ITcon
www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

A BIBLIOMETRIC AND SCIENTOMETRIC MAPPING OF INDUSTRY 4.0 IN CONSTRUCTION

SUBMITTED: February 2019
REVISED: January 2020
PUBLISHED: June 2020
EDITOR: Žiga Turk
DOI: 10.36680/j.itcon.2020.017

Nadia Safura Zabidin,
Faculty of Civil Engineering, Universiti Teknologi MARA (UiTM), Shah Alam 40450 Selangor, Malaysia;
nadiasafura@gmail.com

Sheila Belayutham, Dr,
Faculty of Civil Engineering, Universiti Teknologi MARA (UiTM), Shah Alam 40450 Selangor, Malaysia;
sheila6913@uitm.edu.my

Che Khairil Izam Che Ibrahim, Associate Professor Dr,
Faculty of Civil Engineering, Universiti Teknologi MARA (UiTM), Shah Alam 40450 Selangor, Malaysia;
chekhairil449@uitm.edu.my

SUMMARY: *Industry 4.0 embraces digitization and smart products or processes that are integrated with several technological developments to control the entire value chain of workflows. The construction industry is also captivated with the idea of Industry 4.0 transformation that changes the traditional system into digital and cyber-physical system that interacts and connects across the geographical and organizational borders. However, as construction is commonly known as a low-technologically advanced industry, studies on Industry 4.0 in construction still remains elusive, as compared to other sectors such as manufacturing, electrical and electronic engineering and computer science. Therefore, this study aims to explore the current state of Industry 4.0 application from the construction engineering perspective. A systematic literature review (SLR) was conducted to identify publications related to Industry 4.0 in construction. A bibliometric analysis has been outlined through exclusion and inclusion principles, while a scientometric analysis has been further applied to enhance the SLR findings through 'science mapping' visualization techniques. This study presents the relevance, along with the movement, adoption and adaption of Industry 4.0 in the construction industry that further enables the spark of new ideas, in effort to realize and comprehend the current and future technological transformation in construction.*

KEYWORDS: *Industry 4.0; Construction; Systematic Literature Review; Bibliometric Analysis; Scientometric Analysis*

REFERENCE: *Nadia Safura Zabidin, Sheila Belayutham, Che Khairil Izam Che Ibrahim (2020). A bibliometric and scientometric mapping of Industry 4.0 in construction. Journal of Information Technology in Construction (ITcon), Vol. 25, pg. 287-307, DOI: 10.36680/j.itcon.2020.017*

1. INTRODUCTION

The term Industry 4.0 or Industrie 4.0 have been globally introduced by the German federal government in 2011 (Bahrin et al., 2016). Industry 4.0 is proposed as a new emerging structure that uses information and communications network of data sharing for a widely automated exchange of information between production and processes. Industry 4.0 will change the design, production, operation and service of invention and organization (Rüßmann et al., 2015). According to Vaidya et al., (2018), Industry 4.0 is defined as a new level of organization and control over the entire value chain and life cycle of products, geared towards increasing individualized customers' requirements. The nine pillars of Industry 4.0 are systems integration, augmented reality, additive manufacturing, cyber-security, cloud computing, autonomous systems, simulation, internet of things and big data.

Various studies have been carried out on the applications of Industry 4.0, but only few have been conducted from the construction engineering perspective. For instance, Industry 4.0 is used most in the engineering sector, computer science, business management, decision science, mathematics, material science, social science and many more (Glas & Kleemann, 2016; Lu, 2017; Rüßmann et al., 2015). However, based on a study by Liao et al. (2017), the three engineering fields that applied Industry 4.0 the most are electrical and electronic, industrial and manufacturing and mechanical. Limited studies were found on the applications of Industry 4.0 in construction engineering, as the field of study is still in the process of formation, which necessitates further investigation (Oesterreich & Teuteberg, 2016). This is resonated by Klinc and Turk (2019), who have further shared their thoughts on how construction is considered to be ahead on the adoption of Industry 4.0 elements, as well as the potentials of the concept within the sector.

Construction industry is one of the sectors that contributes to the Gross Domestic Product (GDP) of a nation through economic development, by creating capital trades and resource purchase processes (Osunsanmi et al., 2018). Industry 4.0 consists of technologies and concepts that could automate the construction process and creates new construction environments by adopting smart factories, simulation/modelling and digitization (Oesterreich & Teuteberg, 2016). The adoption of Industry 4.0 in the construction sector is expected to increase the productivity and profitability towards construction's development (Holt & Kearney, 2015). However, the common conception of low-technological adoption in construction still looms the industry and the lack of innovation and technological processes in construction would increase the gap between Industry 4.0 and construction.

