AI-Based Analysis for Industry 4.0 Maturity Models – A Systematic Review and Bibliometric Analysis

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Abstract

The fourth industrial revolution (industry 4.0) is a term used to describe the ongoing transformation of business processes combined with the latest technologies that are changing the way businesses operate, leading to the faster, cheaper, and effective delivery of products and services. Different companies and countries are preparing for this revolution by developing Industry 4.0 strategies. To assist the companies seeking to adopt Industry 4.0 in manageable phases, the maturity models (MMs) were created and used. However, in the context of Industry 4.0, literature reviews indicate that the number of models has increased sharply in recent years. This paper aims to present and analyze the results of bibliometric analysis and systematic literature review, which highlight the recent developments in the field of Industry 4.0 MMs, with a focus on investigating the existing models, their types, levels, and dimensions. Based on our findings, we introduced the core dimensions of the MMs that will require more intensive efforts to set the ground for the transformation journey, utilizing the power of AI and machine learning. This work will enable the scientific community to investigate the publication hierarchy in this emerging filed, and it will serve as a starting point for future MMs developments.

Keywords
industry 4.0, maturity model, bibliometrics analysis, artificial intelligence, and machine learning.

1. Introduction
The fourth industrial revolution, which is known as "industry 4.0" was coined by the German National Academy of Science and Engineering in 2011, to represent a proposed government-sponsored manufacturing digitalization project. However, industry 4.0 is focused on integrating a set of emerging technologies into industrial value chains to improve production efficiency, and make the product/service deliver faster, cheaper, more effective, and more sustainable that are consistent with the transformational goals.

Different companies and countries are preparing for the fourth industrial revolution by developing Industry 4.0 strategies, such as Germany's "Industry 4.0", China's "Made in China 2025", and the Kingdom of Saudi Arabia "National Industrial Development & Logistics Program – Industry 4.0 Strategy". To assist the companies seeking to adopt Industry 4.0 in manageable phases, the Industry 4.0 maturity models were created and used. A maturity model is a tool that assists companies in determining their maturity level based on domain-specific dimensions and describing the roadmap to achieving the desired maturity level to meet the organization's transformation goals. Dimensions are categories of criteria within the company that the model considers in relation to Industry 4.0 concept – such as organization, technology, and so on. The number of stages that a company must go through before fully implementing Industry 4.0 is referred to as maturity levels. Each level of maturity has its own set of criteria. In the context of industry 4.0, there are several maturity models developed by academia, industry, and governments where each model has different dimensions, sub-dimensions, and levels. The importance of industry 4.0 maturity models raised in recent years as they are providing the organizations with a broader understanding of industry 4.0 and implementation roadmap to be prepared for this revolution.

1.1. Objectives
The aim of this paper is to present a bibliometric analysis of the scientific publications and trends of maturity models in the context of Industry 4.0 and investigate the existing industry 4.0 maturity model, its types, levels, developers,

and dimensions with the help of a systematic literature review. In addition, we aim to introduce the core dimensions of Industry 4.0 based on the identified models, utilizing the power of AI and machine learning to assist companies in determining the core dimensions to establish and begin their transformation journey and get the benefits of Industry 4.0. After that, pointing to future research needs, to identify the main dimensions of industry 4.0 regardless of the company size, industry, and geographical location to set the ground for the transformation journey.

The organization of this paper is as follows: Section 2 describes the research method used; Section 3 presents the results of the bibliometric analysis, SLR and text clustering; Section 4 discusses the main findings of the study and their implications; Section 5 presents the final remarks of the paper and suggestions for future directions of research in the field of Industry 4.0 maturity models.

2. Methods

This research is the result of text clustering techniques, systematic literature review (SLR), and bibliometrics. Text clustering is an unsupervised machine learning algorithm that classifies a document collection into clusters based solely on the similarity relationship between documents in the collection. SLR is a type of analytic study that applies a structured methodology to identify, analyze, and interpret all available approaches to a specific research question. Bibliometrics, on the other hand, is a statical method for analyzing current trends in the literature in a specific area and providing guidelines and motivations for future research.

Our review carries out a bibliometric analysis and SLR of industry 4.0 MMs research based on the research publications from Web of Science (WoS) during the year 2013–2021. With 1956 papers reviewed, 400 that met the review requirements were included and 1556 were excluded. For the bibliometric analysis, we used an open-source R-tool called bibliometrix. Furthermore, we used a data science platform called Rapidminer to build the machine leering model for text clustering.

2.1. Planning the review

This phase involves identifying the objectives of performing this study, which is to give researchers a clear and objective view of the current state of research on maturity models in the context of Industry 4.0.

2.1.1. Research questions

The guiding research questions for this systematic literature review are:
RQ1: What are the thematic change and evolution of Industry 4.0 maturity models research?
RQ2: What are the available industry 4.0 maturity models that have been developed by academia, industry, or governments?
RQ3: What are the main dimensions of the identified industry 4.0 maturity models?

2.1.2. Development and validation of the review protocol

To define the search string, we selected a set of keywords from studies about industry 4.0 maturity models and matched them with our research questions. We also established synonyms and alternative spellings and optimized the keywords iteratively. We tested the set of keywords in different databases and refined it. Using Boolean operators to connect the keywords, we defined the following search string and inclusion criteria as shown in Table 1.

