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Industry 4.0: A bibliometric analysis and detailed overview

Pranab K. Muhuri [a,*], Amit K. Shukla [a], Ajith Abraham [b]

[a] Department of Computer Science, South Asian University, New Delhi 110021, India
[b] Machine Intelligence Research Labs (MIR Labs), 3rd Street NW, P.O. Box 2259, Auburn, WA 98071, USA

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ABSTRACT

With the arrival of Industry 4.0, the overall transformation using digital integration and intelligent engineering has taken a giant leap towards futuristic technology. All devices today are equipped with machine learning, automation has become a priority and thus another industrial revolution is in the making. In this state-of-the-art paper, we have performed bibliometric analysis and an extensive survey on recent developments in the field of "Industry 4.0". In bibliometric analysis, different performance metrics are extracted, such as: total papers, total citations, and citation per paper. Further, top 10 of the most productive and highly cited authors, major subject areas, sources or journals, countries, and institutions are evaluated. A list of highly influential papers is also assessed. Later on, a detailed discussion of the most cited papers is analysed and a sectional classification is provided. This paper summarizes the growth structure of Industry 4.0 during the last 5 years and provides the concise background overview of Industry 4.0 related works and various application areas.

1. Introduction

The fourth industrial revolution is upon us and is making rapid strides day by day. In the eighteenth century, the first industrial revolution brought major changes in industries by utilizing steam as the source of power. The second industrial revolution used electric power and the assembly line for mass production. Integration of information technology and computers in manufacturing was seen in the third industrial revolution. Now, the fourth industrial revolution is around the corner, which is said to take us to the next level of manufacturing where machines will redefine themselves in the way they communicate and perform individual functions. Fig. 1 depicts the transformation that takes place.

However, the fourth industrial revolution, commonly termed as industry 4.0, is not just about industry. It is about overall transformation using digital integration and intelligent engineering. It is quoted as the next level of manufacturing where machines will redefine themselves in how they communicate and perform individual functions. The notion of Industry 4.0 was coined by Kagermann et al. (2011) which fuses the virtual and the real world with emphasis on engineering applications such as robotics, digitization, and automatization. For any system to be regarded as Industry 4.0, constant connectivity, human assistance and decentralized decision making are absolute necessities. The essential components of Industry 4.0 comprised cyber–physical systems (CPSs), additive manufacturing, virtual and augmented reality, cloud computing, big data analytics, data science etc. to name a few. Various studies have shown that digitization of products and services has become a necessity for a sound industrial ecosystem. However, these requirements and advanced technologies have made the systems more complex and led to many other challenges such as information security, reliability, integrity, etc. These are the major bottlenecks which needs to be overcome for the successful design and deployment of Industry 4.0.

Bibliometric or the Scientometric analysis is the research area which helps to analyse current trends in the literature regarding a particular area and provides guidelines and motivations for future research work. It basically provides a general outline and overall structure of the research area. In the past, Pritchard (1969) and Broadus (1987) have given us an accurate definition of Bibliometric study. Later, Heck and Bremser (1986) extended the work by performing an analysis on authors and institutions in the accounting field. In recent times, various researchers have analysed various emerging topics such as heuristics (Loock and Hinnen, 2015), big data (Huang et al., 2015; Prathap, 2013), decision support systems (Arnott and Pervan, 2005), fuzzy decision making (Blanco-Mesa et al., 2016) real-time operating systems (Shukla et al., 2018), etc. Apart from the topic centric bibliometric analysis, several works on Journal specific studies have also emerged (Cobo et al., 2015; Xu et al., 2017b; Muhuri et al., 2018; Janmaijaya et al., 2018; Laengle et al., 2017; Yu et al., 2017).

The major contribution of the paper are highlighted as follows:

1. A detailed bibliometric analysis of "Industry 4.0" has been conducted for which two of the most widely used bibliometric databases are utilized viz. Web of Science (WoS) and Scopus.

* Corresponding author.
E-mail address: pranabmuhuri@cs.sau.ac.in (P.K. Muhuri).

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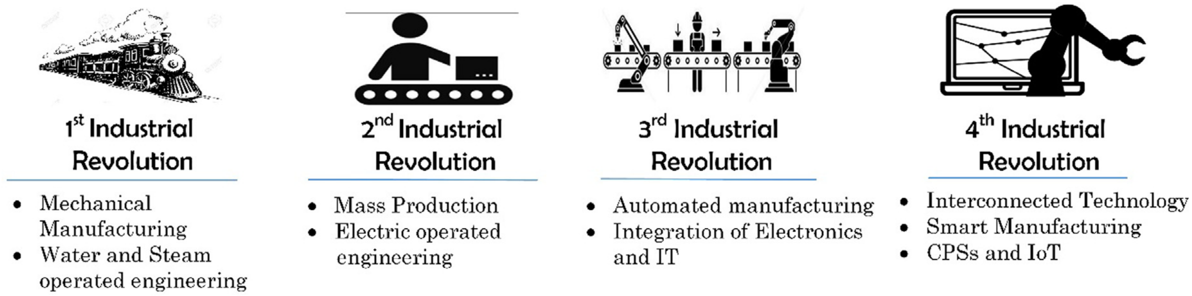

Fig. 1. Evolution of industrial revolution.

2. The research growth of Industry 4.0 are documented over the years.
3. We have discussed the popular parameters such as: highly productive authors, most influential authors, most cited discipline, countries, and highly prolific institutions and have shown the top 10 in each of them.
4. Top 40 papers are listed based on the total citations received till date.
5. The visualization of the most common keywords of this field is displayed which are extracted from both the indexing platforms.
6. Apart from thorough bibliometric study, we have also discussed the core conclusion from all the papers indexed in the WoS repository and the papers cited at least 10 times in Scopus.

The rest of the paper is structured as follows: Section 2 describes the process of data collection and the methodology used in this paper. Detailed and extensive bibliometric analysis is performed in Section 3. We have provided a detailed literature survey of the last few years in Section 4. Section 5 concludes the paper by summarizing the results.

2. Data collection and methodology

In this state-of-the-art study, we have gathered bibliometric data from two of the most widely referred repositories: Web of Science (WoS) and Scopus. Thus, the outcome of these two databases has been compared for all the various publication growth queries. The keyword which has been used for the search query is: "Industry 4.0" for both WoS and Scopus and the search was performed on 10th October, 2017. Two of the most widely used standard indexes used in the computer science and engineering community Indexes have been considered, which are: Science Citation Index-Expanded (SCI-E) and the Social Science Citation Index (SSCI). From WoS and Scopus, we retrieved several tags such as: author, title, abstract, country, citation record, author affiliation etc. While, WoS extracted 194 documents, Scopus showed 1425 documents. From the extracted documents in WoS, 79.38% (154) constitute Articles, 30 Editorials, 9 Reviews and 7 Proceeding Papers. On the other hand, in Scopus, Articles are classified as 573 which is only 40.12% of the total documents. The other major category was Conference Papers which was 45.47% (648). The remaining minor categories were Reviews (37), Article in Press (41), Conference Reviews (36), Book Chapters (34), Notes (20), Short Surveys (19), and Editorials (12). All the document types are compiled in Table 1.

In this paper, various performance indicators have been extracted for the bibliometric analysis. Total Papers (TP), which is the total number of publications from the source, Total Citations (TC), which is the total number of citations received by the publication, and the Citations per Paper (CPP), that is total number of received citations count divided by total publications. In most of the Tables, 'R' denotes the Rank.

Table 1
Distribution of document types in WoS and Scopus.

WoS			Scopus		
Document Type	Total numbers	Contribution (%)	Document Type	Total numbers	Contribution (%)
Articles	154	79.38	Articles	573	40.12
Editorials	30	15.46	Editorials	12	0.84
Reviews	9	4.64	Reviews	37	2.60
Proceedings Paper	7	3.61	–	–	–
–	–	–	Conference Papers	648	45.47
–	–	–	Articles in Press	41	2.88
–	–	–	Conference Reviews	36	2.52
–	–	–	Book Chapters	34	2.38
–	–	–	Notes	20	1.40
			Short Surveys	19	1.34
			Books	5	0.35

3. Bibliometric analysis

In this section, we have shown the bibliometric results for the various performance parameters such as: research growth, most productive and highly cited authors, most sought out discipline, top journals, country-wise analysis, institution wise analysis, and highly influential papers in "Industry 4.0"

3.1. Research growth

Industry 4.0 has been gaining rapid attention since its inception. Fig. 2 shows the total number of publications in WoS and Scopus. In WoS, the first publications on Industry 4.0 came out in 2013 with 2 papers. Later, it increased exponentially till it reached the maximum of 107 in October 2017. In the case of Scopus, the publications started in 2012 (TP = 3). The highest number of publications has been this year with 601 papers.

Total number of citation count in WoS and Scopus is shown in Fig. 3. According to WoS, number of citations was maximum in 2017, which is likely to increase over the time. In Scopus, maximum number of citations came in the year 2015 with the TC count of 852. In the subsequent years, 2016 and 2017, citations count decreased to 594 and 127; which is because these publications are comparatively more recent, the citation counts of which will certainly increase in the coming years.

From the publications and citation analysis, we can see that the field of Industry 4.0 is very young as the first paper published only in 2012. Within the time span of just 5 years, there are 194 total papers in WoS and 1425 papers in Scopus. Moreover, the citation counts have increased exponentially with respect to the number of publications in both the indexing platforms.

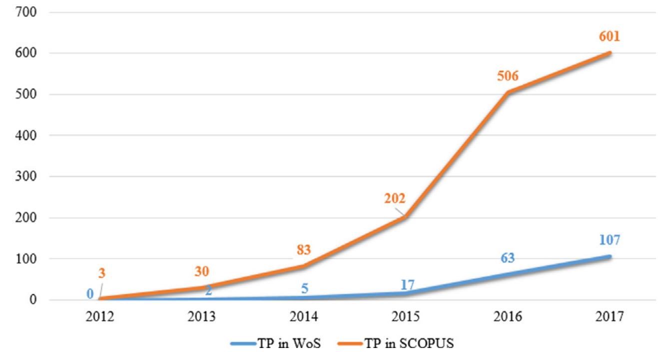

Fig. 2. Total number of publications in WoS and Scopus.

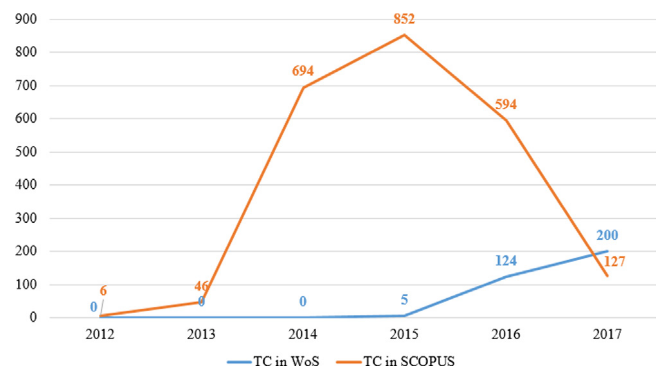

Fig. 3. Total number of citations in WoS and Scopus.