Therefore, this study seeks to explore the current state of Industry 4.0 in the construction industry. From a systematic literature review (SLR), bibliometric analysis, content analysis and scientometric analysis techniques have been conducted to explore the nature of Industry 4.0 in the current construction sector. This study aims to address the following research questions:

- What are the current pillars of Industry 4.0 that have been adopted in the construction engineering practice?
- How has the construction industry adapted the concept of Industry 4.0 within the construction engineering practice?

2. METHODOLOGY

The research methodology for this study is shown in Fig. 1. A combination of several different analyses has been conducted to achieve the purpose of this study, namely bibliometric analysis, content analysis and scientometric analysis through systematic literature review (SLR). SLR is essential in drawing the boundary, gap of research and limitations of study (Comerio & Strozzi, 2018). According to Saunders et al., (2007), a SLR is an interactive cycle of defining suitable search keywords, searching related documents and execute content analysis. In a recent study, Oesterreich & Teuteberg (2016) have adopted the SLR method to obtain the state-of-the-art of Industry 4.0 technologies practiced in the construction industry, which were then analysed through bibliometric and content analysis. The preliminary data source for this study has been retrieved from the Scopus database. According to Zhao & Strotmann (2015), the Scopus database is the most commonly used database for citation because the database covers nearly 60% of the citation index, larger than Web of Science (WoS).

In research method, the SLR approach was first employed to collect the relevant information and data by isolating the papers according to the keywords, language, document types and etc. Secondly, a bibliometric analysis has been conducted to refine influential research and to identify research trends using quantitative analysis. Bibliometric analysis is essential in order to investigate and further understand the research by defining research categories, evaluating relevant sectors and tracking research disciplines (Olawumi et al., 2017). Thirdly, the structural process in content analysis describes the literatures in categorical terms, in order to address the purpose of this study. A careful review of the title and abstract was performed to analyse the current state of Industry 4.0 in construction engineering. Finally, in order to enhance the findings from the bibliometric and content analysis, a scientometric analysis was conducted by using a text mining software.

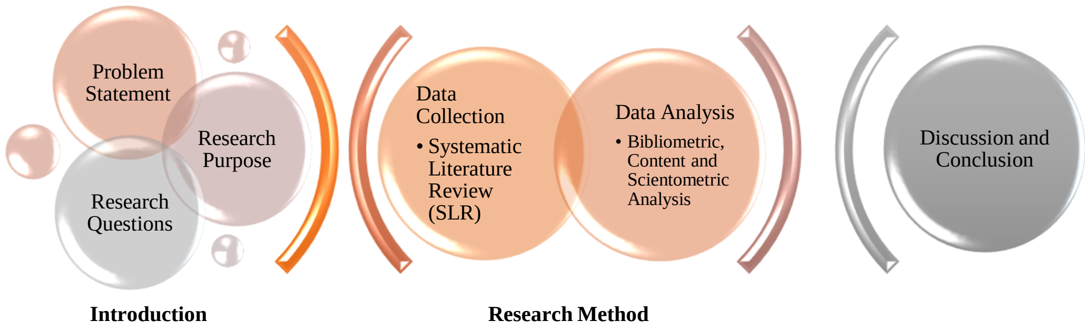

FIG. 1: Research Methodology

According to He et al., (2017), a scientometric analysis could be used to construct knowledge maps by allowing bibliometric data to be interpreted into new insights for research objectives, based on accurate representation and analysis of previous research efforts. Following this method, a summary of current status and future direction of studies can be determined. Van Eck & Waltman (2014) mentioned that there are various text mining software tools that could be used to carry out science mapping analysis, such as CitNetExplorer, CiteSpace, Gephi, HistCite, Pajek, Sci² and VOSviewer. In this study, the VOSviewer software has been used to analyse key findings from the literature and the results will be illustrated in the form of science mapping with further critical discussions. The VOSviewer software has been selected, over the other software, as VOSviewer is most suitable for visualising larger networks (Van Eck & Waltman, 2014). In addition, Jin et al., (2018) have also highlighted the increasing adoption of this software among construction field researchers.

2.1 Systematic Literature Review

Systematic Literature Review (SLR) is an appropriate and suggested technique to summarize current knowledge, as well as to discover conceivable research gaps in a research process (Oesterreich & Teuteberg, 2016). Research gaps are important to strengthen a field of study, as the use of SLR guideline enables the identification and analysis of scientific and practical literatures (Kamble et al., 2018). Fig. 2 shows the six processes adopted for the SLR in this study (Kamble et al., 2018).

The assessment criteria for the SLR of this study is given in Table 1, which comprises of the principles of exclusion and inclusion in order to obtain a precise and related dataset for further analysis.