Table 1. Search boundaries and inclusion criteria

Sources	Web of Science , Google Scholar, Consulting companies' websites.
Search String in Web of Science (WoS)	
((((((TS=("Industry 4.0"AND "Maturity")) OR TS=(("Industry 4.0"AND "model"))) OR TS=(("Industry 4.0"AND "readiness"))) OR TS=(("Industry 4.0"AND"framework"))) OR TS=(("Industry 4.0"AND "index"))) OR TS=(("Industry 4.0"AND "roadmap"))) OR TS=(("Industry 4.0"AND "Capability"))	
Inclusion Criteria	
Document type	Articles or Proceedings Papers or Review Articles or Book Chapters
Language	English
Timeline	2013-2021
Web of Science Index	Social Sciences Citation Index (SSCI) or Science Citation Index Expanded (SCI-EXPANDED)
Research Areas	Engineering or Computer Science or Operations Research Management Science or Business Economics
Publishers	Emerald Group Publishing or Springer Nature or Taylor & Francis or IEEE or Mdpi or Elsevier
Web of Science Categories	Engineering Industrial or Engineering Manufacturing or Engineering Electrical Electronic or Computer Science Information Systems or Computer Science Interdisciplinary Applications or Automation Control Systems or Management or Computer Science Theory Methods or Operations Research Management Science or Computer Science Artificial Intelligence or Telecommunications or Engineering Multidisciplinary or Green Sustainable Science Technology or Business or Industrial Relations Labor or Transportation Science Technology or Engineering Biomedical or Engineering Chemical or Computer Science Software Engineering or Robotics or Engineering Mechanical

2.2. Conducting the review

Based on the above review protocol, we conducted the review process using the following steps illustrated in Figure 1. Our search strategy included the following procedures: (i) searching and extracting the studies using the search string and published from 2013 to 2021 (ii) eliminating the duplicate studies; (iii) filtering publications using inclusion and exclusion criteria; (iv) filtering publications by title and abstract; (v) reading the selected papers; and (vi) extracting data and synthesizing the results.

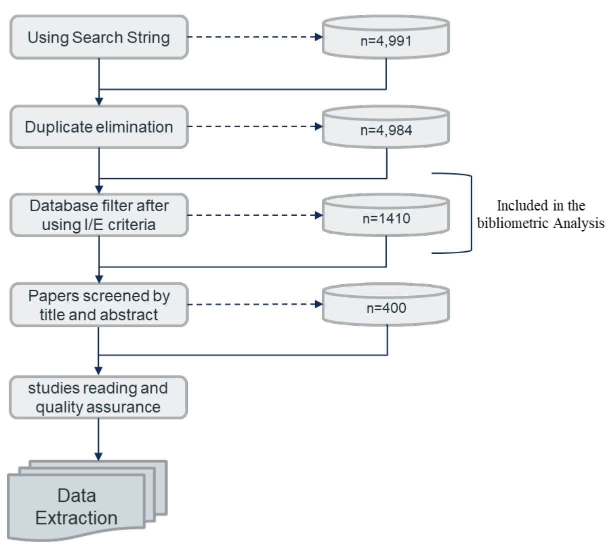

Figure 1. Strategy for search and filtering in the SLR

3. Results

Following the research objectives of this review paper, the bibliometric analysis, and the systematic literature review of targeted articles on Industry 4.0 maturity models highlights three main findings: the thematic change and evolution of Industry 4.0 maturity models research, listing of the different types of Industry 4.0 maturity models, and identifying the core dimensions of the identified models. These findings are further reiterated in this section.

3.1 Thematic Change and Evolution of Industry 4.0 MMs Research

3.1.1. Research growth

The increasing number of publications on the Web of Science database related to Industry 4.0 maturity models have been gaining rapid attention. Figure 2 shows the number of publications in Web of Science (WoS) database for each year from 2015 to 2021. The lowest number of publications came out in 2015 with 1 paper. Later, it increased exponentially till it reached the maximum of 696 in 2021.

Figure 3 shows the average number of citations per year. The average number of citations hit its peak in 2016, with a mean total number of citations (TC) of 26.81 per year. In the following year, 2017, the average TC dropped to 14.71. Then, it fluctuates until 2020, which is because these publications are relatively newer, and their citation counts will surely rise in the coming years.