Table 2
Top 10 most productive authors.

R	WoS				Scopus			
	Authors	TP	TC	CPP	Authors	TP	TC	CPP
1	Li, D.	6	53	8.84	Li, D.	14	30	2.15
2	Wang, SY.	6	53	8.84	Wang, S.	13	31	2.38
3	Wan, IF.	5	53	10.60	Li, Y.	11	77	7.00
4	Diedrich, C.	4	7	1.75	Liu, Y.	10	24	2.40
5	Cheng, K.	4	2	0.50	Franke, J.	10	15	1.50
6	Sauer, O.	3	29	9.67	Jeschke, S.	10	6	0.60
7	Li, Y.	3	17	5.67	Wan, J.	9	29	3.23
8	Sanin, C.	3	17	5.67	Gorecky, D.	8	89	11.13
9	Szczerbicki, E.	3	17	5.67	Fleischmann, H.	8	9	1.12
10	Qin, SF.	3	2	0.67	Marcos, M.	8	6	0.75

3.2. Most productive and highly cited authors

The most productive authors for WoS and Scopus are extracted and sorted out on the basis of the number of publications. The authors with same number of publications count, then the ranking is given on the basis of the TC. The top 10 list of most productive authors is shown in Table 2. Li, D. is the highest contributor in both the databases; with 6 publications in WoS and 14 publications in Scopus.

In WoS, Li, D. is followed by Wang, SY., Wan, Diedrich, and Cheng, with 6, 5, 4, and 4 publications, respectively. There are five authors in the top 10 list from rank 6–10, whose TP is 3. These authors are: Sauer, Li, Y., Sanin, Szczerbicki, and Qin.

In Scopus, Li, D. is followed by Wang and Li, Y. with 13 and 11 publications each. There are three authors Liu, Franke and Jeschke with TP of 10. Even the last three authors in this list viz. Gorecky, Fleischmann, and Marcos have 8 publications each, which is more than the most productive author in WoS. Interestingly, four authors in the top 10 list of the most productive authors in both the databases are common, though the rankings may differ.

Table 3
Top 10 most influential authors.

R	WoS				Scopus			
	Author	TP	TC	CPP	Author	TP	TC	CPP
1	Wan, IF.	5	53	10.60	Kao, H.-A.	5	410	82.00
2	Li, D.	6	53	8.84	Lee, J.	7	410	58.50
3	Wang, SY.	6	53	8.84	Bagheri, B.	4	280	70.00
4	Feld, T.	1	35	35.00	Yang, S.	3	140	46.67
5	Fettke, P.	1	35	35.00	Monostori, l.	1	132	132.00
6	Hoffmann, M.	1	35	35.00	Fettke, P.	2	93	46.50
7	Kemper, HG.	1	35	35.00	Hoffmann, M.	4	90	22.50
8	Lasi, H.	1	35	35.00	Feld, T.	1	89	89.00
9	Schuh, G.	2	31	15.50	Kemper, H.-G.	1	89	89.00
10	Sauer, O.	3	29	9.97	Gorecky, D.	8	89	11.12

To create the list of the most influential authors, the authors were sorted on the basis of total citations received in all the papers and is shown in Table 3. Li, D., who was the most productive author with 6 papers, is at the second spot in the most influential author with 53 citations in the WoS. Wan with same number of citation counts is however at the top position due to the fact that he has less publication count of 5. After them, we have Wang with TP of 6 and TC of 53. Then, there are 5 authors who have only one publication but have 35 citations each, who are ranked from 4–8. These authors are Feld, Fettke, Hoffmann, Kemper, and Lasi.

On the other hand, in Scopus, there is not a single author from the most productive list in the most influential authors list. This could be due to the fact that Scopus indexes wide range of international conferences and journals; thus allowing a larger group of researchers and audience to participate in indexing. Kao has the highest citation count of 410 with only 5 papers. Lee has the same TC count with TP of 7. Quite interestingly, four of the authors in the Top 10 list of WoS with 35 citations each, have different citation counts in the Scopus list. These are: Fettke with 93 citations, Hoffmann with 90 citations, and Feld and Kemper with 89 citations each.

3.3. Discipline wise analysis

Both the repositories, WoS and Scopus, allocate relevant subject categories to the papers in their indexing list. The top 10 subject areas in both the databases are listed in Table 4. Both WoS and Scopus have Engineering ranked first with TP of 107 and 961, respectively. After that, it is Computer Science with TP of 63 in WoS and 671 in Scopus. There are two other disciplines which are common to both the databases, though their ranking differs. These are: Material Science (TP = 12 in WoS, TP = 144 in Scopus) and Chemistry (TP = 11 in WoS, TP = 63 in Scopus).

Apart from publications in the obvious areas, there has been a lot of work in various other disciplines due to the integration of various industries. As in WoS, we can see 14 and 13 publications in Instruments Instrumentation and Operations Research Management Science, respectively. Also, in case of Scopus, Business, Management and Accounting have 235 publications with an 18.87% contribution. The % (contribution) column for both the databases exceeds 100%, since there would be more than one category in which a paper can be categorized. One interesting observation which can be concluded from Table 4 is the wider coverage of the Industry 4.0. This also shows the much broader integration of the interdisciplinary works from various disciplines such as: business, management and accounting, food science technology, social sciences, operations research etc., apart from computer science and engineering.

3.4. Top source journal

In this section, we have extracted the top 10 sources or journals which are publishing most frequently in the emerging area of Industry 4.0. A journal is a time bound (monthly, yearly etc.) publication with

Table 4
Top 10 subject areas covered by Industry 4.0.

WoS			Scopus		
Discipline	TP	%	Discipline	TP	%
Engineering	107	55.16	Engineering	961	64.85
Computer Science	63	32.48	Computer Science	671	45.28
Telecommunications	27	13.92	Business, Management and Accounting	235	15.87
Automation Control Systems	16	8.25	Decision Sciences	208	14.04
Instruments Instrumentation	14	7.22	Mathematics	160	10.80
Operations Research Management Science	13	6.70	Materials Science	144	9.72
Materials Science	12	6.19	Physics and Astronomy	76	5.13
Chemistry	11	5.68	Social Sciences	64	4.32
Food Science Technology	10	5.16	Chemistry	63	4.25
Physics	6	3.09	Energy	38	2.56

Table 5
Top 10 journals publishing works on Industry 4.0.

WoS			Scopus		
Journal	TP	TC	Journal	TP	TC
IEEE Access	12	8	Procedia Manufacturing	87	7
Chinese Journal of Mechanical Engineering	9	8	Procedia CIRP	80	435
at-Automatisierungstechnik	8	13	Zwf zeitschrift fuer wirtschaftlichen fabrikbetrieb	78	61
CIRP Annals-Manufacturing Technology	7	42	Ifip advances in Information and Communication Technology	50	19
Sensors	6	10	Lecture Notes in Computer Science	44	25
International Journal of Production Research	5	16	Productivity Management	33	5
Computers in Industry	5	3	IFAC-papersonline	27	82
Proceedings of the IEEE	4	18	CEUR Workshop Proceedings	23	2
tm-Technisches Messen	4	1	IEEE International Conference on Emerging Technologies and Factory Automation, ETFA	20	27
Journal of Ambient Intelligence and Smart Environments	4	0	wt Werkstattstechnik	19	7

the objective of promoting and monitoring the progress of the discipline it represents. The results are compiled in Table 5. This table consists of TP and TC from the top 10 journals from both WoS and Scopus. The listing is sorted based on the total number of publications.

In WoS, IEEE Access has the highest number with a total publication of 12, followed by the Chinese Journal of Mechanical Engineering with 9 publications. However, the maximum citation count is attained by CIRP Annals-Manufacturing Technology with a citation count of 42 in just 7 publications. The Journal of Ambient Intelligence and Smart Environments have 4 publications each but are yet to start the citation count.

In Scopus, Procedia Manufacturing has published a maximum of 87 papers followed by Procedia Cirp with 80 publications. Procedia CIRP has also got the highest citation count of 435. Interestingly, Productivity Management has got 33 publications in Industry 4.0 but a citation count of only 5. Similarly, CEUR Workshop Proceedings has 23 publications but only 2 citations. Furthermore, there is not a single journal in the top 10 which is common to both the databases. This is because of the larger number of conference proceedings published (IEEE International Conference on Emerging Technologies and Factory Automation, ETFA) and the wider journal (IFAC-papersonline) indexing in Scopus. On the other hand, WoS is very selective in its indexing policy and considers only the very high quality, peer reviewed journals. All these journals publishing papers on Industry 4.0 have wider scopes and belongs to different domains. Thus, this journal specific analysis again shows the broader range of coverage Industry 4.0 has gained in its starting years.

3.5. Country-wise analysis

From the extracted data, the top 10 most productive countries in terms of the number of publications, from both WoS and Scopus, is presented in this section. Table 6 shows the order of the countries sorted by TP, also taking into account the TC and CPP.

In WoS, Germany tops the list with 48 publications and highest citation count of 128, followed by China, Taiwan, and USA with 34, 17, and 16 publications, respectively. There are a total of 6 countries which have published more than 10 papers. Interestingly, Portugal is in the 10th position with 6 papers but no citations.

Table 6
Top 10 countries publishing work on Industry 4.0 in WoS and Scopus.

R	WoS				Scopus			
	Countries	TP	TC	CPP	Countries	TP	TC	CPP
1	Germany	48	128	2.67	Germany	547	1060	1.94
2	China	34	99	2.91	China	124	214	1.73
3	Taiwan	17	19	1.12	Italy	83	115	1.39
4	USA	16	35	2.19	United Kingdom	82	157	1.92
5	Spain	15	32	2.13	Spain	78	176	2.25
6	England	14	26	1.86	USA	76	474	6.24
7	France	9	15	1.67	Austria	69	75	1.09
8	Poland	7	17	2.43	Taiwan	44	26	0.60
9	Australia	6	21	3.50	Portugal	43	56	1.30
10	Portugal	6	0	0.00	France	34	36	1.06

In the listing by Scopus, Germany again is in the 1st position with 547 publications which is more than 10 times number of the publications in WoS. Germany is followed by China with TP of 124. Portugal, which has no citations in WoS, has 56 citations in 43 publications.

3.6. Institution wise analysis

From both of the databases, WoS and Scopus, the institutions wise analysis with the top 10 organizations publishing papers in Industry 4.0 is compiled in Table 7. The first rank is acquired by the South China University of Technology with 6 papers in WoS and 10 papers in Scopus. After this, the National Chiao Tung University in Taiwan has 5 papers indexed in WoS with only 4 citations followed by three institutions that have published 4 papers each. These are: RWTH Aachen University, Germany (TC = 31), Shanghai Jiao Tong University, China (TC = 4), and Brunel University, London (TC = 2).

