressure to revitalize manufacturing industries with Smart Manufacturing capability within the Industry 4.0 (I4.0) context, companies have uneven readiness reflecting their gaps and barriers for transforming to the I4.0 state. Understanding factors and measuring a company's maturity in addressing the I4.0 transformation is crucial to diagnose the company's current condition and provide corresponding prescriptive action plan effectively. Despite the positive trend of maturity models for the industries, companies still face challenges with low I4.0 adoption rate. Designing a corresponding diagnostic framework into an intelligent maturity model will ultimately lead the company's pathways toward the desired capabilities. In response, we systematically review and select the state-of-the-art research through a Systematic Literature Review (SLR) conduct to scrutinize the main characteristics of 14.0 Maturity Models. Subsequently, 35 exceptional articles published between 1980-2020 were selected for in-depth analysis of their structure, dimensions, and analytical features. Our analysis revealed the descriptive method have been widely used in many maturity models while few more-advanced prescriptive models design adopt fuzzy rule-base analytical hierarchy, knowledge based, Monte-Carlo methods, and even expert-system approaches. Furthermore, people, culture, organization, resources, information system, business processes, and smart technology, products and services have been treated as the popular evaluation dimensions which will define the state of an industry's maturity level.

Keywords: *maturity model; intelligent systems; smart manufacturing; industry 4.0*

1. Introduction

The unprecedented growth in information and communication technology (ICT) has successfully reshaped the way people produce and use products and services over the past two decades. The manufacturing industry has leveraged this momentum to pursue solutions in addressing business challenges such as increasingly customized demands, quality, and reduced time-to-market [1], by increasing their capacity to be more "intelligent" manufacturing factories have deployed sensors, controllers, and intelligent logics in machinery through Industrial Internet of Things (IIoT) devices that allow equipment to self-sense and self-act. The devices communicate between [2] and enable real-time data acquisition to support rapid and accurate decision-making. These building blocks formed a cyber-physical production system (CPPS) that integrate the whole manufacturing value chain processes in a Smart Manufacturing (SM) system. To achieve SM capabilities, manufacturing companies have attempted to revive their operation covering broad range of applications from product design to supply chain management [3]. [4]. Despite myriad barriers and challenges, the attempts have subsequently triggered many digital transformation initiatives pursuing the I4.0 adoption benefits. The activity often involved experts to assist a firm on setting up I4.0 strategy and direction [5].

Introduced in Germany during the Hannover Messe Trade Fair in 2011, the Industry 4.0 agenda had grabbed substantial attention from industry, academia, and government practitioners. It presented a high-tech transformative strategy towards fully integrated, optimized, and digitized manufacturing systems [6]. The strategy later portrayed as I4.0 characteristics pillars include: additive manufacturing augmented reality, simulation, autonomous robots, industrial IoT, Big Data analytics, Cloud computing, cyber security, horizontal and vertical integration, and other enabling technologies [7]. The realization of I4.0 requires capacity building towards SM design principles which include: interoperability, information transparency, decentralization, real-time capability, technical assistance and service orientation with human-machine interaction, and modularity.

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Commenced by the US Smart Manufacturing Leadership Coalition (SMLC), the SM term has gained global popularity in recent years [8], defined as a set of manufacturing practices that leverage the networked data and ICT capability to oversee manufacturing operations [9]. SM has been perceived as the next-generation manufacturing practice that adopted advanced sensing, control, modeling, and platform technologies aligned with I4.0 envision. However, companies face challenges in adopting current manufacturing systems [10], namely the ability for self-configuration, self-optimization, early awareness, decision making, and predictive maintenance. The emerging pressure to gain these intelligent capabilities in the manufacturing sector has urged the industry to formulate a suitable maturity model to help assess the state and progress towards SM roadmap realization.

Maturity models (MM) refer to stage-of-growth of a company assuming that predictable pattern conceptualized in terms of stages exists in the organization's growth. It represents synthesis of theories on how organizational capabilities progress as described at a stage-by-stage level along with an anticipated, desired, or logical maturation path. The stages are characterized as sequential, occur as a hierarchical progression, and evolve a broad range of organizational activities [11],[12]. MMs have common characteristics depicted in a generic structure that consists of: design structure maturity models, which contains dimensions of the object measure and stage-wise levels that indicate progressing step of the maturity, and measurement instrument part using hierarchical relationships between components [13]. The figure depicted a basic generic structure that is commonly applied in existing MMs. However, to the best of our knowledge, the existing model lacks advanced features in decision-making characteristics and processes, such as in the contexts of analytics. Furthermore, many of MM models are tailored to a unique organization. In recent developments, the industry is looking for a universal model representing complex characteristics, including aggregation, benchmarking, and knowledge management features.

Adopting the business analytics point of view, MM main capabilities can be distinguished into the following main features: (1) descriptive, comparative, and diagnostic, (2) predictive, and (3) prescriptive levels of analytics [14]. The principles fall with the business analytics knowledge area, which formed an intelligent instrument. Note that business analytics refers to the broad utilization of data acquired through various data sources, statistical and quantitative analysis, explanatory and predictive modes, and fact-based management to make actionable decisions [15]. It extracts the required data and transforms it into actionable business insights to support the decision-making process. As it employed in various business processes, business analytics produce outcomes which levelled its maturity according to its features, namely: (1) descriptive analytics extracts and present historical data to obtain hindsight such as in the enterprise data management and operational reports which commonly employs static and interactive dashboard or reports techniques (2) diagnostic analytics, as an extension of the descriptive analytics [15], it develops insights that involves extraction and consolidation of all system and data, visualization and modelling to assist the root-cause analysis (3) predictive analytics of foresight creates prospective analysis based on pattern of input, output and their relationship through scenario simulation and predictive modeling or optimization, and (4) prescriptive analytics examines data or content to answer the question “What should be done?” or “What can we do to make it happen?”, and is characterized by techniques such as graph analysis, simulation, complex event processing, neural networks, recommendation engines, heuristics, and machine learning for the automated decision making [16].