TABLE 1: Inclusion and exclusion criteria

Inclusion/ Exclusion	**Criteria**	**Criteria Explanation**	**Results (No. of Documents)**
Exclusion	Search Engine Reason (SER)	SER 1: The search engine used was Scopus SER 2: All searches were limited to works published from 2011 until the current year because the IR 4.0 have been officially introduced in year 2011 at the Hanover Fair by the German Government SER 3: Papers with relevant title, abstract and keywords in English only	SER 1: 6086 SER 2: 6081 SER 3: 5440
	Without Full-text (WF)	Papers without full texts were assessed	WF: 5440
	Non-Related (NR)	Excluded articles published in letter, editorial, note, short survey, business article or press article-in-press, review, editorial, short survey and erratum	NR: 4646
	Loosely	The content is irrelevant with keywords searched:	LR: 4646

Inclusion/ Exclusion	Criteria	Criteria Explanation	Results (No. of Documents)
	Related (LR)	"Industrial Revolution 4.0", "Industry 4.0", "IR 4.0" and "Industrie 4.0"	
Inclusion	Partially Related (PR)	Search mentioning construction engineering based on the four major keywords and Engineering ("Industrial Revolution 4.0", "Industry 4.0", "IR 4.0" and "Industrie 4.0" + Engineering)	PR: 3004
	Strongly Related (SR)	Focus on papers containing the descriptions of Construction Engineering within the four keywords ("Industrial Revolution 4.0", "Industry 4.0", "IR 4.0" and "Industrie 4.0" + Engineering + Construction)	Closely Related (CR): 299
		Only papers on the application of "Industrial Revolution 4.0", "Industry 4.0", "IR 4.0" and "Industrie 4.0" topics are selected	Relevant Papers: 12