In listings by Scopus, the second position is attained by the University of Auckland, New Zealand with TP of 5 which is same as that of Beihang University, China. However, the University of Auckland has a higher citation of 21 as compared to 16 of Beihang University. The University of Stuttgart, Germany has three different departments which are publishing papers on Industry 4.0 and are also positioned in the top 10. These three departments are: Institute of parallel and distributed

Table 7
Top 10 leading institutions publishing on Industry 4.0.

R	WoS			Scopus		
	Institutions	TP	TC	Institutions	TP	TC
1	South China University of Technology, China	6	30	South china university of technology, China	10	30
2	National Chiao Tung University, Taiwan	5	4	University of Auckland, New Zealand	5	21
3	RWTH Aachen University, Germany	4	31	Beihang university, China	5	16
4	Shanghai Jiao Tong University, China	4	4	Institute of parallel and distributed systems, University of stuttgart, Germany	4	8
5	Brunel University, London	4	2	Free University of bozen-bolzano, Italy	4	5
6	University of Stuttgart, Germany	3	55	Chalmers University of Technology, Sweden	4	3
7	Luleå University of Technology, Sweden	3	29	Graduate school of excellence advanced manufacturing engineering, University of Stuttgart, Germany	4	1
8	Technical University of Munich, Germany	3	24	Institute of industrial automation and software engineering, University of Stuttgart, Germany	3	44
9	Tongji University, China	3	23	Gdansk university of technology, Poland	3	28
10	Hungarian Academy of Sciences, Hungry	3	20	Guangdong mechanical and electrical college, China	3	20

systems (TP = 4, TC = 8), Graduate school of excellence advanced manufacturing engineering (TP = 4, TC = 1), and Institute of industrial automation and software engineering (TP = 3, TC = 44).

3.7. Top 40 highly influential papers

This section lists the top 40 most highly cited papers in WoS and Scopus. Table A.1 in the Appendix gives the list of the 40 highly influential papers ranked by most citations in WoS. This table also contains the name of the authors, year of publication, and publishing source. The paper by Lasi et al. (2014) in 2014 has got the highest citation count of 35 as it provides the basic overview of this area. It is preceded by Wang et al. (2016b) with 23 citations. Noticeably, there are only 11 papers with a citation count of at least 10. In 2016, there were 22 papers in the list of the 40 most influential papers and they have a combined citation count of 147. 2017 has 10 papers in this list with a total count of 40 citations. This trend of the last two year depicts that researchers are working in this field for developing the smart and intelligent industry in future.

Table A.2 in the Appendix gives the most influential papers as indexed in Scopus with publishing source, name of the authors and year of publication. Lee et al. (2015) is cited 259 times in Scopus and it tops the list, followed by Monostori (2014) and Lee et al. (2014) with a citation count of 132 and 127, respectively. These are the three papers whose citation count is more than 100. There are four papers Lasi et al. (2014), Zhan et al. (2015), Hermann et al. (2016), and Gorecky et al. (2014), with a citation count of more than 50. All the papers in the list of the top 40 in Scopus have got more than 10 citations which is due to the diversity of sources it indexes. This can be seen in the source title column, where there is listing of various conferences proceedings are listed: Proceedings of the Annual Hawaii International Conference on System Sciences (TC = 57), Proceedings — 2014 12th IEEE International Conference on Industrial Informatics, INDIN 2014 (TC = 53), Proceedings of the 2014 IEEE International Conference on Automation, Quality and Testing, Robotics, AQTR 2014 (TC = 41) etc.

3.8. Topmost keywords in WoS and Scopus

In this section, we have used the VOSviewer, which is the most widely used information visualization software to select the topmost keywords used by the authors in their papers.

As can be seen, Industry 4.0 is surrounded by Cyber–physical systems, the internet of things, smart factory, manufacturing systems, cloud computing etc. Fig. 4 shows the connected network of the most common keywords indexed in WoS.

Fig. 5 gives the visualization of the most popular keywords used by the authors in Scopus. Almost all the keywords emanating from Industry 4.0 are common to keywords in WoS. The intensity of the keywords depicted by the circular node may be higher since Scopus indexes papers from different and wider sources. We can also notice that one keyword in the topmost list of keywords, augmented reality is different.

4. Industry 4.0: Background overview and application areas

In this section, we discuss what the authors have tried to achieve in the fourth industrial revolution termed as Industry 4.0. All the papers in WoS are covered and papers with at least 10 citation counts in Scopus are discussed. This sections gives the reader the rationale and technologies used by various researchers in recent times with respect to Industry 4.0.

Overview on Industry 4.0

The abstract level description of Industry 4.0 was given by Lasi et al. (2014), which is the top most cited paper in WoS, in this domain. According to the authors, Industry 4.0 was the main component of the fourth industrial revolution, which revolves around the evolution and variations in the manufacturing systems. The paper also defined the basic concepts and the applicability of this domain in the modern industry. The research area of Industry 4.0 is growing rapidly with each year. Stock and Seliger (2016) presented extensive background research on the development of Industry 4.0. They also discussed the macro and micro perspectives of Industry 4.0 with regard to sustainable manufacturing and provided future scope in this domain. The two editorials (Beyerer et al., 2015; Vogel-Heuser and Hess, 2016) on developments in Industry 4.0 are worth mentioning for the readers. They provide an overall perspective of this area in a concise manner. The authors in Vogel-Heuser and Hess (2016) mention that Industry 4.0 is actually taken from the German term Industrie 4.0 which is often used as CPS and Cyber-Physical Production System (CPSS) in manufacturing systems. The article by Webster (2015) dwell on the transition of the technology in the 4th industrial revolution. The paper by Zhou et al. (2015) was one of the first to start exploring the area of Industry 4.0. The authors categorized Industry 4.0 in CPS, CPPS and smart factory. Further, they assessed the infrastructure of china's manufacturing industry from the perspective of Industry 4.0. Hoeme et al. (2015) presented a detailed overview of the challenges of another Industrie 4.0 component viz. semantic industry. Su et al. (2017) discussed the issues related to the progress of Industry 4.0 and how to stabilize the industry in case of inconsistency etc.

Another detailed survey on the methodologies and challenges in Industry 4.0 was conducted by Lee et al. (2017). Here, the authors discussed the consequences of digital transformation in industries such as IoT and services. Liu and Xu (2017) focused on two most important domains, Industry 4.0 and cloud computing, in the manufacturing systems. These two concepts are compared with each other and future prospects are envisioned with respect to production systems. Shamim et al. (2017) provide an overview for management techniques in Industry 4.0. This was a pioneer study in management practices. Various case studies were conducted to point out the challenges and future scope. Marques et al. (2017) discussed the techniques for decentralized decision making in industrial manufacturing, while focusing on the challenges and the scope in Industry 4.0. In an attempt to overcome the doubts regarding the use of Industry 4.0 for production, Kolberg and Zühlke (2015) provide the summary and the theory of lean automation

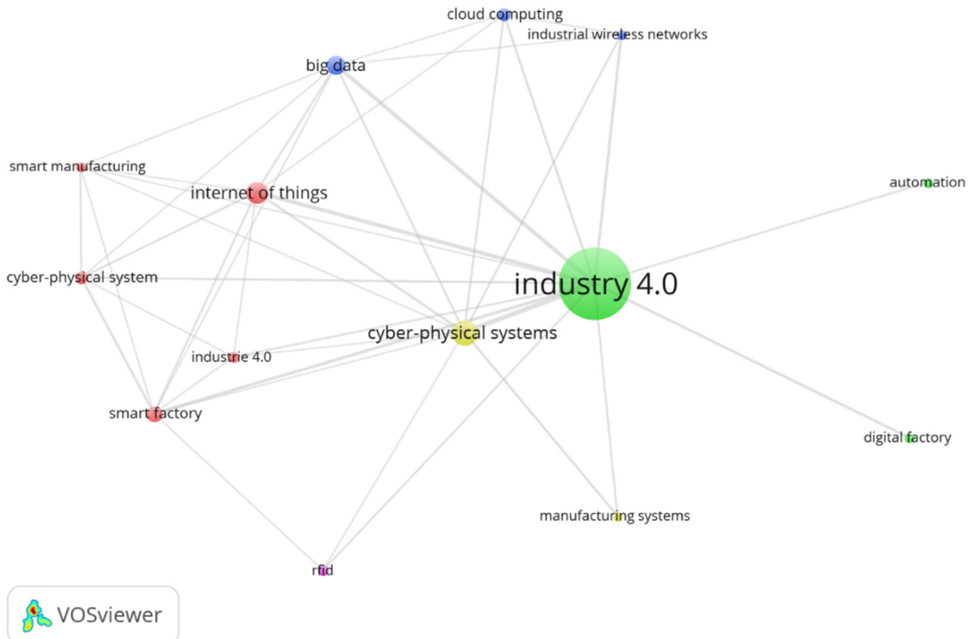

Fig. 4. Most popular keywords in WoS.

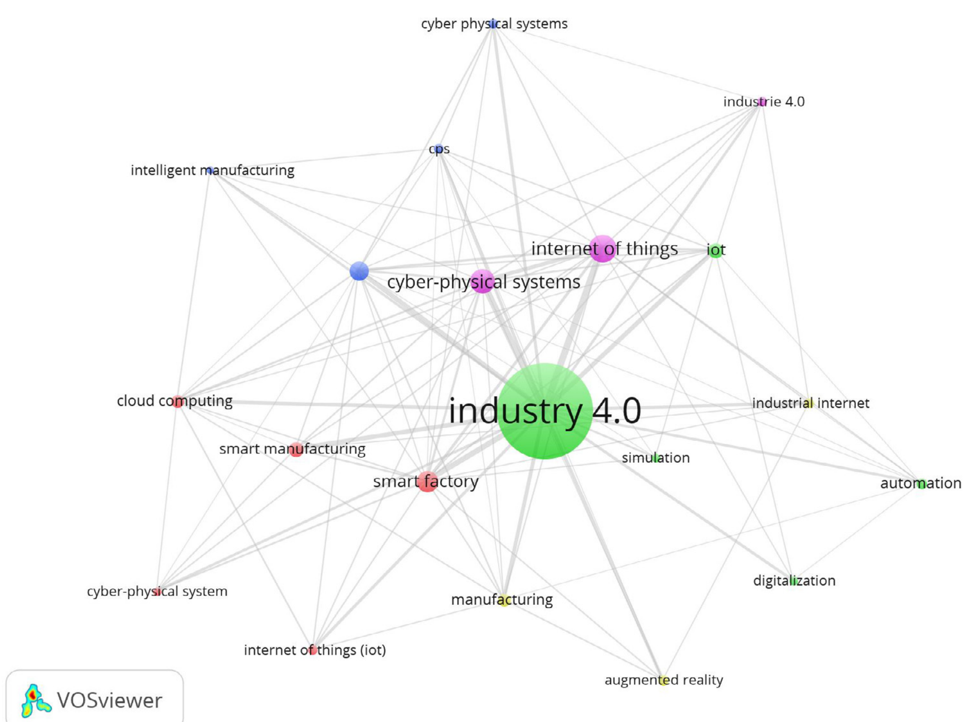

Fig. 5. Most popular keywords in Scopus.

which is a combination of lean production and automation technology. They also come up with the notion of inherent work between Industry 4.0 and lean automation. Examples of smart watches and CPSs are dealt in this paper. Mueller et al. (2017) provide an extensive survey and focus on the bottlenecks associated with the implementation of Industry 4.0. A modulated architecture constituted of products, system software, processing and manufacturing process was proposed by the authors. An in-depth analysis of the CPS with the methodology of the processed architecture was also highlighted.