Industry practitioners and academia have developed various I4.0 maturity models (MM) as an instrument to diagnose a manufacturer’s capability in various aspects. The assessment commonly produces a score that represents a maturity level based on a product of weighted average multiple dimensions sub-scores. While the engagement could ensure accuracy, objectivity and promoted business opportunities for the industry eco-systems, it requires inevitable costs and significant effort from company resources that may push back the adoption. Furthermore, spanning across various I4.0 MMs, a suitable model must be chosen from pool of academic literature or industry practitioners. Unfortunately, not all of them provide their specification details publicly open. Primarily due to commercial reasons, these models can provide assessment in high level as a tool to lead to the consultancy services. On the other side, the models from academic research also available, but unfortunately have lacked on practical relevance.

To bridge the gap, the government in several countries that sponsored the I4.0 at an industry-wide level have developed readiness index models such as SIRI in Singapore or INDI4.0 in Indonesia. Even though their purpose does not assess the maturity respectively, the readiness assessment provides a comprehensive measure to evaluate the company’s I4.0 readiness level based on several dimensions or pillars, including element variables that can be assessed with relevant questionnaires. Policymaker utilized the aggregated industry level result to evaluate nation-wide progress, assist the diagnostic effort to understand main issues and adjust the corresponding regulation to accelerate the I4.0 adoption. Despite I4.0 implementation complexity faced by the industry, government has launched relentless effort to significantly increase

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overall GDP through various I4.0 adoption initiatives, particularly addressing the manufacturing sectors.

Despite many existing models are available, organization finds the difficulty to design a suitable model with ability to provide recommended actions to support the I4.0 transformation program. Therefore, we discover the need to develop an alternative method to assist the industry in assessing their maturity, in understanding the root cause of I4.0 implementation problems, and in formulating a better policy in a more systematic and intelligent manner. To do so, this research explores relevant articles focused on I4.0 maturity models in manufacturing sectors through a systematic literature review (SLR).

The paper is organized as follows: Section 1 elaborates the information background on I4.0 maturity models development, smart manufacturing, intelligent features classification. Section 2 outlines the SLR method and subsequently, Section 3 discusses the results and analysis. Lastly, Section 4 summarizes this study's main findings and clarifies its theoretical and practical contributions in the I4.0 adoption and related research areas. Through these steps, this study aims to determine the advanced features and dimensions as building blocks to design an "intelligent" or "smart" model that leveraged the feature of I4.0 principles itself.

2. Research Methods

Adopted from Systematic Review and Meta-Analyses PRISMA 2009 framework, the SLR exploration identified search criteria and rules defined in publication databases. The SLR method identifies, assesses, and interprets processes to research articles to answer a particular research question [17].

In this study, we explore possible answers to the underlying question: "what are the main factors that determine the I4.0 adoption maturity for manufacturing firms?" that lead to the initial research topic of designing an intelligent system instead of traditional maturity models adaptation. Furthermore, a follow up research question is also defined as follows "In the context of adopting smart manufacturing I4.0, what are the characteristics that determine an intelligent maturity model?"

This review approach is propositioned with the preliminary research topic "intelligent maturity model development for smart manufacturing adoption toward industry 4.0". The related keywords and their combination consist of "maturity model," "intelligent maturity," "industry 4.0," "fourth industrial revolution," "manufacturing," and "smart manufacturing," were used as the search terms input to the database query to target the literature's title, abstract, and keywords metadata. Table 1 describes the literature records with relevant bibliographies from references used in the selected papers relevant to the topic once retrieved from each database. During the process, all duplicated papers were removed throughout the screening stage using Mendeley software prior to conducting further in-depth analyses.

Table[1] 1. Literature Identification using Online Databases

No	Criteria	Values	Rationale
1	Database sources	Scopus and ScienceDirect	Well recognized sources for academic articles index from various journals
		Relevant bibliographies from selected journals	Relevant content with the topic which was not retrieved from the database searches
		Secondary sources	Seek for industry/ technology news
2a.	Search terms 1	"Maturity Model" OR "Intelligent Maturity" "Manufacturing" OR "Smart Manufacturing" "Industry 4.0" OR "Fourth industrial revolution"	Logical queries from the database source based on "AND" logical keywords' rule and metadata fields to find relevant articles for the Maturity Models topic for Smart Manufacturing within the Industry 4.0 context
2b.	Search terms 2	("Maturity Model" OR "Intelligent Maturity")	Logical queries based on keywords' rule and metadata relevant to Maturity Model
3	Limits applied	Published from the year 2010 until 2020 (10 years) and English language	Significant development of MM and Industry 4.0 context, other older concept/theories/ applications to be searched as applicable
4	Screening process	Scanning [Article title], [Abstract], [Keywords] for relevance	The metadata fields contain essential keywords to reduce unwanted articles, e.g., compared to search 'Full text."
5	Inclusion/ Exclusion Criteria (IEC)	Refer IEC table	Systematic rule to filter article's relevance

The screening for eligibility stages review produces literature to be included in the qualitative synthesis. It begins by assessing key metadata such as titles, abstracts, keywords, and database categories, including only papers written in English with full-text availability. The following review is continued with applying effective reading to identify the relevance of each paper with the research topic and research questions for exclusion or inclusion through several criteria as illustrated in Table 2.

Based on the reviews, the activities sequence and their correspondent's number of papers results are outlined in Figure 1. It shows the process diagram for selecting papers after performing effective reading, validation with the research questions to explore what research

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activities have been done, the insights, and recommended further research through synthesis and finding the linkage to the research objectives. Each process corresponds to PRISMA's selection task group i.e., identification, screening, determine eligibility, and decision to include papers in state-of-the-art synthesis that resulting 35 articles for this study.

Table 2. Inclusion and exclusion criteria (IEC)

Inclusion	Activity	Rationale
Exclude	Review article list	Duplication removed and excluded articles are written not in the English language and unretrievable full-text articles (e.g., accessibility)
Exclude	Review article list	Exclude non-primary academic sources (e.g., editorial, conference reviews/contents, and institutional releases) since articles related to research mainly covered in journals, reviews, and proceedings
Exclude	Review title, keyword, and abstract for each article	Exclude articles that the context of the I4.0 or fourth industrial revolution is not related explicitly to maturity models, smart manufacturing area (NR1)
Exclude	Review title, keyword, and abstract for each article	Exclude articles that do not focus on the review, survey, discussion, problem-solving, case study, and another type of research of I4.0, maturity model, and smart manufacturing (e.g., use these objects only as an example, cited, keywords, references) (NR2)
Include	Review full text for each article	Include articles that contain maturity models, Industry 4.0, smart manufacturing as objects reviewed, surveyed, or discussed, used as support the description, challenges, issues of the research
Include	Ensure full access to the paper and review full text for each article	The research is dedicated to maturity models, system, or frameworks model development as the core subject of the description, methodology, problem, discussion, and references in the context of developing smart manufacturing under I4.0 context.