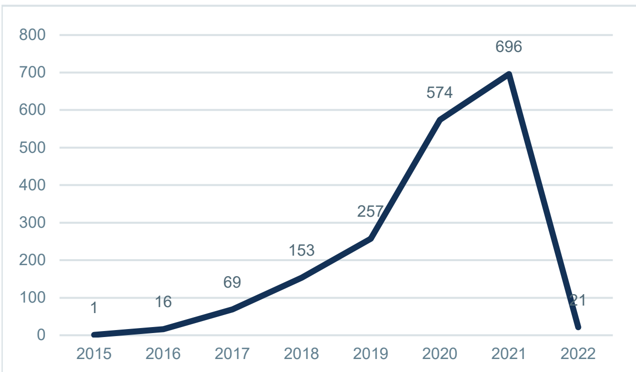

Figure 2. Total number of publications in WoS

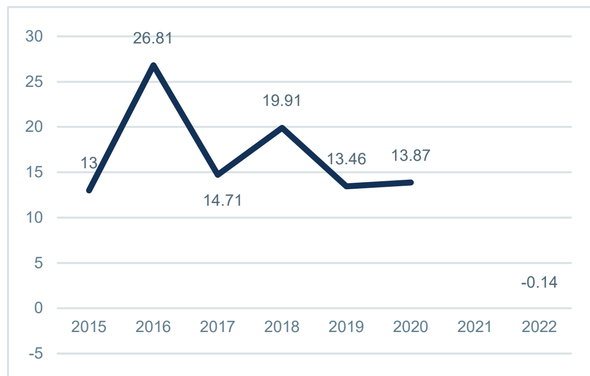

Figure 3. Average number of citations per year

3.1.2. Thematic Evolution and Research Trends

The occurrence and co-occurrence of keywords can reflect themes focused in a special field to some extent. Figure 4 shows the top 10 keywords with a high frequency of occurrence, which are framework (548), model (507), management (439), industry 4.0 (421), future (416), design (406), internet (242), systems (369), big data (281), system (271). The connected network of co-occurrence relationships among 50 keywords is visualized in Figure 5 using Louvain community detection method, which is a clustering algorithm that can quickly find clusters with high modularity in large networks. The keywords in the various clusters are coloured differently. The size of nodes can reflect the frequency of keywords: the larger the node, the higher the frequency of keywords. The closeness of connections between two keywords is proportional to the thickness of the line between them. The thinker lines between keywords like Industry 4.0 and framework, Internet, and things, and future and challenge, as shown in Figure 5, represent a closer relationship.

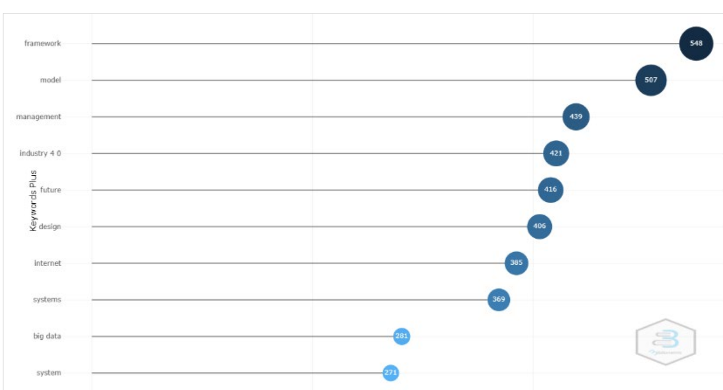

Figure 4. Top 10 keywords with a high frequency of occurrence

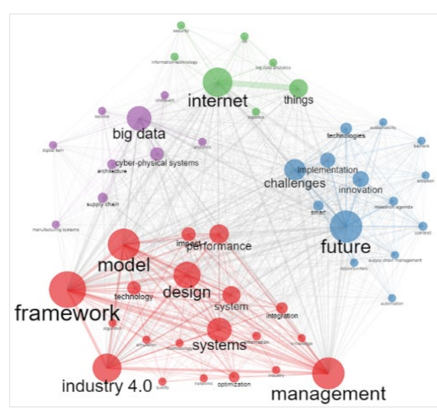

Figure 5. Keyword co-occurrence network

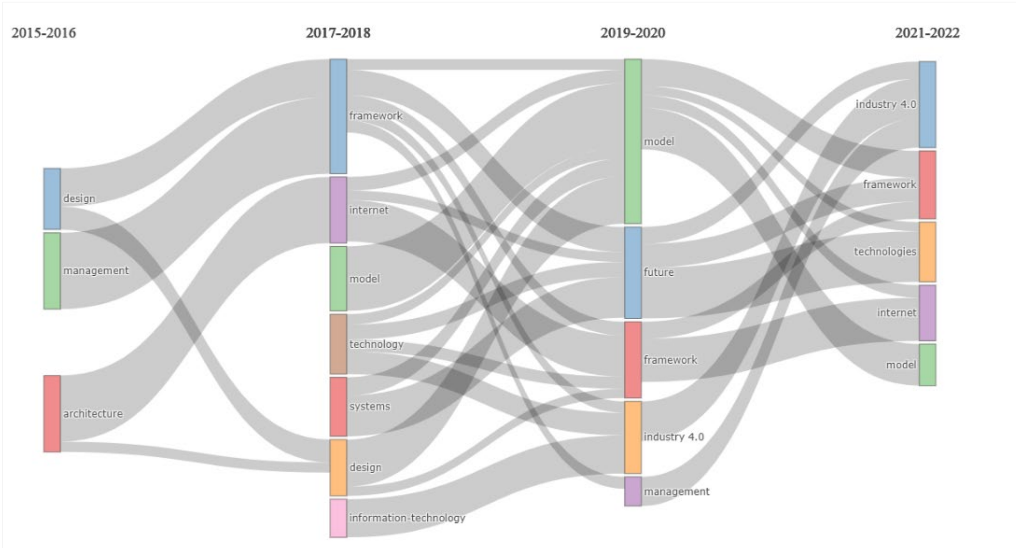

Figure 6. Thematic Revolution

To discover the thematic change and evolution for industry 4.0 research field an analysis of the evolution of the themes detected over three periods from 2015-2022 based on their keywords. Figure 6 shows that the internet, industry 4.0, framework, and model are among the major thematic areas identified. Some thematic areas, such as the model and framework are present in the research over two periods, as shown in Figure 6. Some thematic areas, such as industry 4.0 and future, appear in later periods.