Cyber–Physical Systems (CPS) and Manufacturing Systems

The paper by Lee et al. (2015) deals with the implementation of cyber–physical systems (CPSs) in industry 4.0. CPSs provide the framework for close connections between physical devices and the cyber world. Thus, the efficient deployment of CPS is very crucial. The 5C level architecture (Connection, Conversion, Computation, Cognition, and Configuration), which consists of smart connections, data to information conversion, cyber, cognition, and configuration for a CPS was discussed in this paper. Extending the work in Lee et al. (2015), Trappey et al.

(2016) presented an overview of the available literature of CPS and patent portfolios of the 5C's of manufacturing systems. Furthermore, the latest and upcoming Industry 4.0 standards, followed by international organizations globally were also discussed in the paper. A new type of systems other than the CPS, known as Cyber–Physical Production Systems (CPPSs) was discussed in Monostori (2014). CPSSs not only monitor recent developments in computer science but also keep track of the process of manufacturing systems. Authors also laid out the major challenges to be addressed in future. Lee et al. (2014) discussed the challenges in the manufacturing systems of the CPSs. Innovations and hidden information were extracted using the big data environment for industry 4.0 which was based on a case study of a heavy duty equipment vehicle for mining and construction.

With the extension of the work in Monostori (2014) and Monostori et al. (2016) dwell on the suggestion made by the International Academy for Production Engineering (CIRP), and concluded that CPPSs are the most crucial aspect in the growth of sustainable manufacturing systems. Moreover, the scope for future research and development was also explored in the paper. Schuh et al. (2014a) discussed the evolution of production systems and factories with the development of new technologies. Since the introduction and growth of CPS is linked to the evolution of fourth generation industries, they examine the revolutions in the last three industrial systems. Further, the importance and future prospects of CPS were laid down with emphasis on Industry 4.0. A new specialization of CPSs, i.e., Virtual Engineering Objects (VEO) was given in Shafiq et al. (2015b). VEO was a smart industry product which can perform various operation using previously acquired knowledge as well as new information. Two test models, such as, Set of Experience Knowledge Structure (SOEKS) and Decisional DNA (DDNA), were also considered for the validation of VEO. The standard structure of the engineering collective intelligence for the industrial stream was discussed in Sanin et al. (2017). Three basic structures were VEO, Virtual Engineering Process (VEP), and virtual engineering factories (VEF).

In Shafiq et al. (2015a), authors first provided a concise review of the VEO or VEP and CPS. They classify the VEO with CPS and VEP with the CPPS. As an extension to Shafiq et al. (2015b,a, 2016) proposed a novel concept regarding the integration of the VEO, VEP and VEF. The applicability of this concept with respect to Industry 4.0 was also studied through a separate case study. There are many application specific architectures available for the CPS. Bagheri et al. (2015) proposed a new CPS architecture for self-aware machines for Industry 4.0. The 5C structure explained in Lee et al. (2015) was extended and an adaptive clustering approach was introduced for more insights. A manufacturing process case study was also considered in the paper. Francalanza et al. (2017) provided a novel CPPS design structure and its requirement specifications, which was adaptable to new challenges. Their approach was reliable enough to accumulate future interferences. The model for a digital factory tool was used for the implementation of this CPPS design. Also, various industrial and academic scenarios were considered for the validation of the approach using the digital factory tool.

Harrison et al. (2016a) discussed the utilization of engineering techniques in the industrial context for exploring the capability of the CPS. Authors first reviewed all the available engineering practices and then explored the CPS engineering toolset. They extended their work in Harrison et al. (2016b) and pointed out the limitations in the engineering techniques presented in Harrison et al. (2016a), as well as discussed the CPS engineering tools from the perspective of the automation. In Mosterman and Zander (2016), authors focused on the collaborative utility dimension and present few examples for CPSs. The pick and place machine for the towers of Hanoi puzzle was taken as a case study. With growing demands and growing needs, the complexity and the design of the industrial applications in CPS was getting problematic. To tackle these issues, Bangemann et al. (2016) suggested that the classical approaches could integrated with the CPS to ease the process of movement to the automation systems. The challenges in logistics manufacturing within effective cost and rising demand was discussed in Seitz and Nyhuis (2015). They also lay out the usefulness of integrating CPS techniques with logistic management for effective processing. Xu et al. (2013) discussed the involvement of the CPS, Machine to Machine (M2M) communication etc. in the coal mining industry. Further, they also presented an Ultra-Wideband (UWB) radio localization and tracking system for the coal mining applications. The automation industry is sweeping all over the manufacturing and production engineering services. Ma et al. (2017) proposed a smart lean automation engine enabled by CPS (SLAE–CPS). This hybrid CPS was the outcome of the analysis of Jidoka functions and the intelligent capability of CPS methodologies.

The semantic heterogeneity in the environment of CPS was proposed by Jirkovský et al. (2017). The problem of CPS incorporation suffered by many challenges. Further, the implementation of semantic heterogeneity is highlighted with emphasis on web technologies, from the perspective of big data. The mechatronic systems were extended to the CPSs by Penas et al. (2017), while underlining the similarities and differences between them. This extension was tested on the framework with similar modelling techniques. Schlechtendahl et al. (2015) presented a novel approach to production engineering to let non-Industry 4.0 systems be ready and modulated into actual Industry 4.0 smart systems. By Industry 4.0, the authors meant CPPSs. Later, they also validate their approach by showing its applicability. The efficient embedding of the industry 4.0 techniques in the supply-chain management was reported in Majeed and Rupasinghe (2017). Authors considered the ERP system of the footwear industry to demonstrate the efficient management of the inbound and outbound operations.

Internet of Things (IoT)

IoT is the field responsible for the smart and smooth functioning of digital manufacturing. However, the digitization of products and services has led to the fear of information hacks. Moreover, the complexity of the system has increased manifold due to the use of smart products. Thus, Riel et al. (2017), proposed a novel architecture to tackle these safety issues and deal with the complex machinery. Hermann et al. (2016) focused on the role of IoT in the revolution of Industry 4.0, though they referred to it as 'Industrie 4.0'. An extensive literature survey was provided and classification and design issues of industrie 4.0 were discussed. According to authors, only companies and research centres were focusing on industry 4.0 and there is a challenge for the academic community to implement the scenarios in this domain. Moreover, they also provided some case studies for the design principles mentioned. Jazdi (2014) focused on the influence of interconnected devices under IoT and the impact of CPSs in the everyday life of individuals. They argued that Industry 4.0 will have a huge influence on the development of new technologies and life style of consumers. Further, they worked on distributed remote applications. In a developed country like Germany, digitization and IoT helped in the sustainable setup of healthcare, manufacturing and many other industries. Kagermann (2015) addressed the scope and challenges of this digitization in IoT.

Imtiaz and Jasperneite (2013) proposed to scale down the OPC-UA, an industrial standard, to the chip level without affecting its standard performance and features, so that, the utility of IoT in the industrial applications was maintained. Another variant of IoT, termed Industrial IoT, was proposed by Wan et al. (2016a) for the larger scalability of Industry 4.0. Authors defined the novel architectural designs and protocols for industrial arrangement. The possible challenges and solutions were also discussed in the paper. A novel architecture based on OPC.NET for the industrial products in the IoT domain was presented in Ungurean et al. (2014), that can also be utilized for the implementation of IoT. Condry and Nelson (2016) proposed a more secure and efficient model for the IoT approaches as compared to traditional models. Their model considered the challenges and threats in the real-world scenarios and modelled them in the smart IoT devices. Thongpull et al. (2015) consider the smart integrated multi-sensory self-x systems to represent the general automated design perception. These designs are effective in medical services, IoT, Industry 4.0 etc. The progress of the manufacturing industry was monitored using IoT protocols by Thramboulidis and Christoulakis (2016).

Weinberger et al. (2016) introduced the usage of the high-resolution management (HRM) to accumulate and process high resolution data to form a compatible environment with the IoT. The issue of ingesting large-scale heterogeneous and multi-type device data in IoT was discussed in Ji et al. (2016a) and presented a problem prototype for a big data industrial environment. The techniques for the packaging of self-operated sensor systems called the small-scale thermoelectric generators (TEGs) was discussed in Zoller et al. (2017) from the perspective of IoT. Moreover, the applicability of products with several underfills (UFs) was demonstrated experimentally. With the increase in distributed embedded systems, the load over the communication devices increased exponentially. Barkalov et al. (2017) provided a novel fault detection scheme for IoT occupied distributed embedded systems with a CloudBus protocol.

Smart Industry and Smart Manufacturing

To explore the collaborative works in smart factory, IoT, and energy management Shrouf et al. (2014) discussed the role of IoT in sustainable smart factories with the objective of achieving energy efficiency. These smart factories are identical to Industry 4.0. Many authors explored the architecture of these factories and their role in production management. Wang et al. (2016b) proposed a novel algorithm to perform the operations of the smart factory. They simulate intelligent manufacturing products that can communicate and cooperate with each other without human intervention. Further, this setup was made reliable by preparing a better decision making environment to prevent deadlocks. The approach was validated through some numerical experimentations. Zawadzki and Zywicki (2016) laid out the essential components of the smart factory, viz. smart design and production control. They discussed the maximum utilization of the manufacturing process with the latest resources in defiance of Industry 4.0. The extensive growth of Industry 4.0 has revolutionized in the shipyard domain, which lead Fraga-Lamas et al. (2016) to propose a smart pipe system for this domain. A novel Radio Frequency Identification (RFID) technology was suggested for the implementation of these smart pipes. Another use of RFID was to integrate it into the machining process of the smart factory where data-on-tag is one of its applications. However, RFID tags accumulated a large quantity of data which ultimately slows down the manufacturing process. Thus, Wang et al. (2017) proposed a hybrid data-on-tag approach to keep the manufacturing process flexible. Lv et al. (2017) emphasized the urgent need for a constant monitoring process of product manufacturing for standardized quality. Such a real-time planning system was required for better functioning of the growing manufacturing systems. RFIDs were used in this approach for the correctness of the process flow. Balog et al. (2016) experimentally verified the qualitative characteristics of RFID transponders through the regression analysis techniques for the rationalization of the processes as the software and the manufacturing products are prone to agility in an Industry 4.0 setup. A novel manufacturing system, known as the Line Information System Architecture (LISA) was proposed in Theorin et al. (2017), where they address the durability, reliability, and persistent aspects of the Industry 4.0. Authors argued that LISA was flexible enough to integrate new changes and provide smart service.