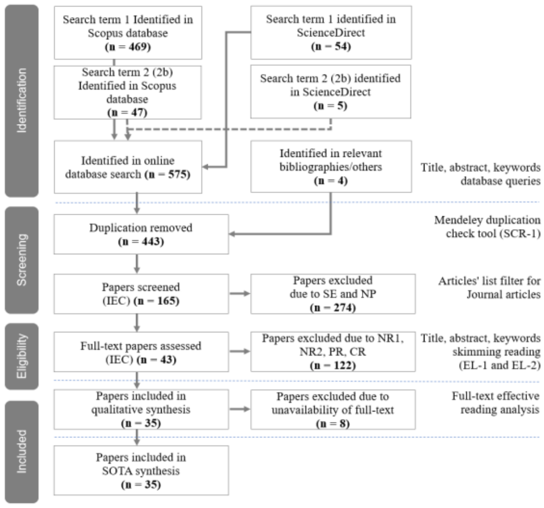

Figure 1. The conduct of systematic literature review framework.

3. Results and Discussions

3.1 Phase 1: Trend and Identification

The search of the "maturity model" keyword to the Scopus publication database query tool from 1980 until 2020 shows a positive trend (see Figure 2). This trend indicates that the topic has still been studied and published every year until recently. The query report has shown the publications within Computer Science is the majority (34.4%) followed by Engineering (19.2%), Business Management (12.3%), Decision Science (7.4%), and Social Science (7.1%) as the top-five academic disciplines.

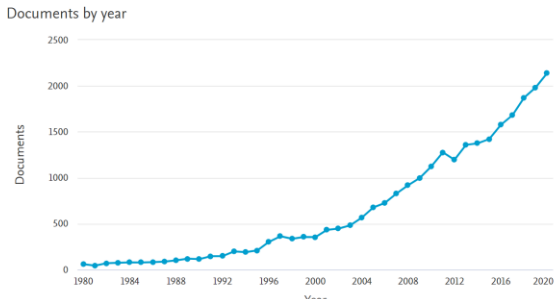

Figure 2. Maturity models publication trends

The identification phase applies the search of a set of "term 1" and "term 2", applying period limits of ten years publications across Scopus and ScienceDirect databases. The chosen keywords applied considering the awareness of the maturity model and intelligent feature within the context of smart manufacturing and Industry 4.0 in general. The search identified 575 documents resulting from the online databases and four related bibliographies.

From the initial extraction, following Table 3 describes types of papers, number of records and contribution

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percentages where conference paper and journal articles are shown dominance.

Table 3. Distribution of Document Types

Type	Records	Contribution%
Conference Paper	180	40.63%
Journal Article	169	38.15%
Book Series	86	19.41%
Book Chapter	6	1.35%
Book	2	0.45%
Total	443	

3.2 Phase 2: Screening

The screening phase applies two steps of filtering, first by removing duplicated articles using Mendeley software. Secondly, by manually reviewing the list to exclude non-English articles (SE) and non-primary (NP) academic sources criteria (e.g., editorial, conference reviews/contents, and institutional releases). The review filtered articles related to research mainly covered in journals, reviews, and proceedings as outlined in Table II. There are 165 publications screened at this stage, including the additional items from relevant bibliography such as [51] for the process audit tool kit and [52] Indonesian Industry 4.0 Readiness Index (INDI4.0) to enrich the exploration.

3.3 Phase 3: Eligibility and Inclusion

The eligibility of articles to be included for further review has been determined through reviewing the document's title, keyword, and abstract for each item. The step excludes articles in the Industry 4.0 or fourth industrial revolution context, which is not specifically related to maturity models and smart manufacturing area (NR1 criteria). Furthermore, the phase excludes articles that do not focus on the review, survey, discussion, problem-solving, case study, and another type of research of Industry 4.0, maturity model, and smart manufacturing (e.g., use these objects only as an example, cited, keywords, references) (NR2). As a result, 122 articles were excluded reducing the eligible number of items to 43 articles. Subsequently, the full-text review considered 35 articles to be included after excluding several articles where the full-text content could not be retrieved using the provided online access.

3.4 Bibliometric Analysis

Toward identifying a potential research gap, an advanced bibliometric analysis method was performed using VOSviewer software. The technique is used to analyze the bibliographic data of the published papers during the identification step in Fig.1. Collective list literature because of the queries that combined "MM" and "Intelligent" or "MM" and "I4.0", or "MM" and "SM." This exercise aims to provide an overview of the body of knowledge for the area of inquiry. The tool examines networked patterns depicted by linked articles' keywords from the exported list of the database queries. The report visualized a graph displaying concentrated nodes resulting from text mining for related queries from literature databases. As depicted in Figure 3, four main clusters, i.e., "maturity model," "industry 4.0", and "software engineering," are displayed, including networked links among them.

These links showed how close the relationship is, such as for the maturity model with software engineering as the core logical layer of I4.0. Related to MM term, the network indicates that "smart manufacturing" is related to "Industry 4.0" term has linkages to the core "maturity model" term that indicates relationship. Based on the nodes' size revealed that these considerations have potential areas with emerging issues for further exploration.

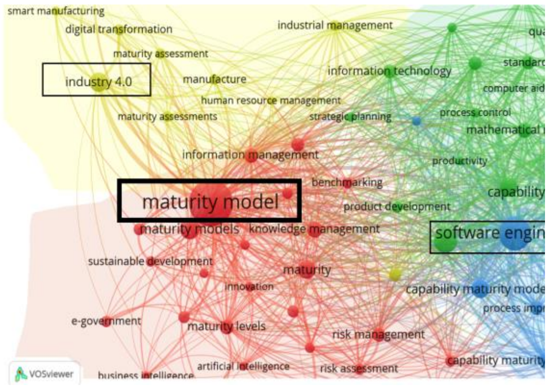

Figure 3. Bibliometric cluster analysis of I4.0 MM research gap

3.5 Analytical Features and Popular MM Reference

Further analysis of the literature inclusion revealed that most MMs provide descriptive analytics as a common feature (see Fig. 4). The finding is not surprising, as the common purpose of MMs is portraying the existing level of I4.0 maturity condition of a company. While there are few articles which highlight additional analytical capability, such as predictive and prescriptive, the descriptive analytics feature is commonly used in MM models as the basis of diagnostic analysis.