3.1.3. Productivity and Collaboration Networks of Authors, Countries, and Institutions

Figure 7 is showing the 10 most productive authors with the highest citation impact. The highest contributor is XU X., who has an h-index of 13, followed by LIU C., LI D., LU Y., and WANG S. who have an h-index of 10, 9,9, and 8, respectively. Five authors in the top ten list have the same h-index, which is 7. FRANK AG, IVANOV D, LI X, LIU Y, MUELLER JM, and WAN J are the authors.

Scientific collaboration is a distinguishing feature of modern research, as more and more scholars work as part of teams rather than as individuals. To assess collaboration trends and to identify leading scientists, the authors were assessed in terms of their strong tendency for collaborating. Figure 8 illustrates the co-authorship network. Only the first 20 authors and at least one co-authored publication were considered, ensuring that only the strongest connections were represented. We presented three distinct author groups. Each of the two largest groups has four authors, followed by one group with two authors.

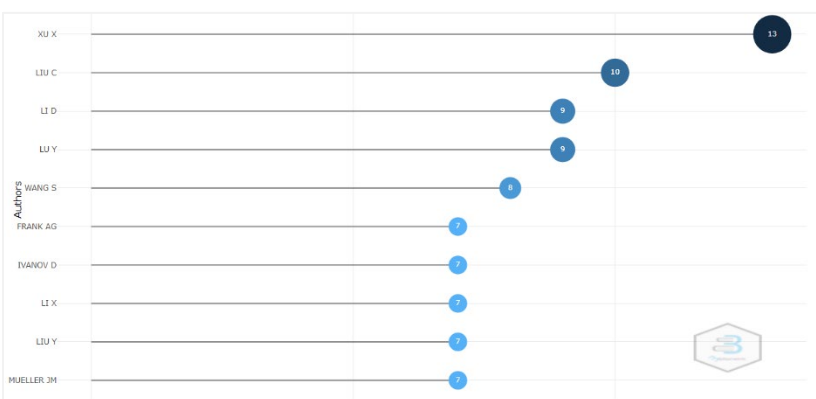

Figure 7. Author local impact by H index

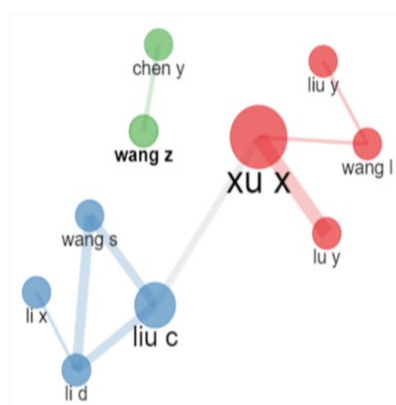

Figure 8. Collaboration Network

Table 2 shows the top 20 most productive countries in terms of the number of publications and citations from WoS. However, China tops the list both in terms of both the total number of publications (TP) and the TC with 1177 publications, followed by seven countries with more than 300 publications, which are Italy, India, UK, Spain, USA, Brazil, and Germany. On the other side, we can observe that the rank by the TC is totally different where the USA is in 2nd position instead of Italy, with 3775 citations, followed by Italy, Germany, Brazil, and UK with 2991, 2729, 2321, and 1828 citations, respectively.

Table 2. Top 20 countries publishing work on Industry 4.0 in WoS

Rank	Region/ Country	TP	Rank	Region/ Country	TC	ACd
1	CHINA	1177	1	CHINA	5111	15.35
2	ITALY	594	2	USA	3775	43.9
3	INDIA	449	3	ITALY	2991	15.91
4	UK	429	4	GERMANY	2729	29.99
5	SPAIN	370	5	BRAZIL	2321	25.23
6	USA	368	6	UNITED KINGDOM	1828	16.77
7	BRAZIL	312	7	NEW ZEALAND	1401	93.4
8	GERMANY	306	8	INDIA	1251	10.78
9	FRANCE	207	9	FRANCE	1236	25.22
10	PORTUGAL	185	10	SPAIN	1022	9.38
11	AUSTRALIA	165	11	SWITZERLAND	766	63.83
12	POLAND	152	12	KOREA	725	16.48
13	SOUTH KOREA	152	13	AUSTRALIA	585	11.47
14	TURKEY	132	14	IRAN	582	32.33
15	SWEDEN	128	15	SWEDEN	558	20.67
16	CANADA	103	16	NORWAY	505	26.58
17	MALAYSIA	90	17	PORTUGAL	464	9.67
18	AUSTRIA	85	18	FINLAND	402	30.92
19	GREECE	77	19	AUSTRIA	395	17.17
20	PAKISTAN	74	20	HUNGARY	356	15.48

TP = publications, TC = citations, ACd = average citations per document

Figure 9 illustrates a more comprehensive view of collaboration among the first 20 countries. Furthermore, we used the community detection algorithm to find a group of countries with a similar collaboration pattern. However, we notice that there are two distinct communities. The first one shows that Chinese authors collaborated with researchers from the United Kingdom, the United States, India, Turkey, Korea, Pakistan, Australia and Malaysia. On the other hand, we noticed that the other community is connected to European countries, Canada, and Brazil, due mainly to their strong historical, cultural, economic, and political ties.