One of the essential components of Industry 4.0 is smart manufacturing which has revolutionized the production industry. Kang et al. (2016) discussed the challenges and bottlenecks in smart manufacturing in the past and the present and then provided an extended investigation into the future distribution of research work in smart manufacturing. To make Industry 4.0 acceptable and widely popular, the proprietary approach towards its implementation sources should be removed and replaced by open and homogeneous solutions. For this purpose, a multi-vendor production scheme with high modularity is available in the literature known as SmartFactory^{KL}. Balog et al. (2016) discuss the findings and future scope of this technique after extensive exploration. Baccarelli et al. (2017) provided a collaborative survey on the two evolving industrial components i.e. Fog computing (FC) and Internet of Everything (IoE). Later, case studies were provided to find out new application paradigms in big data, Industry 4.0, smart industries etc. The structure and design principles of FC and IoE were also explained and their performance was compared with the benchmark test cases. Siddiqui et al. (2016), discussed the smart architecture, new business ventures and the low latency setup of the latest 5G technology. Kadera and Novák (2017) first highlighted the importance of the distributed and smart industrial systems of Industry 4.0, then proposed some key points to tackle the problems faced in communications between the interconnected devices. A prototype of the chilled water management system was taken as an example and executed on the Raspberry Pi hardware.

The inability of traditional automotive welding systems to address as cellular manufacturing systems (CMS) was discussed in Tuominen (2016). The flexible demand in the smart industry was addressed by the concept of a measurement-aided welding cell (MAWC) for the first time in this paper. Pacaux-Lemoine et al. (2017) provided the prototypes to measure the effectiveness of the human–machine systems. More importantly, the involvement of the smart industry with the humans was emphasized, called the human-centric approach. Parlanti (2017) further explained the importance of end-to-end communication between humans and smart devices by proposing shop-floor solutions for the integration of supported protocols for connected environments. Qin and Cheng (2017a,b) focused on the futuristic digital design methodologies and protocols to be utilized by smart systems. Cheng et al. (2017) presented four smart cutting tools in the context of smart machining such as a force-based cutting tool, a temperature operated internally cooled cutting tool, a fast tool servo (FTS) and a collets for ultraprecision and micro manufacturing drives. They also explained the implementation, design issues and applications of these smart tools. Kongchuenjai and Prombanpong (2017) proposed a novel mathematical model to optimize the total production time in the manufacturing process with the help of integer linear programming. Their approach was robust and handled the complexity in process planning of flexible manufacturing smart systems. Li et al. (2017b) analysed the big data issues related to the smart manufacturing of devices and evaluated it to minimize load-unbalance. A novel and efficient software design framework for smart cameras with an upgraded processor, memory, and interface was proposed by Lee and Yang (2017). The simulation environment of the proposed framework had the potential to handle complex computations with the help of an efficient GPU utilization for smart industrial cameras.

With regard to the 3D printing application framework, which is the enabling element of Industry 4.0, four technical challenges and seven managerial aspects were discussed by Chen and Lin (2017). Some of the aspects mentioned in the paper were: 3D object database, property rights, lean manufacturing, low productivity, optimized use of resources etc. For the required output, smart manufacturing with a continuous 3D printing environment was needed. The relationship between the clusters and Industry 4.0 was studied by Götz and Jankowska (2017). The features of Industry 4.0 were mapped onto the theory of the clusters, to identify the effect of the local ecosystem in the transformation of smart industry. With the instant boost in smart industry, there is a widespread demand for the temporal correctness of cooperative behaviours, although their complexity was one of the major issues in Industry 4.0. Therefore, Ren et al. (2017) introduced a multi-perspective approach to examine the corporative behaviour from the macroscopic and the microscopic point of view. Kymäläinen et al. (2017) developed a novel model considering an exhaustive user experience in a smart industry environment. Veza et al. (2016) researched on industrial transformation to adapt the novelist standards of Industry 4.0 in Croatia and develop a country specific Innovative Smart Enterprise (HR-ISE) prototype. A smart distribution system for industrial devices and components was provided in Alexopoulos et al. (2016). This system took the input reading and collective feedback from the sensors and used them to provide useful services which can be accessed by consumers. Karaköse and Yetiş (2017) proposed a novel approach for smart city inhabitants for mass customization of products with insights from smart production and intelligent retail. The waiting time among the customer was optimized to address the major challenges in customization.

Industrial Wireless Networks

To handle security issues in smart industry, Cai et al. (2016) proposed a routing protocol for the mobile wireless sensor networks with real-time analysis. The protocol was analysed with the OPNET tool. Another exploration through a precise survey was conducted in the wireless communication in Industry 4.0 by Varghese and Tandur (2014). This was another important domain where all the devices were interconnected through this communication. Another survey and overview on wireless networks, as an extension to Varghese and Tandur (2014), was given in Li et al. (2017a) where the authors discussed industrial wireless networks, their architecture, coverage, and the future scopes. Design issues was also addressed from the application point of view.

Lin et al. (2016a) presented the ways for the best spectrum utilization for industrial wireless sensor networks (IWSNs). A collection of rules for this purpose was proposed and such rules were named local equilibrium-guided autonomous channel switching (LEQ-AutoCS). Lin et al. (2016b), proposed the use of group-based industrial wireless sensor networks (GIWSNs) to deal with technological challenges and advancement in the WSN sector. Further, the energy efficient scheduling schemes were proposed for the remotely placed WSNs. This energy efficiency is achieved through the use of a hybrid harmony search and genetic algorithm.

Semiconductor Industry

Lobo (2016) discussed the importance of the semiconductor manufacturing industry in Industry 4.0. Zheng et al. (2017) proposed a smart inventory management model for the production of spare parts in the semiconductor industry, and highlighted the usefulness of IoT and big data analytics in this manufacturing process. The maximum equipment exploitation in Photolithographic (Photo) for the semiconductor industry was addressed by Hsieh et al. (2017), which was achieved by a simulation approach linked to the insights from big data. They also identified and addressed the two critical nodes in this approach i.e. dynamic photo configurator and abnormality detector. Chiang et al. (2017) presented a detailed analysis of the use of big data in various industries such as energy, pharmaceuticals, chemicals, and semiconductors. They also discussed the framework, mechanism and challenges for these industries.

Cloud Computing and Cloud based Manufacturing Systems

As it had already been pointed out by many researchers, Industry 4.0 is the booming research area with scope for further expansion with respect to sustainable manufacturing and human development. Schmidt et al. (2015) experimented to find the capability of this field in various application domains such as big data analytics, cloud computing etc. The effective utilization of cloud computing resources was classified in Zhan et al. (2015), where they present the scheduling aspect with respect to the application layer, virtualization layer, and deployment layer. Moreover, this scheduling objective was also discussed for big data and CPSs. A review of cloud based manufacturing system was compiled in Pisching et al. (2015) which are one crucial components of the Industry 4.0 including IoT and CPSs. Major research issues for further work were also identified.

Tao et al. (2017) addressed the less explored area of manufacturing services of supply–demand matching in cloud computing. A simulator based on this area was proposed which utilized network based techniques for statistical analysis and predictions. Yue et al. (2015) focused on cloud-assisted industrial CPS by providing a widespread survey on its technology, challenges and scope. They also argued that while CPS provides internet connectivity, cloud gives the storage capability and processing methodology. Also, emphasis was given to the ability of smart factories to help users fulfil their rising demands. The authors also proposed to generate applications for cloud computing and big data for further development in Industry 4.0. Maintenance of the software or the products of the manufacturing sector is a trivial challenge, faced by the industries. Moreover, with continuous connectivity problems and security issues, the maintenance services for Industry 4.0 need to be reliable. A constructive approach, focusing on the methodology of the maintenance sector was outlined in Roy et al. (2016). The authors also claimed that IoT and cloud computing would be the next big thing in the growth of Industry 4.0.

Wu et al. (2017) presented a detailed overview of the software and services of cloud computing such as manufacturing processes and digital design. This study was aimed at decision makers to help them select appropriate services on the cloud for their various production systems. Wan et al. (2016b) highlighted the need for the collaboration of cloud computing and mobile services to the smart industries in Industry 4.0. A customized manufacturing system was designed and this was essentially done to meet user demands on a regular basis. A locality-aware least recently used (LLRU) replacement algorithm in a cloud computing environment was proposed by He et al. (2017). The algorithm could efficiently exploit the access and locality characteristics. The results of their experiments demonstrated that LLRU outperforms the traditional approaches. The differences and variations in service oriented manufacturing approaches were discussed by Liu et al. (2017). The theory of some of the approaches considered are: Industry 4.0, connectivity through smart internet, and cloud manufacturing (CMfg). CMfg is mainly explored by discussing its potential with respect to industrial engineering. There is an urgent need for the manufacturing systems to adapt to the latest technologies such as: 3D printing, big data, IoT and cloud computing etc. Almada-Lobo (2016) studied the manufacturing execution systems (MES) which advances the methodology of the production control.

Energy based systems and energy efficiency issues

Ang et al. (2017) focused on energy efficient machinery and devices in the marine industry, for which they argued that it should be smart enough to optimize itself for better productivity. According to the authors, computational intelligence and CPSs are the main techniques for futuristic enhancement in the marine industry. The importance of sustainable engineering through energy efficiency in robotics was studied by Bukata et al. (2017). They proposed that energy consumption can be optimized using robotic cells. Their approach could reduce energy consumption by 20% as compared to prevalent approaches.

Kleineidam et al. (2016) studied the load balancing and related technologies for handling distributed energy systems, and suggested that smart home machineries can be used for the growth of futuristic smart grids. They argued that the latest systems with enhanced computational power need to be properly optimized for valid energy emission and efficient energy consumption. As stated earlier by various researchers, efficient energy consumption is a crucial issue in new technologies. Oh and Son (2016) highlighted such concerns for green manufacturing systems and suggested that not only environmental havocs could be reduced but also that technical issues in production can be solved through it. Huang et al. (2017) talked about the latest work in the growth of the community energy system planning (CESP) and explain the basis of the smart industry techniques utilized in this community, supporting their work with a case study and showed that CESP is the next big thing for energy systems in Industry 4.0 for which they have developed a platform.