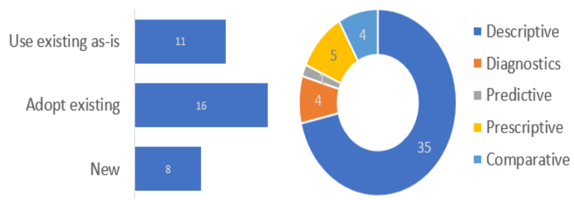

Figure 4. Maturity models' analytical characteristics

The review (Fig 4) also revealed that most MM articles adopted from existing maturity models without substantial modifications or new model developments. Table 4 summarizes the list of common maturity models as the basis for adaptation. Besides various adaptations used for specific purposes, many studies adopt the Capability Maturity Model (CMM) and

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various I4.0 MM-based models. The researchers adapted models such as Acatech Industrie 4.0 Maturity Index (AIMI) and IMPULS proposed by the *Verband Deutscher Maschinen und Anlagenbau* (VDMA) or German's Mechanical Engineering Industry Association for various purposes and contexts.

Table 4. Popular MM Reference

Basis	Popular MM Reference	Reference
CMM	Capability Maturity Model	[39], [40], [42], [43], [46], [47], [48]
I40MM	I4.0 Specific MM E.g., Acatech I4.0 MI, IMPULS-VDMA	[21], [31], [32], [33], [34], [52]
OSCM	Open-Source Center Model	[18], [22]
BPMM	Business Process Maturity Model	[49]
CASE-MM	Constraints and Success criteria-based Evaluation Metrics Model	[27]
FAHP	Fuzzy Analytic Hierarchy Process	[24]
IPBOMM	Intelligent Project-based Organization Model	[37]
KBM	Knowledge Based Maintenance	[26]
MAT	Maturity Assessment Tool	[38]
RMMM	Risk Management Maturity Model	[41]
SIRI	Smart Industry Readiness Index	[23]
AHP4.0	Analytic Hierarchy Process	[19]
Various	Various basis, specific purposes	[20], [25], [28], [29], [30], [35], [36], [44], [45], [50]
	Total publications	35

3.6 Industry 4.0 Maturity Models

Table 5 enlists various maturity models and their characteristics based on their type, structure, and usage. The list is derived from various publications and industry practices by an individual company or government-sponsored model.

As outlined, both academic and industry sectors contribute evenly to the MM development. From the industry sector, MMs were developed by (1) associations of industry sectors, (2) governments, and (3) consulting companies. The model design consists of three to nine dimensions, followed by various sub-dimension variables in the structure. Maturity score is commonly calculated based on the summation of a weighted average of sub-scores.

3.7 Advanced Analytical Features

The intelligent MM in this research context stands for the following three properties: (1) Representation of different maturity models due to a generic structure, (2) integration of the Intelligent Maturity Model-Tool with a BPM system, and (3) the proposal of optimization recommendations provided by a special assistance function [49]. The first property refers to leveraging the system to select different MM designs based on certain criteria automatically.

Table 5. Applicable Maturity Models for Industry 4.0

Model	Type	Structure	Usage
AIMI – Acatech Industrie 4.0 Maturity Index (Germany), 2017 by Schuh et al. [53]	IN	4 Structural dimensions, six stages, five functional, roadmap, diagnostic	Manufacturing processes / industrial engineering through expert consultation.
IMPULS – Industrie 4.0 Readiness (Germany), 2015 by VDMA [54]	IN	6-dimension, 18 items readiness in 5 stages, descriptive	Manufacturing/ industrial engineering readiness by self-assessment and consulting.
PWC – I4.0 Digital operations self-assessment, 2016 by PwC [55]	IN	7-dimension, 4 stages, descriptive	Generic, online self-assessment, application as a consulting tool.
AIMM – Industry 4.0 Maturity Model (Austria), 2016 by Schumacher et al. [34]	AC	9-dimension, five stages, 62 evaluation criteria, descriptive	Specific for I4.0, academic paper. However, detailed sub-dimensions not available.
SIMMI – System Integration Maturity Model for I4.0 (SIMMI 4.0) (Germany), 2016 by Leyh et al. [56]	AC	4-dimension, five stages, descriptive	The model focuses on IT area, academic paper, detailed not available.
IMRM – Industry 4.0 Maturity and Readiness Model, 2018 by Akdil et al. [57]	AC	3-dimension, 13 fields of action, four stages, descriptive	Generic Industry 4.0 for comprehensive assessment purposes.
SIRI – Singapore Smart Industry Readiness Index, 2017 by EDB [58]	IN	3-dimension, 8 sub-dims, 16 vars, 6 stages, descriptive, roadmap.	Specific for I4.0 assessment by certified assessors.
INDI – Indonesia Industry 4.0 Readiness Index INDI4.0 (Indonesia), 2019 Kemenperin [52]	IN	Five dimensions (pillars), 17 fields, five stages, descriptive.	Specific for I4.0. Collective measurement through self-assessment by Indonesian government
M2DDM - Maturity Model for Data-Driven Manufacturing (Germany), 2017 by Weber et al. [59]	AC	Six dimensions, six stages, descriptive.	Specific for I4.0 data-driven manufacturing, assessment based on I4.0 reference architectures.

Note: Type AC: Academic, IN: Industry practices

The second property depends on external factors or context where the system will be deployed, e.g., integrated with the existing system in a firm, or an independent system centrally located could be a feasible solution to enable the aggregation for comparative analytics purposes across the companies. Finally, the optimization and intelligent level of analytics recommend a model's feature to have prescriptive analytics.

The intelligent maturity architecture model in [49] provides a design architecture approach that could be closely relevant to this study to be adapted. The MM Tool architecture outlines logical connections between data and storage, processing blocks, and presentation components. Furthermore, the subject topic relates to general MM design that specifies Business Process Management (BPM) related maturity. Hence, the modularity directly connects MM and BPM systems, allowing minimum human intervention during maturity measurement for this object.