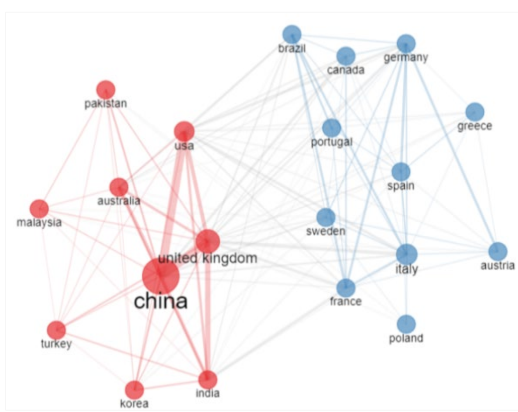

Figure 9. Country collaboration network

An in-depth analysis of the authors' affiliation demonstrates additional insights into the history and evolution of Industry 4.0. The top ten most productive Affiliations in terms of the number of publications are listed in Table 3. We observe that three out of the top ten most productive universities are Chinese where China is the most productive country. On the other hand, we can see that two of the top ten institutions are in Italy, and one of them are in United Kingdom, both of which are in the top 20 countries in terms of the number of publications. Although New Zealand, Norway, and Hong Kong are not listed among the top 20 most productive countries, three universities located in these countries, are listed.

Table 3. Top 10 most important institutions in terms of publications

Rank	Affiliations	Country / Region	TP
1	UNIV CAMBRIDGE	United Kingdom	41
2	BEIHANG UNIV	China	39
3	UNIV AUCKLAND	New Zealand	38
4	SOUTH CHINA UNIV TECHNOL	China	35
5	UNIV POLITECN MADRID	Italy	34
5	SHANGHAI JIAO TONG UNIV	China	33
6	HONG KONG POLYTECH UNIV	Hong Kong	31
7	UNIV PADUA	Italy	31
8	ZHEJIANG UNIV	China	31
8	NORWEGIAN UNIV SCI AND TECHNOL	Norway	30

TP = publications

3.2 Listing the Different Types of Industry 4.0 Maturity Models

Table 4 shows the results of our analysis of 32 Industry 4.0 maturity models. The majority of them were developed by academia (17), followed by industry (12), and governments (3), respectively. Furthermore, Germany is the leading player in the development of maturity models, with 9 of the 32 modes developed by the country. We can see that the manufacturing industry appears to be a major focus for the developers. There are 161 dimensions identified, as each model has its own set of dimensions. These dimensions are associated with various aspects of the business, such as processes, employees, technology, products/services, strategy, and so on. The models have either 4,5 or 6 maturity levels, with the majority of them (14) having five maturity stages. However, some of the developers did not share their maturity levels publicly.