Automated Engineering

Lean automation is one of the areas to be explored for smart production in the Industry 4.0. Lean production is the methodology to generate highly effective products with low cost and less complexity. Kolberg et al. (2017) presented a collective survey of all the literature in this area. For better user understanding, the authors utilized CPSs for digitizing lean production methods. Since the essential components of manufacturing systems change frequently, Schleipen et al. (2015a) considered the adaptability of IT systems in these environments and their importance in the automated functioning of these systems. Diedrich and Riedl (2016) described the major components needed for the Industry 4.0 environment, emphasizing the architecture, automation applications and design principles of the components. As mentioned in Agarwal and Brem (2015), the integration of technologies in manufacturing systems was indeed a critical task. Thus, Lalanda et al. (2017) proposed a meditation middleware called Cilia for the manufacturing process. It was a reliable and flexible tool which provided several automatic features with minimal human interference.

Himstedt and Maehle (2017) discussed the influence of semantic maps upon the functioning of automated directed automobiles. Global map representation was utilized and a suitable warehouse was chosen for verifying the operations. The craft industry was also growing with the integration and collaboration with designers, engineers, and the manufacturers. Gutierrez-Guerrero and Holgado-Terriza (2017) proposed a novel prototype for the development and installation of the Industrial Automation System called iMMAS (Industrial Meta-Model for Automation System). This prototype was efficient to execute on the OPC UA setup and could be used to write programs for various industrial devices. The article by Koenig (2017a) mentioned the $64 million investment to produce anti-pollution machinery by the automotive supplier company, Faurecia, to fasten the processes in Industry 4.0.

Human–Machine Interface

Gorecky et al. (2014) addressed the issues and the challenges in the human–machine interface by laying out specifications and requirements to understand the concepts and principles of Industry 4.0. The use of human–machine fused technologies for monitoring and management of yield optimization in the polymer film industry was proposed by Kohlert and König (2016). They discussed big data approaches and control issues with respect to Industry 4.0.

Augmented Reality

Paelke (2014) provided the core technical paper on the applicability of augmented reality in the real-domain by providing interaction with the augmented environment and discussing the results of the experience.

Production Engineering

A content analysis based explanation of Industry 4.0 for construction in production systems was presented in Oesterreich and Teuteberg (2016). A concise literature overview and a pragmatic view of the performance of the construction industry was also discussed. A multi-agent approach for production systems in synchronization with CPPSs was proposed by Vogel-Heuser et al. (2014). The authors developed a novel architectural model and used the myJoghurt demonstrator application for experimentation and evaluation purposes. By combining the user input feedback and intelligent systems, they validated their approach. Dombrowski and Wagner (2014) discussed the likely changes in the development of human and machine interactions with the introduction of the fourth generation industrial revolution by studying the mental strain constantly received by workers in production engineering and machinery by using techniques such as VERA and RHIA (RHIA/VERA is the German acronym used in the context for investigating the regulation problems and regulation requirements in the work activities). An efficient and an ingenious procedure for strategic production planning (SPP) was proposed in Flatscher and Riel (2016). SPP is highly modulated and its design is based on the integrated structure of technology roadmaps (TRM). Such procedures are required for new technologies in the industrial process. In an editorial, Quezada et al. (2017) highlighted various international publications, the challenges and motivation for sustainable development goals in production and operations management research in Industry 4.0. Boorla et al. (2017) formulate a mechanism to measure the robustness of the Process Manufacturing Concept (PMC). PMC ensures stability in performance all across production engineering processes. The focus on end-to-end regular manufacturing processes in the chemical and pharmaceutical industry was studied in Kirschneck and Petek (2017). However, this end-to-end process faces various challenges, which can only be tackled by corporation between producers and the suppliers.

Security Issues

An overview of security concerns in the ICS (Industrial Control Systems) was presented by Kobara (2016), since security issues and threats were also increasing at an alarming rate with the enhancing techniques in the Industry 4.0. Batista et al. (2017) studied the security issues and various technical supports in smart industry products. Further, authors proposed a novel architecture which provided a solution for smart grids and smart services, to provide an efficient smart system with more safety, with an optimized and easy to use design.

Optimization

An interesting automated e-fulfilment packaging system for automated packaging in an e-commerce domain was proposed by Li et al. (2017), which was completely based on IoT due to its capability of regular connectivity among devices. Moreover, an adaptive Particle Swarm Optimization (PSO) was utilized for the challenging 3-D Multiple Bin Size Bin Packing Problem (3-DMBSBPP). A robotic simulator was used to demonstrate the successful implementation and efficacy of the system. Cost optimization from the standpoint of Industry 4.0 for future infrastructure was given in Schuh et al. (2014b). Genetic Algorithms (GAs) have been used as the heuristic approach for this purpose. An optimization technique to schedule automatic cells production of a wheel manufacturing industry was proposed by Hsu and Yang (2017), which was a fusion of a mixed integer linear programming and rolling-horizon optimization approaches. Most importantly, they argued that the approach was best suited for mass customization in Industry 4.0. The optimization problem, Partner Selection Problem (PSP), for non-hierarchical production networks in smart industrial systems was dealt in Mladineo et al. (2017). They proposed a fusion with the ant colony optimization method known as HUMANT (HUManoid ANT) algorithm.

Virtual Engineering

Jardim-Goncalves et al. (2017) reviewed the scope and challenges of the building paradigms of the Factories of the Future (FoF), in some major areas such as CPSs, Virtual Organisation (VO) of manufacturing engineering etc. The research community was moving towards the factory of the future by easily adapting to futuristic systems. Gorecky et al. (2017) discussed virtual training systems in the EU-FP7 project named VISTRA, taking note of design issues and challenges as well as ways to deal with them. A fusion of the industrial research areas between discrete event simulation (DES) and virtual reality (VR) was reviewed in Turner et al. (2016), using VR DES the tool for the analysis of complex data sets. The protocols to follow and future challenges for research on this topic were also elaborated in detail. In Jopp (2013) and Kube and Rinn (2014), the author focused on the importance of Industry 4.0 and the motivation to switch over to this fourth revolution of industry, emphasizing the integration of real and virtual world tools and technologies for successful adaptation to the new technology.

Visual Computing

Posada et al. (2015) discussed one of the key components of Industrie 4.0 i.e. visual computing as the software. The new technologies in visual computing helped in revolutionizing the manufacturing industries and discussed future prospects for research in this area. Xu et al. (2017) considered ViDX and demonstrated the design and implementation issues in this area. The pilot application was used to show the efficacy of the considered approach in the smart industry.

Scheduling

The scheduling aspect of due dates in autonomous manufacturing was addressed by Grundstein et al. (2017). The three main issues in job shop manufacturing such as: capability management, ordering, and release of order were considered. Ivanov et al. (2016) provided the theoretical and practical approaches towards scheduling schemes in smart factories covering the multi-objective flow-shop scheduling problem within the manufacturing industry. A proposal for smart factories in China by 2025, with the help of various intelligent technologies, was provided in Fengque et al. (2017). Some of these were: smart structure, efficient classification, scheduling, RFID, GAs etc. The scheduling process was a critical aspect in manufacturing systems. Zhu et al. (2017) provided a widespread review of this area and the semiconductor wafer fabrication background was considered as a prototype. Apart from this, the authors proposed a big data scheduling outline for CPSs for smart manufacturing systems. The assembly system design was studied extensively with the perspective of Industry 4.0 in Bortolini et al. (2017). Authors laid out some major challenges related to assembly line such as: environmental factors, performance metrics, scheduling issues etc.

Artificial Intelligence

The approach to efficiently and automatically handling industrial equipment was proposed by Adamson et al. (2017). This approach was adaptive to CPS based manufacturing setup. Also, it has feature based outline with the ability of function block (FB) in the robotics application. Chung and Kim (2016) compiled a list of under explored areas which could be studied by the research community such as robotics, driverless automobiles, 3D printing etc. Apart from these, the hot-topics in this area are wireless sensor networks and IoT. A concise review of US patents to figure out the mechanisms for manufacturing the major components of nanoscale microelectronics was conducted by T-H Lee (2017). This mechanism, intended for applications in artificial intelligence for Industry 4.0, fuses interactive visualization with the machine learning approaches, termed as Intelligent Viewer (iV) model. This approach was studied in Lotzmann et al. (2017) which could be used to analyse and perform statistics on the parameters of laser processes like cutting, printing, joining etc. The AI technique with pattern recognition was utilized to develop a block recognition system using convolutional neural network by Chou and Su (2017).

Hybrid approaches in Industry 4.0

Another survey and analysis paper on the growth and development in IoT and CPSs was provided by Preuveneers and Ilie-Zudor (2017). Such studies help researchers to gain more insights into the area and provide future scope for work in smart industry. Wan et al. (2017) consider the issue of active preventive maintenance and the related system architecture for manufacturing big data solutions in smart manufacturing systems. The data collection and data processing stages with respect to the cloud computing environment were also elaborated.

Evolving technologies such as Computer Integrated Manufacturing (CIM), CPSs and Cloud Manufacturing (CM) were explored by Yu et al. (2015) and they concluded that CPS and CM were the major components for the industrial fourth generation revolution. They also suggested that the real-time embedded systems (RTES) combined with CPS form the CIM and the internet domain for Industry 4.0. Advancements in simulation modelling with the introduction of CPSs and Industry 4.0 are presented by Bohács and Rinkács (2017). They provided a novel approach based on ontology-driven component while explaining it is functioning. Onyeiwu et al. (2017) emphasized the need of quality control in manufacturing systems. In Industry 4.0, an additional challenge, real-time product quality assurance, has attracted lot of attention from the research community.

Miscellaneous technologies

Richter et al. (2017) undertook review of a solution based film deposition in Industry 4.0. These organic films would provide a wider scope for the emerging technologies including IoT, medical care etc. The framework of PESTEL was demonstrated for inferences in this industry. A detailed overview of the ubiquitous manufacturing, achievable area for Industry 4.0 was provided by Chen and Tsai (2017). They also laid out challenges and future scopes. Faller and Feldmüller (2015) provided three unique Industry 4.0 training setups for the learning factory in the regional SMEs of the Velbert/ Heiligenhaus campus, Germany. Hortelano et al. (2017) proposed a novel Bluetooth Low Energy (BLE) topology for Industry 4.0. They first discussed the available literature related to mesh technologies and then introduced a new mesh technique which had been tested and verified for the industry 4.0 setup. Apart from providing solutions to the challenges in manufacturing systems, goals and challenges with respect to the user interface also needed to be tackled. For this purpose, Pfeiffer et al. (2016) classified three types of user requirements for the interface such as: situation aware, user-aligned, and self-reflective and suggested that user-centred design (UCD) be integrated with the development phase. The influence of Industry 4.0 on the industrial engineering (IE) in South Africa and possible approaches was discussed in the Sackey and Bester (2016). They provided a related literature survey and questionnaire surveys on IE techniques. They also mentioned that the methodology will upgrade with the development of Industry 4.0.