Table 6. Design and Analytical Feature Comparison

	Design			Analytical Feature						
Ref.	New	Adopt existing	Use existing as-is	Descriptive	Diagnostics	Predictive	Prescriptive	Comparative	Industry/ Sector	Location
[18]		x		x	x		x		Aviation	Brazil
[19]			x	x					Multiple	Brazil
[20]		x		x					Multiple	Multiple
[21]			x	x	x			x	Multiple	Brazil
[22]		x		x					Construction	India
[23]			x	x					Multiple	Taiwan
[24]			x	x					Electronics	India
[25]		x		x					Textile	Poland
[26]			x	x		x	x		Manufacturing	Austria
[27]			x	x					Multiple	Italy
[28]	x			x					Multiple	Italy
[29]				x					Multiple	Italy
[30]			x	x					Services	Poland
[31]			x	x					Engineering	Denmark
[32]			x	x					Steel	Slovenia
[33]		x		x					Multiple	Hungary
[34]			x	x					Multiple	Austria
[35]	x	x		x					Manufacturing	Canada
[36]		x		x					Manufacturing	Ireland
[37]	x	x		x					Engineering	Morocco
[38]			x	x				x	Manufacturing	Multiple
[39]		x		x				x	Multiple	Brazil
[40]	x			x					Manufacturing	Switzerland
[41]		x		x					Construction	Indonesia
[42]		x		x					Government	Indonesia
[43]		x		x					Textile	China
[44]	x			x	x		x		Manufacturing	Brazil
[45]	x			x					Multiple	UK
[46]		x		x					Multiple	Italy
[47]		x		x					Manufacturing	France
[48]		x		x					Construction	UK
[49]		x		x	x		x		Multiple	Multiple
[50]	x			x			x		Multiple	Multiple
[51]	x			x					Multiple	Multiple
[52]		x		x				x	Multiple	Indonesia

Additionally, the adapted design from the "Intelligent Project-based Organization Maturity Model" or IPBOM [37] could be considered, although it does not specifically define the prescriptive decision on its design. The model integrates its data source with the company's business intelligence system supporting the decision-making. However, many publications rarely formulated and depicted more detailed logical connections, approaches, diagnostic, predictive, and prescriptive analytics features. For describing intelligent features, the prescriptive capability represents the key characteristics as one assessment factor for the articles' comparison. As outlined in Table 6, five MM literature explore prescriptive analytics feature out of 35 selected publications. The portion could represent considerably a gap area that opens a great possibility for further study.

From these articles, we learned to consider several ways to design the level of prescriptive analytics. As outlined in paper [18], seven guidelines were defined to provide an action plan in correlation with the descriptive measurement and determination using fuzzy rule-based and Monte-Carlo methods for the MM design based on smart operations and supply chain management. Although the methods aimed to eliminate ambiguity statistical uncertainties, the study suggests exploring an expert-system method for addressing the maturity gaps, business intelligence, and displaying a dashboard for a real-time capability within the organization.

The paper in [26] revealed the capability of knowledge-based maintenance (KBM) framework in assessing & diagnosing, prediction model building, decision support, planning, and lastly, execution and documentation. The study considered the quality path through quantified input, throughput, and output quality of each element, followed by assessing the effects on the quality of maintenance decision-making that interprets the KBM maturity. Despite the fact that the strong point of this study includes procedures within the KBM framework, the systematic road maps to improve the maturity of specific quality indicators towards desired maturity level are yet to be explored.

The [44] paper introduces the ecodesign maturity model, a framework to support the implementation by diagnosing the current maturity level for a company's product development and related processes.

The model proposes the most suitable ecodesign practices and improvement projects that are considered as prescriptive determination features. However, the study suggests including organizational factors such as organizational structure and culture, clear framework, and resources. We also identified various methods applied in the MMs such as comparative, cluster analysis, fuzzy logic-based, analytic hierarchy process, Monte Carlo simulation, discrete event simulation, and data-driven simulation. The statistical-based approach is commonly applied for most models, particularly for validation and verification purposes.

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3.8 I4.0 Maturity Model Structure and Stages

Considering the general representation of Maturity Models, the design structure mainly consists of two parts: (1) stages levels and (2) dimensions matrix. The stage levels determine the maturity hierarchy is formed through selecting criteria descriptions for the corresponding dimension variables.

As outlined in Table 7 and 8, this study reveals unique characteristics of each I4.0 MM. Table 7 defines stage 0 until stage 3 represents the fundamental capabilities of I4.0 and Table 8 outlines more sophisticated capabilities of I4.0 represented as stage 4 until 7.

Table 7. Stages of I4.0 Maturity Models (Stage 0 – 3)

Model	Stage 0	Stage 1	Stage 2	Stage 3
AIMI [53]	NA	Digitalization stage: Computerization	Digitalization stage: Connectivity	Industrie 4.0 stage: Visibility – What is happening? "Seeing"
IMPULS [54]	Newcomer stage: Outsider	Newcomer stage: Beginner	Learner stage: Intermediate	Leader stage: Experienced
PWC [55]	NA	Digital novice	Vertical integrator	Horizontal collaborator
AIMM [34]	NA	Stage 1: Not implemented	Stage 2	Stage 3
SIMMI [56]	NA	Basic digitization level: The company has not addressed Industry 4.0. Requirements are not or only partially met integration	Cross-departmental digitization: The company is actively engaged with Industry 4.0 topics. Digitization is implemented across departments, and first, Industry 4.0 requirements are implemented throughout the company.	Horizontal and vertical digitization: The company is horizontally and vertically digitized. Requirements of Industry 4.0 have been implemented within the company, and information flows have been automated.
IMRM [57]	Level 0: Absence	Level 1: Existence	Level 2: Survival	Level 3: Maturity
SIRI [58]	Band 0 Undefined	Band 1 Defined	Band 2 Digital	Band 3: Integrated
INDI [52]	Level 0	Level 1	Level 2	Level 3
M2DDM [59]	0 – Non-Existent IT Integration	1 – Data and System Integration	2 – Integration of Cross-Life-Cycle Data	3 – Service-Orientation

Each described level on these tables represents the current stage of maturity. The stage levelling can motivate the assessed company to act further by finding out the root causes within a diagnostic activity to determine an appropriate action plan for improving the I4.0 level. However, as seen in these tables, each model has distinctive way to define maturity level in term of: (1) number of defined stages, (2) starting and ending stages number, and (3) definition of each stage.