Table 4. List of Industry 4.0 Maturity Models

Model Name	Year	Type	Country	Industry	Dimensions	Levels	Model Developer Reference
Fraunhofer Industrie 4.0 Layer Model	2013	Industry	Germany	Manufacturing	Enterprise Transformation, Information & Communication, Data-driven Technologies	5	(Neugebauer et al., 2016)
Industry 4.0 Barometer	2014	Industry	Germany	Manufacturing	Technology, IT Integration, Strategy & Goal, Drivers & Barriers, 5G & Cloud Services	N/A	(Thomas Klüe & Andreas Stangl, 2020)
Roland Berger Industry 4.0 Readiness Index	2014	Industry	Germany	Manufacturing	Industrial excellence, value network	5	(Berger Strategy Consultants et al., 2014)
Digital Economy and Society Index (DESI)	2014	Government	European Union	Manufacturing	Connectivity, Human Capital, Use of Internet, Integration of Technology, Digital Public Services	N/A	(European Commission, 2014)
Reference Architecture Model for the Industry 4.0 (RAMI4.0)	2015	Industry	Germany	Manufacturing	Hierarchy Levels, Life Cycle & Value Stream, Layers	N/A	(Karsten Schweichhart, 2016)
The McKinsey Digital Compass Maps Industry 4.0	2015	Industry	United State	Manufacturing	Resource/processes, Asset utilization, Labor, Inventories, Quality, Supply/demand matching, Time to market, Service/aftersales	N/A	(Cornelius Baur et al., 2015)
IMPLUS	2015	Industry	Germany	Mechanical Engineering & Manufacturing	Strategy & organization, Smart factory, Smart products, Smart operations, Data-driven services, Employees	6	(Lichtblau et al., 2015)
PWC Industry 4.0 Maturity Model	2016	Industry	Global	Multiple Industry	Digital business models & customer access, Product & Service, Value Chains & Processes, Data & Analytics, Agile IT architecture, Compliance, security, legal & tax, Organization, employees, & culture	4	(PWC, 2016)
SIMMI 4.0–System Integration Maturity Model Industry 4.0	2016	Academia	Germany	Information Technology and Services	Vertical integration, Horizontal integration, Digital product, Cross-sectional technology	5	(Leyh et al., 2016)
Roadmap Industry 4.0	2016	Academia	Austria	Manufacturing	Purchasing, Production, Intralogistics, Sales, Human	5	(Pessl et al., 2020)
Industry 4.0 maturity model for Industrial Enterprises	2016	Academia	Austria	Manufacturing	Products, Customers, Operations,Technology,Strategy,Leadership,Governance,Culture, People	5	(Schumacher et al., 2016)
EY – Digital Readiness Assessment	2016	Industry	United Kingdom	Multiple Industry	Strategy, innovation & Growth, Customer Experience Supply Chain & Operations, Finance, Legal, Tax, & HR, Information Technology, Risk and Cybersecurity, People and Organization	5	(Ernst & Young, 2018)
ACATECH Industrie 4.0 Maturity Index	2017	Industry	Germany	Multiple Industry	Resources, Organizational structure, Culture, Information system	6	(Schuh et al., 2017)
Industry 4.0 Maturity Model-SPICE	2017	Academia	Turkey	Manufacturing	Asset Management, Data Governance, Application Management, Organizational Alignment, Process Transformation	6	(Gökalp et al., 2017)
Industry 4.0 Readiness Model for Tool Management	2017	Academia	Germany	Manufacturing	Competencies, Databases, Tool Identification, Time Horizon of Data, Location of Data Use, Residual Tool Life, Degree of Networking, IT-Security, Degree of Standardization	5	(Schaupp et al., 2017)
An Industry 4 Readiness Assessment Tool	2017	Academia	United Kingdom	Manufacturing	Products and Services, Manufacturing &Operations Strategy & Organization, Supply Chain, Business Model, Legal Considerations	4	(Onur Agca et al., 2017)
DREAMY Digital Readiness Assessment Maturity model	2017	Academia	Italy	Manufacturing	Process, Monitoring & Control, Technology, Organization	5	(de Carolis et al., 2017)
The Singapore Smart Industry Readiness Index (SIRI)	2017	Government	Singapore	Manufacturing	Technology, Process, Organization	6	(Lim Kok Kiang et al., 2017)
Deloitte – Digital Maturity Model (DMM)	2018	Industry	United Kingdom	Telecommunication	Customer, Strategy, Technology, Operations, Organization & Culture	5	(Deloitte, 2018)
Industry 4.0 Maturity Model	2018	Academia	United Kingdom	Defense Manufacturing	Strategy, People & Culture, Factory of the Future	4	(Bibby & Dehe, 2018)
BMS Smart Industry Research Roadmap	2018	Academia	Netherlands	Manufacturing	Technology, Business, Society, People	4	(Techn, 2018)
Industry 4.0 Maturity Model	2018	Academia	Turkey	Multiple Industry	Smart Products & Services, Smart Business Processes, Strategy and Organization	4	(Akdil et al., 2018)
Readiness for Industry 4.0	2018	Academia	Germany	manufacturing	Technology, Management & strategy, Employees, Production & Logistics, Interfirm cooperation	4	(Horvat et al., 2018)
Industry 4.0 Readiness Model for Manufacturing	2018	Academia	Thailand	Food	Manufacturing & Operation, Technology, Employee, Strategy, Supply chain, Customer, Products	N/A	(Methavitakul & Santiteerakul, 2018)
BCG – Digital Acceleration Index (DAI)	2018	Industry	US	Multiple Industry	People & Organization, Data & Analytics, Technology, Ecosystem	4	(BCG, 2018)
KPMG – Digital Readiness Assessment	2018	Industry	Netherlands	Manufacturing	IT, Governance & risk management, Strategy & Business model, Employees & Competencies, Systems & Processes, Services & Network	N/A	(KPMG, 2018)
SSCM Assessment for Industry 4.0	2019	Academia	India	Manufacturing	Business, Technology, Sustainable Development Collaboration, Management Strategy	N/A	(Manavalan & Jayakrishna, 2019)
Assessment Model for Organizational Adoption of Industry 4.0 Based on Multi-criteria	2019	Academia	Turkey	Multiple Industry	Manufacturing & Operations, Strategy & Organization, Products & Services, Supply Chain & Industry 4.0 Integration, Business Model, Legal Considerations	5	(Demircan Keskin et al., 2019)
Maturity model for Industry 4.0 Assessment for SMEs	2019	Academia	Portugal	Manufacturing SMEs	Technology, Production Processes, People, Smart Product, Organization, Change	5	(Soares Branco Cardoso do Amaral & Miguel Nogueira Peças, 2019)
Industry 4.0 Readiness in the Chemical industry sector	2020	Academia	Indonesia	Manufacturing	Smart factory, Smart products, Employees, Digitization & value chain integration, Strategy & organization, Compliance, security, legal & tax, Culture, Leadership, Business model	5	(Mayusda & Wiratmadja, 2020)
BHARAT 4.0- Digital Readiness Assessment Tool	2021	Government	India	Multiple Industry	Manufacturing, Digitalization, Organization	5	(National Productivity Council, 2021)
Maturity Model for Smart Manufacturing Enterprises	2021	Academia	Turkey	Manufacturing	Factory, Logistics, Operator, Management	5	(Murat Çınar et al., 2021)

3.3 The main dimensions of the identified industry 4.0 maturity models

The identified models have a huge number of dimensions (161) for measuring Industry 4.0 maturity, making it challenging for companies to figure out which are the most important to consider when starting their transformation journey. In order to tone down the volume of the models' dimensions and easily understand the broader spectrum, we used the power of machine learning and natural language processing to group a set of dimensions in such a way that dimensions in the same group are more similar to each other than dimensions in other groups. Figure 10 illustrates the general framework for text clustering:

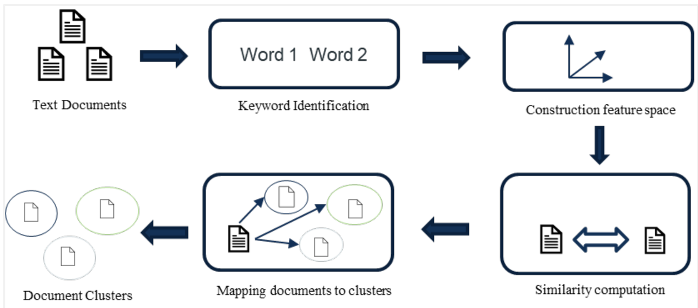

Figure 10. The main framework for text clustering system by (Liu et al., 2012), recreated for this paper.