Agarwal and Brem (2015) focused on technology integration between operational technology (OT) and information technology (IT) and considered General Electric (GE) Company as a case study. From the analysis of their adaptation to new technology, it was concluded that such a revolution was non-linear and few alterations were required before implementing these technologies to current systems. Liu and Lu (2016) proposed a crowdsourcing design framework (CDF) for the refinement of online reviews of products by customers for generation maintenance. The experimentations performed showed the effectiveness of the proposed CDF with regards to innovation in technology. A physical model of ARM-based Server Cluster Board (SCB) and its working principle architecture was proposed in Xu and Chang (2017a). The SCB's performance was verified on a micro-server. The authors claimed that their scheme was tested on server level processors whereas traditional schemes tested performance only on embedded processors.

Chen et al. (2016) discussed the new paradigm for this problem and developed gene clustering approach based product known as pan-ethnic group. The title of Gentner (2016) was a self-explanatory parameter for the work done in the paper which discussed the motivation of Industry 4.0. The major bottlenecks such as agile project management, secure communication etc. were also pointed out together with Industry 4.0 and manufacturing systems. A no-regret-solution approach was discussed in Mothes (2015) for the modularization, smooth upgradation to new technology, and futuristic product manufacturing. This approach was flexible and could accommodate risk management along with the maximization of profit. The authors had taken the chemical–pharmaceutical industry as the major point of their discussion. The engineering and technical aspects of the rotating machinery in the self-aware health management system for Industry 4.0 was discussed in Guo et al. (2017). A novel pallet detection technique with the help of forklifts was proposed by Syu et al. (2016). They exploited an Adaptive Structure Feature (ASF) and Direction Weighted Overlapping (DWO) for this purpose. The results showed improved design as compared the traditional detection techniques. Polyvyanyy et al. (2017) proposed a querying method for the design process for Industry 4.0. A semantic background survey and a business process management was conducted for the validation of the method. Hofmann and Rüsch (2017) discussed the situation and prospects of logistics management in Industry 4.0. Readers could find a detailed overview of this topic in this paper. The authors concluded with several case studies that logistics management has the potential to play a large part in the growth of Industry 4.0.

Alexandre et al. (2017) proposed a methodology for the smooth integration of various industrial factors to justify the standards of craftsmanship. Attanasio (2017) focused on the importance of the micro manufacturing process which is now followed by all the known industries because of the optimized size of the devices and the less cost associated with it, in the future. The tool run-out in micro milling was measured in this paper. Industry 4.0 aims to have maximum output and minimum downtime. Maintenance is another issue which can be dealt with through various methodologies. Koenig (2017b) presented the presetters, which were the building blocks of Industry 4.0 and were already optimized to achieve the above mentioned goal. The preventive maintenance approach in Industry 4.0 was discussed in Upasani et al. (2017). The drawbacks of the current distributed system was monitored in this study. Also, the authors concluded that the proposed approach was flexible enough for next generation planning and implementation. Sikorski et al. (2017) explained the technicality of the blockchain technology. They also detailed a novel implementation of this technology for the electricity market and the relativity of blockchain technology with Industry 4.0.

Martinez et al. (2017) proposed an independent platform for industrial communication and device deployment termed as Intelligent Industrial Internet Mote (I3Mote). This platform had the potential to handle the challenges in industrial computing with optimized power consumption. The analysis report on the innovation policy framework was highlighted with regard to Industry 4.0 in Lin et al. (2017). They also performed a descriptive and statistical analysis for this framework. Demartini and Benussi (2017) examined the research work done in the field of education, industry and technology, so as to answer the question of availability of education X.0 by examining Web 4.0 and Industry 4.0. An extension to the work in Sackey and Bester (2016) was compiled in Sackey et al. (2017). They further introduced the learning factory to study the effect of Industry 4.0 on IE. The finding is that technical institutions have evolved more in this field as compared to traditional programmes in the region of South Africa.

Ai and Cheffena (2017) examined the channel ability and end-to-end average bit error rate (BER) for the noisy network in a multi-hop relay network. This network was based on the widely used Middleton's class-A model. Khare and Chin (2017) presented the importance of switching from data to knowledge gathering and strategies to attain goals within an industry. They elaborated the need for digitization for the progress of the manufacturing industry especially, intelligent chemical industry. Snášel et al. (2017) provided an extensive summary of the research work in topological techniques in big data. These techniques are characterized as geometrical and topological by the authors and discussed trend and future prospects. Kaihara et al. (2017) proposed a new manufacturing industry which relied on the incensement from various other industries depending on the availability of demand and resources. This manufacturing industry was called crowdsourced manufacturing. The paper was centralized around Industry 4.0. A kinetic-SDK speech recognition mechanism for diversifying the performance of traditional Kinect-SDK speech recognition systems was proposed by Ding and Lin (2017) since standard speech recognition systems were unreliable and used only one kinetic sensor. Authors used multiple kinetic sensor clients and a TCP/IP decision server. For server calculations with sensor recognized commands are what was needed for the Industry 4.0 environment. The validity of their proposed approach was tested on a two-wheel vehicle. A procedural architecture for an intrusion detection system to address the challenges and bottlenecks in advanced technology for Industry 4.0 was proposed in Haller and Genge (2017). A three-phase design policy was provided in this study which included cross-association, optimal design of intrusion detection system and examining through sensitivity analysis. A practical application of Industry 4.0 in the education system was detailed in Wanyama (2017). Here, an online laboratory simulation setup was developed to enable students to perform multiple experiments for better understanding of the theory. This application also had scope for performance analysis and feedback control centre. Liao et al. (2017) presented the literature survey for Industry 4.0 till June 2016. Chen and Sun (2017) proposed an intelligent computer-aided process planning (i-CAPP), which addressed the two most popular performance measures i.e. ease of manufacturing and efficiency which was used to enhance the readiness of Industry 4.0.

A theory for an automated online coordinated system was proposed by Wang et al. (2016a). This system was called coordination control policies (CCP) and had the potential to learn online from large-scale custom manufacturing tasks. This huge online multitask leaning approach could learn large-scale high-dimensional CCP in a flexible manufacturing environment. Giannetti and Ransing (2016) introduced a novel approach which uses quantile regression to enhance the robustness in Industry 4.0. Their approach could also be used in the tolerance synthesis problem. Tao et al. (2016) covered the vibration ride comfort level in latest vehicle systems within the Industry 4.0 framework. Chien et al. (2016) proposed a mathematical model to optimize two objectives; one to minimize total distance travelled and second to minimize the amount of manpower needed. This model was applied to the manual material handling system (MMHS). The necessities of the digital management aspect in precision casting enterprises are put forwarded in Ji et al. (2016b). Further, the basic principle and practical usage of these requirements were explained in brief. Schleipen et al. (2015b) discussed the flexibility of the equipment used in modern transport systems in Industry 4.0. Prause (2016) introduced the business administrative models related to the e-business perspective for Industry 4.0. For that, the effect of e-residency platform of the Estonia was studied. Yuksel and Sener (2017) discussed the organizational effect of Industry 4.0 using the content analysis method. The data was gathered based on some specific set of questions which were asked from several organizational heads. The initial outcomes and proceedings of the project on the robotic framework for re-manufacturing in jet engine was discussed in French et al. (2017). The future objective of the proposed framework was to produce an intelligent sensor routine for the aerospace related problems. Fuchs (2016) discussed the advancement in the capabilities of the industrial trucks and their role in the growth of Industry 4.0. Author also studied the enhanced efficiency in logistics with the connectivity and use of new technologies in industrial trucks. Schweer and Sahl (2017) researched and questioned the potential of the countries like Germany in the emerging era of Industry 4.0 technologies.

5. Discussion and conclusion

In this paper, a detailed bibliometric analysis in the emerging field of "Industry 4.0" has been conducted. Bibliometric analysis helped to discover the structures and development in this area. Two widely used repositories were used for the bibliometric analysis such as: WoS and Scopus. While 194 publications are indexed in WoS, Scopus mentioned 1425 publications, as it indexes various kinds of sources. Li is the most productive author in both the databases. Further, Li remains the most influential author in WoS while Kao is most influential in Scopus. Engineering and Computer Science are the subject areas which are mostly targeted in Industry 4.0. IEEE Access is the most productive journal in WoS and Procedia Manufacturing in Scopus. Germany and China are the most productive countries in Industry 4.0 while the South China University of Technology in China is the institute with the highest number of publications. The bibliometric analysis in this paper provided the intrinsic structure of the publications on Industry 4.0. This is a much needed study for the emerging field like Industry 4.0 so that the research community could probe the publication hierarchy in this area.

Table A.1
Top 40 highly cited papers on Industry 4.0 in WoS.