Table 8. Stages of I4.0 Maturity Models (Stage 4 – 7)

Model	Stage 4	Stage 5	Stage 6	Stage 7
AIMI [53]	Industrie 4.0 stage: Transparency – Why is it happening? "Understanding"	Industrie 4.0 stage: Predictive capacity – What will happen? "Being prepared"	Industrie 4.0 stage: Adaptability – How can an autonomous response be achieved? "Self-optimizing"	NA
IMPULS [54]	Leader stage: Expert	Leader stage: Top performer	NA	NA
	Stage 4	Stage 5	Stage 6	Stage 7
PWC [55]	Digital champion	NA	NA	NA
AIMM [34]	Stage 4	Stage 5: Fully implemented	NA	NA
SIMMI [56]	Full digitization: Company is completely digitized even beyond corporate borders and integrated into value networks.	Optimized full digitization: The company is a showcase for Industry 4.0 activities.	NA	NA
IMRM [57]	NA	NA	NA	NA
SIRI [58]	Band 4: Automated	Band 5 Intelligent	NA	NA
INDI [52]	Level 4	NA	NA	NA
M2DDM [59]	4 – Digital Twin	5 – Self-Optimizing Factory	NA	NA

3.9 I4.0 MM Dimensions and Elements

Through exploring the characteristics for each MM model for the I4.0, Table 9 outlined a list of models' dimensions and the corresponding elements/ variables. The analysis aimed to identify common dimensions which could be considered when defining or adapting the proposed MM. The MM dimensions area can be summarized as follows.

People and culture. The area covers human resources, employees, competencies, adaptability, openness to change, collaboration.

Organization and resources. This aspect covers management structure, strategy, tools and funding resources, leadership, management commitment, business model, innovation, governance, policy, and management systems.

Information systems. The area includes digitalization, integration, information processing, IT infrastructure, data management, cyber security, IT applications/ systems, information sharing.

Business processes. The area covers the value chain, functional/operational process, product lifecycle, production, development, logistics, services, and marketing & sales.

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Smart technology and products/services. The area includes autonomous processes, cloud usage, the internet of things, advanced robotics, additive manufacturing, augmented reality, digital twin. Smart products/ services cover the product's technology functionalities, data analytics usage, digital product development, intelligent products, data-driven services.

Table 9. I4.0 Maturity Models Dimensions and Elements

Model	Dimension	Element/ Variable
AIMI [53]	Resources	Digital capability
		Structured communication
	Information Systems	Information processing
		Integration
	Organization Structure	Organic internal organization
		Dynamic collaboration in value networks
	Culture	Social collaboration
		Willingness to change
	Corporate Process	Development
		Production
		Logistics
		Services
		Marketing & Sales
IMPULS [54]	Employees	Skill acquisition
		Employee skill sets
	Strategy & organization	Strategy
		Investments
		Innovation management
	Smart factory	Digital modeling
		Equipment infrastructure
		Data usage
		IT systems
	Smart operations	Cloud usage
		IT security
		Autonomous processes
		Information sharing
	Smart products	Data analytics in the usage phase
		ICT add-on functionalities
	Data-driven services	Share of data used
		Share of revenues
		Data-driven services
PWC [55]	Digital Business	Digital business model's customer access
		Digitization of product and service offerings
		Digitization & integration of vertical and horizontal value chains
	IT Infrastructure & Data	Data & Analytics as a core capability
		Agile IT architecture
	People & Org.	Compliance, security, legal and tax
		Organization, employees, and digital culture
AIMM [34]	Organization	Strategy
		Leadership
	Customers	Customers
	Products	Products
	Operations	Operations
	Organization	Culture
		People
		Governance
	Technology	Technology
SIMMI [56]	Integration	Vertical Integration
		Horizontal Integration
	Product	Digital Product Development
	Technology	Cross-sectional technology criteria
IMRM [57]	Smart product service	Smart products and services
	Smart business processes	Smart production and operations
		Production, logistics, and procurement
		R&D—Product development
		Smart marketing and sales operations
		After-sales service
		Pricing/Promotion
		Sales and Distribution channels
		Supportive operations
		Human resources
		Information technologies
		Smart finance
	Strategy and Organization	Business models
		Strategic partnerships
		Technology investments
		Organizational structure and leadership
SIRI [58]	Process	Operations
		Supply Chain
		Product Lifecycle
	Technology	Automation
		Connectivity
		Intelligence
	Organization	Talent readiness
		Structure & Management
INDI [52]	Management & Organization	Strategy & leadership
		Investments for I4.0
		Innovation policy
	People & Culture	Culture
		Openness to changes
		Competency development
		Product customization
	Product & Services	Data-driven services
		Intelligent product
	Technology	Digitalization
		Intelligent machines
		Connectivity
		Cybersecurity
	Factory Operations	Storage & sharing data
		Supply Chain & Smart logistics
		Autonomous processes
		Intelligent maintenance system
M2DDM [59]	Infrastructure & Data	Data Storage and Compute
		Service-oriented Architecture
	Integration	Information Integration
	Technology	Digital twin
		Advanced Analytics
		Real-time Capabilities

4. Conclusion

This paper explores various areas of intelligent maturity model research and characteristics of prominent MMs used specifically for assessing the I4.0 of a company. We found that MM is still an emerging topic indicated by increasing numbers of published academic articles in major academic publication databases. The study remarks the close link between I4.0 maturity model topic with the software engineering discipline. The linkage to Industry 4.0 area including smart manufacturing and digital transformation exists although it has less density, particularly because the topic has emerged only in the last ten years.

From the characteristic analytical perspective, we found that the descriptive type is typical of all MMs. Only a few models accounted for by less than 15% offered

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more advanced diagnostics, predictive, and prescriptive features. Various methods such as fuzzy rule-based combined with Monte-Carlo, expert-system, quality synthesis within knowledge-based maintenance (KBM) framework, and ecodesign maturity framework for deciding and prioritizing the improvement projects could be adapted to develop a model that applies a prescriptive analytics feature. A distinctive levels and related definition are found on the I40 maturity stages in describing advancement of each dimension and variables being measured.