The text clustering algorithm goes through five stages presented in Table 5, as follow: (i) Get the Text Data; (ii) Text Processing; (iii) Vectorization (TF-IDF); (iv) K-Means Clustering; and (v) Find the Optimal Number of Clusters.

Table 5. Text clustering algorithm stages

1.Extract the data	Read the file contain the models' dimensions files type used is. xlsx
2.Text Processing	Tokenizes a document: splits the text of a document into a sequence of tokens Information Technology → Information | Technology
	Transforms cases :transforms all characters in a document to lower case Technology → technology
	Filter Stopwords :Removes English stopwords from a document. models | and | customer → models | customer
	Stem (Porter) : Stemming is a technique used to extract the base form of the words by removing affixes from them technology | technologies → technolog
	Filter Tokens (by Length) : filters tokens based on the number of characters they contain (e.g. Min:4 and Max: 21)
3.Vectorization - (TF-IDF)	Term Frequency-Inverse Document Frequency (TF-IDF) : It's a tool to determine the importance of words within a document and across a group of documents all at the same. $TF{-}IDF(t,d)=TF(t,d)\times IDF(t)$ $TF(t,d) = \frac{Number\ of\ times\ t\ appears\ in\ d}{Total\ number\ of\ words\ in\ d}$ $IDF(t) = \log\frac{Total\ number\ of\ documents}{Number\ of\ documents\ contain\ t}$
4. K-Means Clustering	The k-means algorithm determines a set of k clusters and assigns each Examples to exact one cluster. The clusters consist of similar Examples. The similarity between Examples is based on the Euclidean Distances measure between them (Suwanda et al., 2020), K-means algorithm is an iterative approach.
5. Find the Optimal Number of Clusters	It starts by compute clustering algorithm for different values of k.then, For each k, calculate the average distance within cluster .after that, Plot the curve of avg.distance according to the number of clusters k. Finally, the location of a bend (knee) in the plot is generally considered as an indicator of the appropriate number of clusters.

In order to get the optimal number of clusters (k), we compute different values for k from 1 to 20 and calculate the average distance within a cluster. After that, we plot the curve shown in Figure 11. When k = 7, the slope of the graph starts to get more stable, making it an appropriate candidate parameter for clustering the data.

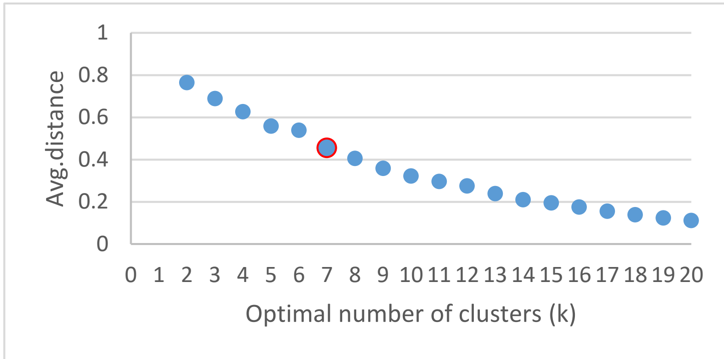

Figure 11. Elbow graph for k-means clustering.

Figure 12 shows the seven clusters that were created. Each cluster has a different number of dimensions grouped, as can be seen. Cluster 0 has four dimensions, cluster 1 has seven dimensions, cluster 2 has six, and etc. However, the centroid or main maturity dimensions for each cluster can be highlighted as follows: **Cluster 0 :** digital, integration ,and manufacturing; **Cluster 1:** value, smart, and product; **Cluster 2:** supply, chain, and legal; **Cluster 3:** data , business, people ; **Cluster 4:** management, employee, and factory; **Cluster 5:** culture, customer, strategy; **Cluster 6:** process, organization, technology. We can observe that some dimensions have the same meaning (synonym) but different words such as people and employee, factory and manufacturing.Thus, it mapped to different clusters.