R	Authors & Year	Title	Source title	TC
1	Lasi et al. (2014)	Industry 4.0	Business & Information Systems Engineering	35
2	Wang et al. (2016b)	Towards smart factory for industry 4.0: a self-organized multi-agent system with big data based feedback and coordination	Computer Networks	23
3	Monostori (2014)	Cyber–physical systems in manufacturing	CIRP Annals-Manufacturing Technology	19
4	Kang et al. (2016)	Smart Manufacturing: Past Research, Present Findings, and Future Directions	International Journal of Precision Engineering and Manufacturing-Green Technology	19
5	Zhan et al. (2015)	Cloud Computing Resource Scheduling and a Survey of Its Evolutionary Approaches	ACM Computing Surveys	17
6	Wan et al. (2016a)	Software-Defined Industrial Internet of Things in the Context of Industry 4.0	IEEE Sensors Journal	14
7	Shafiq et al. (2015a)	Virtual Engineering Object (VEO): Toward Experience-Based Design and Manufacturing for Industry 4.0	Cybernetics and Systems	14
8	Li et al. (2017a)	A review of industrial wireless networks in the context of Industry 4.0	Wireless Networks	13
9	Ivanov et al. (2016)	A dynamic model and an algorithm for short-term supply chain scheduling in the smart factory industry 4.0	International Journal of Production Research	11
10	Schuh et al. (2014b)	Global Footprint Design based on genetic algorithms — An Industry 4.0 perspective	CIRP Annals-Manufacturing Technology	11
11	Yue et al. (2015)	Cloud-assisted industrial cyber–physical systems: An insight	Microprocessors and Microsystems	10
12	Harrison et al. (2016a)	Engineering Methods and Tools for Cyber–Physical Automation Systems	Proceedings of the IEEE	8
13	Roy et al. (2016)	Continuous maintenance and the future — Foundations and technological challenges	CIRP Annals-Manufacturing Technology	7
14	Mosterman and Zander (2016)	Industry 4.0 as a Cyber–Physical System study	Software and Systems Modelling	6
15	Hortelano et al. (2017)	From Sensor Networks to Internet of Things. Bluetooth Low Energy, a Standard for This Evolution	Sensors	5
16	Fraga-Lamas et al. (2016)	Smart Pipe System for a Shipyard 4.0	Sensors	5
17	Harrison et al. (2016b)	Engineering the Smart Factory	Chinese Journal of Mechanical Engineering	5
18	Schleipen et al. (2015a)	Requirements and concept for Plug-and-Work Adaptivity in the context of Industry 4.0	At-Automatisierungstechnik	5
19	Theorin et al. (2017)	An event-driven manufacturing information system architecture for Industry 4.0	International Journal of Production Research	4
20	Cao et al. (2017)	The concept and progress of intelligent spindles: A review	International Journal of Machine Tools & Manufacture	4
21	Beyerer et al. (2015)	Industry 4.0	At-Automatisierungstechnik	4
22	Tao et al. (2017)	SDMSim: A manufacturing service supply–demand matching simulator under cloud environment	Robotics and Computer-Integrated Manufacturing	3
23	Gorecky et al. (2017)	Introduction and establishment of virtual training in the factory of the future	International Journal of Computer Integrated Manufacturing	3
24	Condry and Nelson (2016)	Using Smart Edge IoT Devices for Safer, Rapid Response With Industry IoT Control Operations	Proceedings of the IEEE	3
25	Bangemann et al. (2016)	Integration of Classical Components Into Industrial Cyber–Physical Systems	Proceedings of the IEEE	3
26	Pfeiffer et al. (2016)	Empowering User Interfaces for Industrie 4.0	Proceedings of the IEEE	3
27	Vogel-Heuser and Hess (2016)	Industry 4.0-Prerequisites and Visions	IEEE Transactions on Automation Science and Engineering	3
28	Shafiq et al. (2016)	Virtual Engineering Factory: Creating Experience Base for Industry 4.0	Cybernetics and Systems	3
29	Alexopoulos et al. (2016)	A concept for context-aware computing in manufacturing: the white goods case	International Journal of Computer Integrated Manufacturing	3
30	Hoeme et al. (2015)	Semantic Industry: Challenges for computerized information processing in Industrie 4.0	At-Automatisierungstechnik	3
31	Wan et al. (2017)	A Manufacturing Big Data Solution for Active Preventive Maintenance	IEEE Transactions on Industrial Informatics	2
32	Pfeiffer (2017)	The Vision of Industrie 4.0 in the Making-a Case of Future Told, Tamed, and Traded	Nanoethics	2
33	Liu and Xu (2017)	Industry 4.0 and Cloud Manufacturing: A Comparative Analysis	Journal of Manufacturing Science and Engineering-Transactions of The ASME	2
34	Wang et al. (2017)	A hybrid-data-on-tag-enabled decentralized control system for flexible smart workpiece manufacturing shop floors	Proceedings of the Institution of Mechanical Engineers Part C-Journal of Mechanical Engineering Science	2
35	Sackey and Bester (2016)	Industrial Engineering Curriculum in Industry 4.0 in a South African Context	South African Journal of Industrial Engineering	2
36	Oesterreich and Teuteberg (2016)	Understanding the implications of digitization and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry	Computers in Industry	2
37	Qin and Cheng (2017b)	Special Issue on Future Digital Design and Manufacturing: Embracing Industry 4.0 and Beyond	Chinese Journal of Mechanical Engineering	2
38	Lin et al. (2016a)	Autonomous Channel Switching: Towards Efficient Spectrum Sharing for Industrial Wireless Sensor Networks	IEEE Internet of Things Journal	2
39	Trappey et al. (2016)	A Review of Technology Standards and Patent Portfolios for Enabling Cyber–Physical Systems in Advanced Manufacturing	IEEE Access	2
40	Flatscher and Riel (2016)	Stakeholder integration for the successful product-process co-design for next-generation manufacturing technologies	CIRP Annals-Manufacturing Technology	2

Table A.2
Top 40 highly cited papers on Industry 4.0 in Scopus.

R	Authors	Title	Source title	TC
1	Lee et al. (2015)	A Cyber–Physical Systems architecture for Industry 4.0-based manufacturing systems	Manufacturing Letters	259
2	Monostori (2014)	Cyber–physical production systems: Roots, expectations and R & D challenges	Procedia CIRP	132
3	Lee et al. (2014)	Service innovation and smart analytics for Industry 4.0 and big data environment	Procedia CIRP	127
4	Lasi et al. (2014)	Industry 4.0	Business and Information Systems Engineering	86
5	Zhan et al. (2015)	Cloud computing resource scheduling and a survey of its evolutionary approaches	ACM Computing Surveys	63
6	Hermann et al. (2016)	Design principles for industrie 4.0 scenarios	Proceedings of the Annual Hawaii International Conference on System Sciences	57
7	Gorecky et al. (2014)	Human–machine-interaction in the industry 4.0 era	Proceedings — 2014 12th IEEE International Conference on Industrial Informatics, INDIN 2014	53
8	Posada et al. (2015)	Visual Computing as a Key Enabling Technology for Industrie 4.0 and Industrial Internet	IEEE Computer Graphics and Applications	45
9	Jazdi (2014)	Cyber–physical systems in the context of Industry 4.0	Proceedings of 2014 IEEE International Conference on Automation, Quality and Testing, Robotics, AQTR 2014	41
10	Shrouf et al. (2014)	Smart factories in Industry 4.0: A review of the concept and of energy management approached in production based on the Internet of Things paradigm	IEEE International Conference on Industrial Engineering and Engineering Management	41
11	Kang et al. (2016)	Smart manufacturing: Past research, present findings, and future directions	International Journal of Precision Engineering and Manufacturing — Green Technology	38
12	Stock and Seliger (2016)	Opportunities of Sustainable Manufacturing in Industry 4.0	Procedia CIRP	26
13	Schmidt et al. (2015)	Industry 4.0 - Potentials for creating smart products: Empirical research results	Lecture Notes in Business Information Processing	22
14	Imtiaz and Jasperneite (2013)	Scalability of OPC-UA down to the chip level enables "internet of Things"	IEEE International Conference on Industrial Informatics (INDIN)	22
15	Kagermann (2015)	Change through digitization—value creation in the age of industry 4.0	Management of Permanent Change	21
16	Yue et al. (2015)	Cloud-assisted industrial cyber–physical systems: An insight	Microprocessors and Microsystems	19
17	Varghese and Tandur (2014)	Wireless requirements and challenges in Industry 4.0	Proceedings of 2014 International Conference on Contemporary Computing and Informatics, IC3I 2014	19
18	Schlechtendahl et al. (2015)	Making existing production systems Industry 4.0-ready: Holistic approach to the integration of existing production systems in Industry 4.0 environments	Production Engineering	19
19	Zhou et al. (2015)	Industry 4.0: Towards future industrial opportunities and challenges	2015 12th International Conference on Fuzzy Systems and Knowledge Discovery, FSKD 2015	18
20	Wan et al. (2016a)	Software-Defined Industrial Internet of Things in the Context of Industry 4.0	IEEE Sensors Journal	17
21	Ivanov et al. (2016)	A dynamic model and an algorithm for short-term supply chain scheduling in the smart factory industry 4.0	International Journal of Production Research	17
22	Roy et al. (2016)	Continuous maintenance and the future — Foundations and technological challenges	CIRP Annals — Manufacturing Technology	17
23	Paelke (2014)	Augmented reality in the smart factory: Supporting workers in an industry 4.0. environment	19th IEEE International Conference on Emerging Technologies and Factory Automation, ETFA 2014	17
24	Shafiq et al. (2015b)	Virtual engineering object (VEO): Toward experience-based design and manufacturing for industry 4.0	Cybernetics and Systems	16
25	Vogel-Heuser et al. (2014)	Coupling heterogeneous production systems by a multi-agent based cyber–physical production system	Proceedings — 2014 12th IEEE International Conference on Industrial Informatics, INDIN 2014	15
26	Yu et al. (2015)	Computer-Integrated Manufacturing, Cyber–Physical Systems and Cloud Manufacturing — Concepts and relationships	Manufacturing Letters	14
27	Weyer et al. (2015)	Towards Industry 4.0 - Standardization as the crucial challenge for highly modular, multi-vendor production systems	IFAC-PapersOnLine	14
28	Kolberg and Zühlke (2015)	Lean Automation enabled by Industry 4.0 Technologies	IFAC-PapersOnLine	14
29	Schuh et al. (2014b)	Global Footprint Design based on genetic algorithms — An "industry 4.0" perspective	CIRP Annals — Manufacturing Technology	14
30	Schuh et al. (2014a)	Collaboration moves productivity to the next level	Procedia CIRP	14
31	Pisching et al. (2015)	Service composition in the cloud-based manufacturing focused on the industry 4.0	IFIP Advances in Information and Communication Technology	13
32	Dombrowski and Wagner (2014)	Mental strain as field of action in the 4th industrial revolution	Procedia CIRP	13
33	Harrison et al. (2016a)	Engineering Methods and Tools for Cyber–Physical Automation Systems	Proceedings of the IEEE	12
34	Mosterman and Zander (2016)	Industry 4.0 as a Cyber–Physical System study	Software and Systems Modelling	12
35	Shafiq et al. (2015a)	Virtual engineering object/virtual engineering process: A specialized form of cyber–physical system for industrie 4.0	Procedia Computer Science	12
36	Seitz and Nyhuis (2015)	Cyber–physical production systems combined with logistic models-a learning factory concept for an improved production planning and control	Procedia CIRP	12
37	Faller and Feldmüller (2015)	Industry 4.0 learning factory for regional SMEs	Procedia CIRP	11
38	Ungurean et al. (2014)	An IoT architecture for things from industrial environment	IEEE International Conference on Communications	11
39	Zawadzki and Zywicki (2016)	Smart product design and production control for effective mass customization in the industry 4.0 concept	Management and Production Engineering Review	10
40	Bagheri et al. (2015)	Cyber-physical systems architecture for self-aware machines in industry 4.0 environment	IFAC-PapersOnLine	10

After the bibliometric analysis, top papers ranked on the basis of total citations are analysed. Then, the visualization of the most common keywords in Industry 4.0 is presented. The most common keywords are: cyber–physical system, internet of things, smart manufacturing, simulation etc. Finally, the contribution of the publications in WoS and Scopus are extensively discussed. The overview of the published work in Industry 4.0 is categorized into various sub-sections which would help the reader to get an overall picture of its different applications areas.

The limitation of this study is that the bibliometric study provides the number of papers and their citations. However, numbers represent the quantity but citations does not signify quality. Moreover, we have covered the widely used WoS and Scopus for bibliometric study, however, there are some other sources which include open-access journals. Thus, more analysis with other indexing databases such as Google Scholar could be considered as a future scope of this study.

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Appendix

See Tables A.1 and A.2.

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