The result of this literature review in this study revealed that maturity models are mostly-used designed in the descriptive analytics contexts. Few studies have applied advanced prescriptive analytics method including, Fuzzy rule-based analytical hierarchy, Knowledge Based, and Monte-Carlo methods and the expert-system method. The numerous I4.0 MM dimensions can be categorized into five areas: (1) people and culture, (2) organization and resources, (3) information systems, (4) business processes, and (5) smart technology and products or services. Lastly, as represented in most publications, we found many studies deductively adapting existing models developed by industry practices or academics for their empirical cases. These results are essential in designing an intelligent maturity model system. In the future, other evaluation dimensions can also be further explored.

To address these issues, we suggest further research that scrutinize (1) broader the online publication database sources such as by including Web of Science, Google Scholars, and ProQuest databases, (2) review the exclusion criteria during the article selection process, such as the inclusion of non-manufacturing, (3) enrich state of the art by comparing and contrasting the models such as based on the size of the firms, elaborating further for industry sectors, and the unit of analysis.

Ultimately, this study contributes to the literature by the presentation of conceptual research by comprehensively reviewing past MM concepts/models to identify new dimensions and operationalization approaches. Furthermore, it could address a new way of assessing a firm's maturity contributing to the applied research area.

References

[1] Rittinghouse, J. W., & Ransome, J. F., "Cloud Computing Implementation, Management, and Security", *CRC Press*, 2009.

[2] Zhang, Y., Zhang, G., Wang, J., Sun, S., Si, S., & Yang, T. "Real-time information capturing and integration framework of the internet of manufacturing things", *International Journal of Computer Integrated Manufacturing*, vol. 28, no. 8, pp. 811–822, 2005.

[3] Zheng, P., wang, H., Sang, Z., Zhong, R. Y., Liu, Y., Liu, C., Mubarok, K., Yu, S., & Xu, X. "Smart manufacturing systems for Industry 4.0: Conceptual framework, scenarios, and future perspectives", *Frontiers of Mechanical Engineering*, 2018.

[4] Bueno, A., Godinho Filho, M., & Frank, A. G. "Smart production planning and control in the Industry 4.0 context: A systematic literature review", *Computers and Industrial Engineering*, 2020.

[5] Felch, V., Asdecker, B., & Sucky, E. "Maturity Models in the Age of Industry 4.0 – Do the Available Models Correspond to the Needs of Business Practice?", *Proceedings of the 52nd Hawaii International Conference on System Sciences*, 2019.

[6] Kagermann, Wahlster, W., & Helbig, J. "Recommendations for implementing the strategic initiative INDUSTRIE 4.0", *Final Report of the Industrie 4.0 WG*, April. 2013.

[7] Butt, Javaid. "Exploring the Interrelationship between Additive Manufacturing and Industry 4.0", *Design*, 2020.

[8] Mittal, S., Khan, M. A., Romero, D., & Wuest, T. "Smart manufacturing: Characteristics, technologies and enabling factors", *Proceedings of the Institution of Mechanical Engineers, Journal of Engineering Manufacture*, 2017.

[9] Davis, J., Edgar, T., Graybill, R., Korambath, P., Schott, B., Swink, D., Wang, J., & Wetzel, J. "Smart Manufacturing", *Annual Review of Chemical and Biomolecular Engineering*, 2015.

[10] Phuyal, S., Bista, D., & Bista, R. "Challenges, Opportunities and Future Directions of Smart Manufacturing: A State of Art Review", *Sustainable Futures*, 2020.

[11] Gottschalk, P. "Maturity levels for interoperability in digital government", *Government Information Quarterly*, 2009.

[12] Kazanjian, R. K., & Drazin, R. "An empirical test of a stage of growth progression model", *Management Science*, 1989.

[13] Lasrado, L. A., Vatrapu, R., & Andersen, K. N. "Maturity Models Development in IS Research: A Literature Review", *Proceedings of the 38th Information Systems Research Seminar in Scandinavia (IRIS 38)*, 2015.

[14] Pöppelbuß, J., & Röglinger, M. "What makes a useful maturity model? A framework of general design principles for maturity models and its demonstration in business process management", *19th European Conference on Information Systems (ECIS)*, 2011.

[15] Lepenioti, K., Bousdekis, A., Apostolou, D., & Mentzas, G. "Prescriptive analytics: Literature review and research challenges", *International Journal of Information Management*. 2020.

[16] DuVarney, D. "Data analytics journey: where to start", *Baker Tilly*. https://www.bakertilly.com/insights/data-analytics-journey-where-to-start, accessed 10th Dec 2020. 2020.

[17] Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. "Systematic Reviews and Meta-Analyses: The PRISMA Statement (Flow diagram)", *Annulas of Internal Medicine*, 2009.

[18] Caiado, R. G. G., Scavarda, L. F., Gavião, L. O., Ivson, P., Nascimento, D. L. de M., & Garza-Reyes, J. A. "A fuzzy rule-based industry 4.0 maturity model for operations and supply chain management", *International Journal of Production Economics*. 2021.

[19] Pierin Ramos, Luiz Felipe, et al. "An Analysis of Maturity Models and Current State Assessment of Organizations for Industry 4.0 Implementation", *Procedia Manufacturing*, 2020.

[20] Ryan, William Gerard, et al. "Recognizing Events 4.0: The Digital Maturity of Events", *International Journal of Event and Festival Management*. 2020.

[21] Moura, Luciano Raizer, and Holger Kohl. "Maturity Assessment in Industry 4.0 – A Comparative Analysis of Brazilian and German Companies", *Emerging Science Journal*, 2020.

[22] Bendi, Deepthi, et al. "An Off-Site Construction Readiness Maturity Model for the Indian Construction Sector", *Construction Innovation*, 2020.

DOI: https://doi.org/10.29207/resti.v7i2.4588

[23] Lin, Tzu-Chieh, et al. "To Assess Smart Manufacturing Readiness by Maturity Model: A Case Study on Taiwan Enterprises." *International Journal of Computer Integrated Manufacturing*. 2019.