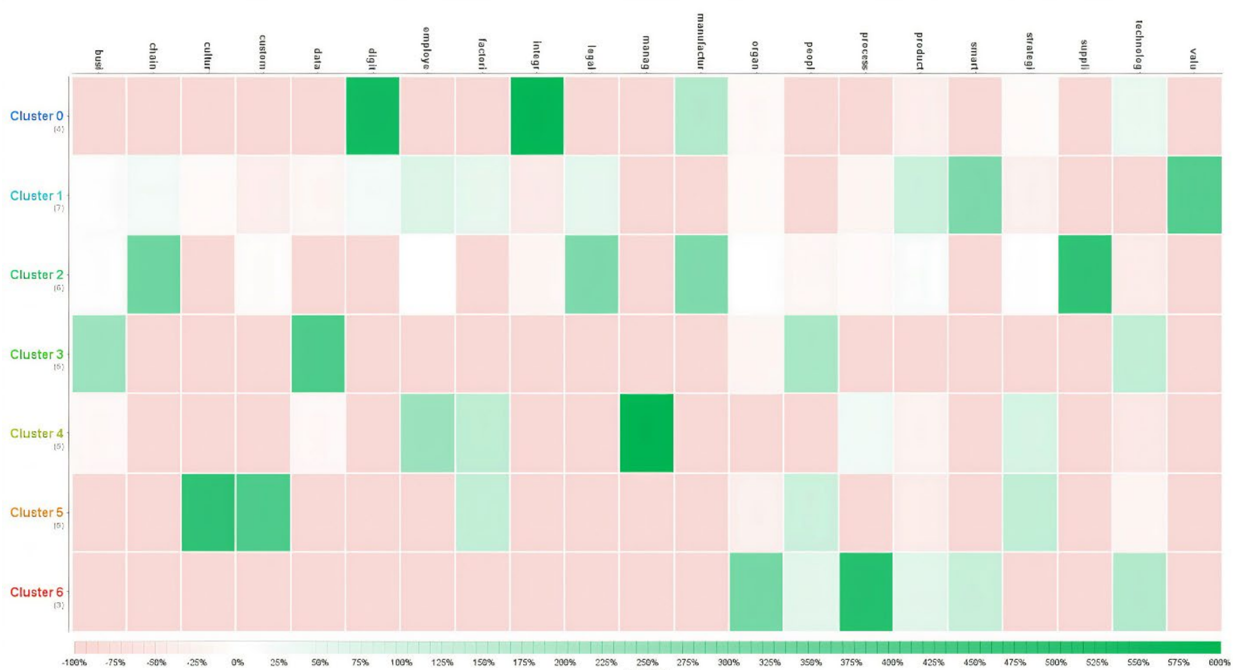

Figure 12. The seven clusters for the maturity models' dimensions

4. Discussion

This study presented significant findings that delineate how the development of maturity models to support industry 4.0 adoption has progressed in the last decade. In this discussion, we highlight the significance of the main findings identified, comparing the evolution of the field, primary contributions, and research directions to address gaps identified. This section will lead the discussion in the same order as the research questions listed.

4.1 RQ1: What are the thematic change and evolution of Industry 4.0 maturity models research?

In this paper, a detailed bibliometric analysis in the emerging field of Industry 4.0 maturity models has been conducted. WoS was used to conduct the quantitative analysis for 1,956 publications. the number of publications reaches the maximum in 2021. Furthermore, the connected network of co-occurrence relationships among 50 keywords is visualized. Additionally, an analysis of the evolution of the themes detected over three periods from 2015-2022 based on their keywords. Productivity and collaboration Networks of authors, countries, and institutions analyzed. The structure of the publications on maturity models in the context of Industry 4.0 was revealed through bibliometric analysis in this paper. This is a highly needed study for an emerging field like Industry 4.0, as it will allow the scientific community to investigate the publication hierarchy in this area.

4.2 RQ2: What is the available industry 4.0 maturity models that have been developed by academia, industry, or governments?

The developer origin country, developer type (industry/academic/governments), dimensions, and maturity levels of 32 industry maturity models are presented and analyzed. Most of the models were created by academics. In addition, Germany is a pioneer in the development of maturity models. The manufacturing industry is the most important in terms of industry. A total of 161 dimensions have been identified. Furthermore, the majority of the models have five levels of maturity. This review can be used as a starting point for future maturity model developments in Industry 4.0.

4.3 RQ3: What are the main dimensions of the identified industry 4.0 maturity models?

In this paper, we toned down the volume of the maturity models' dimensions by utilizing the power of AI and machine learning to enable companies seeking to adopt Industry 4.0 to easily understand the broader spectrum of this industrial revolution. We created the clusters using the k-means clustering algorithm, which grouped the similar models' dimensions, resulting in a reduction of 161 dimensions. The main dimensions extracted from the clustering are digital integration, manufacturing/factory, smart products, value chain, supply chain, legal, data, people/employee, business, management, culture, strategy, customer, organization, process, and technology. We observe that some dimensions like people and employees have the same meaning (synonym) but different words. Thus, it is mapped to different clusters. To eliminate the duplication of dimensions in the clusters we suggest extracting the synonyms and replacing the words with their common synonyms before going through the clustering process.

5. Conclusion

This review aimed to show how the development of maturity models in the context of industry 4.0 has progressed in the last decade. In addition, the thematic change and evolution of the research field are highlighted. To identify which models, show the greatest potential for implementation in industry 4.0 readiness and maturity, 32 different maturity models with a total of 161 dimensions have been identified and analyzed utilizing a set of predefined attributes such as origin country, industry scope, dimensions, maturity levels, and developer type. Our findings show a growing interest in the subject during the review period. To assist the companies in determining the core dimensions out of the 161 dimensions identified, AI and machine learning are used to propose the main dimensions of the identified models that will assist the companies to establish and start their transformation journey and get the benefits of Industry 4.0. As part of future work, it is planned to use advanced methods to identify the core capabilities that are necessary for any company to remain competitive within this industrial revolution regardless of its size, industry, and geographical location.

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