[24] Wagire, Aniruddha Anil, et al. "Development of Maturity Model for Assessing the Implementation of Industry 4.0: Learning from Theory and Practice", *Production Planning & Control,* 2020.

[25] Ellefsen, Anna Paula Tanajura, et al. "Striving for Excellence in AI Implementation: AI Maturity Model Framework and Preliminary Research Results", *Logforum,* 2019.

[26] Nemeth, Tanja, et al. "A Maturity Assessment Procedure Model for Realizing Knowledge-Based Maintenance Strategies in Smart Manufacturing Enterprises", *Procedia Manufacturing*, 2019.

[27] Benedetti, Miriam, et al. "Maturity-Based Approach for the Improvement of Energy Efficiency in Industrial Compressed Air Production and Use Systems", *Energy,* vol. 186, 2019.

[28] Sinnwell, Chantal, et al. "Maturity Model for Product Development Information", *Procedia CIRP*, 2019.

[29] Bertolini, Massimo, et al. "Maturity Models in Industrial Internet: A Review", *Procedia Manufacturing*, 2019.

[30] Werner-Lewandowska, Karolina, and Monika Kosacka-Olejnik. "Logistics 4.0 Maturity in Service Industry: Empirical Research Results", *Procedia Manufacturing*, 2019.

[31] Colli, M., et al. "A Maturity Assessment Approach for Conceiving Context-Specific Road-maps in the Industry 4.0 Era", *Annual Reviews in Control*, 2019.

[32] Gajsek, B., et al. "Using Maturity Model and Discrete-Event Simulation for Industry 4.0 Implementation", *International Journal of Simulation Modelling*, 2019.

[33] Nick, Gábor, et al. "Industry 4.0 Readiness in Hungary: Model, and the First Results in Connection to Data Application", *IFAC-PapersOnLine*, 2019.

[34] Schumacher, Andreas, et al. "A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises", *Procedia CIRP*, 2016.

[35] Maasouman, Mohammad Ali, and Kudret Demirli. "Development of a Lean Maturity Model for Operational Level Planning", *The International Journal of Advanced Manufacturing Technology*, 2015.

[36] O'Donovan, Peter, et al. "IAMM: A Maturity Model for Measuring Industrial Analytics Capabilities in Large-Scale Manufacturing Facilities", *International Journal of Prognostics and Health Management*, 2020.

[37] Alami, Oussama Marrouni, et al. "An Intelligent Project Management Maturity Model for Moroccan Engineering Companies", *Vikalpa: The Journal for Decision Makers*, 2015.

[38] Bititci, Umit S., et al. "Value of Maturity Models in Performance Measurement", *International Journal of Production Research*, 2014.

[39] Alvarez, Rodrigo L. P., et al. "Applying the Maturity Model Concept to the Servitization Process of Consumer Durables Companies in Brazil", *Journal of Manufacturing Technology Management,* 2015.

[40] Neff, Alexander A., et al. "Developing a Maturity Model for Service Systems in Heavy Equipment Manufacturing Enterprises", *Information & Management*, 2014.

[41] Hartono, Budi, et al. "An Empirically Verified Project Risk Maturity Model", *International Journal of Managing Projects in Business*, 2014.

[42] Yulistiawan, Bambang Saras, et al. "Maturity Model To Measure The Government Institutions Of Indonesia (The Environment Bureaucracy Of Education) In The Implementation Of E-Government", *Journal of Computer Science*, 2014.

[43] Ngai, E. W. T., et al. "Energy and Utility Management Maturity Model for Sustainable Manufacturing Process", *International Journal of Production Economics*, 2013.

[44] Pigosso, Daniela C. A., et al. "Ecodesign Maturity Model: A Management Framework to Support Ecodesign Implementation into Manufacturing Companies", *Journal of Cleaner Production*, 2013.

[45] Srai, Jagjit S., et al. "Understanding Sustainable Supply Network Capabilities of Multinationals: A Capability Maturity Model Approach", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 2013.

[46] Rapaccini, Mario, et al. "Service Development in Product-Service Systems: A Maturity Model", *The Service Industries Journal*, 2013.

[47] Haouzi, H. Bril El, et al. "Toward Adaptive Modelling & Simulation for IMS: The Adaptive Capability Maturity Model and Future Challenges", *IFAC Proceedings Volumes*, 2013.

[48] Meng, Xianhai, et al. "Maturity Model for Supply Chain Relationships in Construction", *Journal of Management in Engineering*, 2011.

[49] Krivograd, Nico, et al. "Development of an Intelligent Maturity Model-Tool for Business Process Management", *2014 47th Hawaii International Conference on System Sciences*, 2014.

[50] Xirogiannis, George, and Michael Glykas. "Intelligent Modeling of E-Business Maturity", *Expert Systems with Applications.* 2007.

[51] Hammer, Michael. "The Process Audit", *Harvard Business Review*, 2007.

[52] Kemenperin. "Indonesia Industry 4.0 Readiness Index", *Kementrian Perindustrian Republik Indonesia*, 2018.

[53] Schuh, Günther, Anderl, R., Gausemeier, J., Hompel, M. ten, & Wahlster, W. "Industrie 4.0 Maturity Index - Managing the Digital Transformation of Companies", *Acatech Study*, 2018.

[54] IW, Consult. "Industrie 4.0-Readiness-Check", *IMPULS*, RWTH Aachen. www.industrie40-readiness.de/?lang=en, 2021.

[55] PricewaterhouseCoopers. "Industry 4.0 - Self Assessment.", *PricewaterhouseCoopers*, i40-self-assessment.pwc.de/i40/_landing, 2015

[56] Leyh, C., Bley, K., Schäffer, T., & Bay, L. "The Application of the Maturity Model SIMMI 4.0 in Selected Enterprises", *AMCIS*, 2017.

[57] Akdil, Kartal & Ustundag, Alp & Cevikcan, Emre. "Maturity and Readiness Model for Industry 4.0", *Strategy,* 2018.

[58] Singapore Economic Development Board. "Frameworks & Tools", *SIRI*, www.siri.gov.sg/frameworks-tools, 2020.

[59] Weber, Christian, et al. "M2DDM – A Maturity Model for Data-Driven Manufacturing", *Procedia CIRP*, 2017.

DOI: https://doi.org/10.29207/resti.v7i2.4588