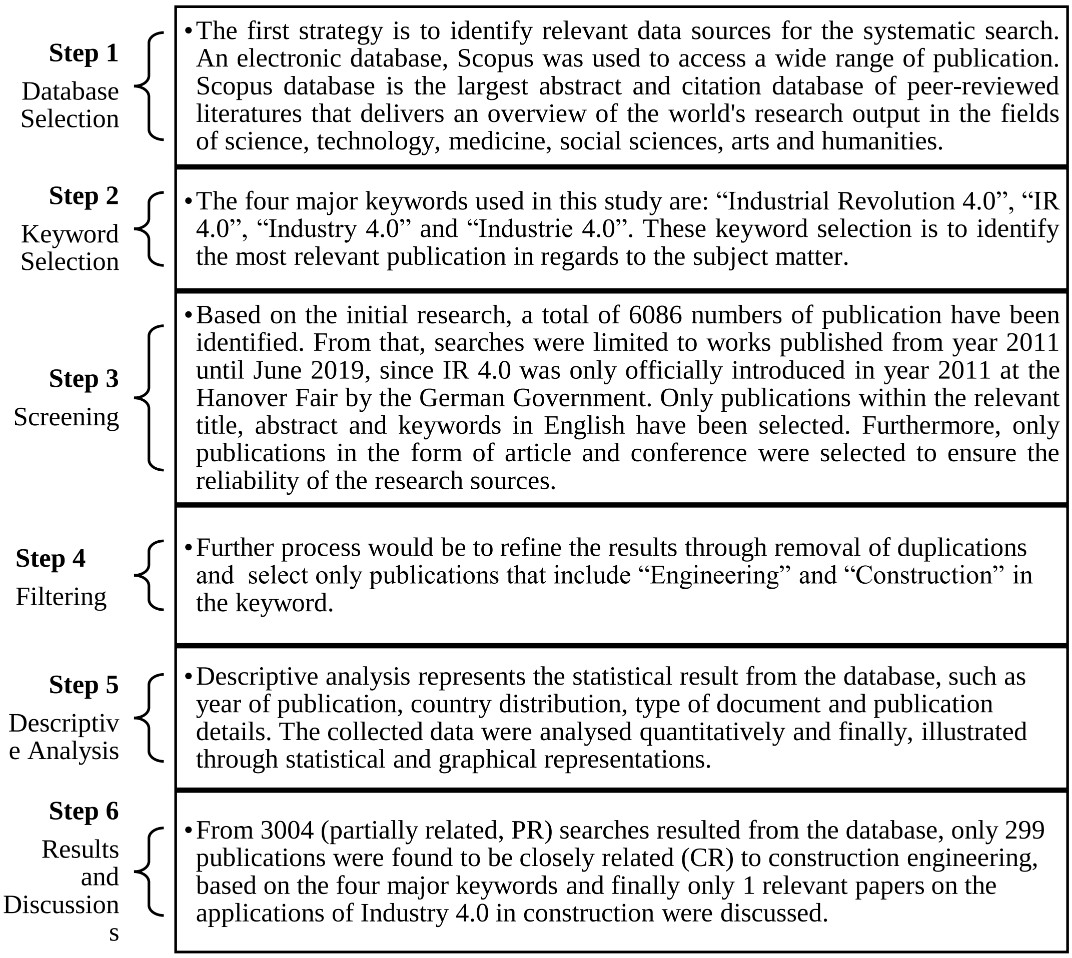

FIG. 2: Steps adopted for the systematic literature review

2.2 Bibliometric Analysis

The aim of this study can be achieved by applying the bibliometric technique in conducting quantitative analysis of previous published papers that are closely related to this study, based on the SLR data. In reference to Table 1, only Strongly Related (SR) 299 publications from the SLR were further analysed. This technique was conducted to obtain an overview of the descriptive data such as year, country, types of documents and trends of publication. Fig. 3 shows the outline for the bibliometric analysis.

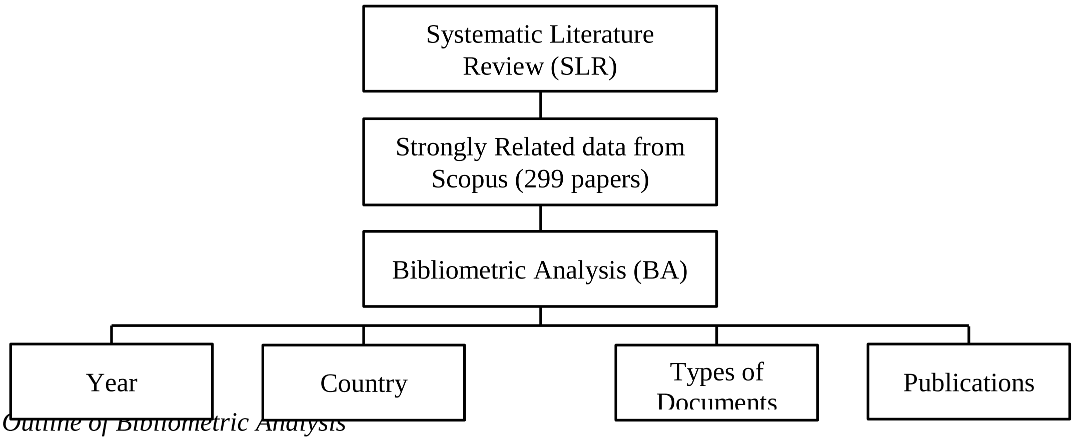

FIG. 3: Outline of Bibliometric Analysis

2.3 Content Analysis

Content analysis has been used to further derive findings from the exclusion and inclusion method given in Table 1. The aim of this method is to investigate the current applications of Industry 4.0 in construction practices from the Scopus database. This method has been applied following Mayring's model, as shown in Fig. 4. Firstly, the research questions were referred in order to align the analysis with the research purpose. Secondly, the formulation of categories is conducted based on the papers' definitions, examples and keywords, and finally, only papers closely related to the subject matter are chosen to be further discussed.

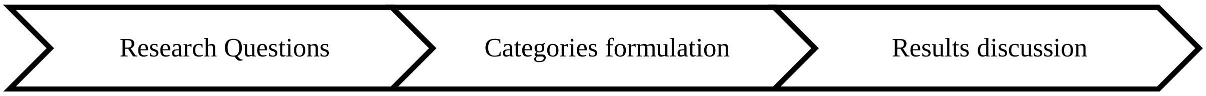

FIG. 4: Content analysis procedure (Mayring, 2000)

2.4 Scientometric Analysis

Scientometric analysis is one of the methods to visualize bibliometric networks in order to synthesize science mapping that describes peculiar disciplines, scientific realms and research framework from comprehensive bodies of literature and large bibliographical dataset (Cobo et al., 2011). A thorough literature review approach was conducted by using a text-mining tool, VOSviewer to scrutinize a large diversity of bibliometric networks. The tool extends from citation relations between publications, to networks of co-authorship relations between researchers, and co-occurrence relationship between keywords (van Eck & Waltman, 2014). Based on the SLR conducted earlier, only limited numbers of related findings have emerged. Therefore, this innovative visualization technique has been selected to analyse and display a larger network from the Scopus database. Fig. 5 shows the data mining process for this study.

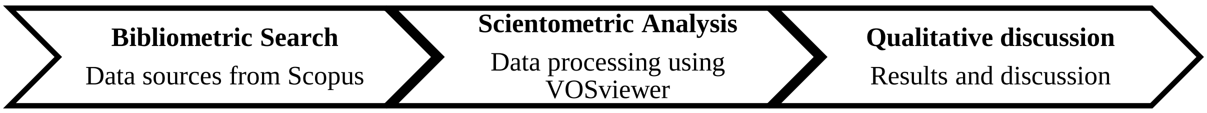

FIG. 5: Processes of Science Mapping Analysis

In this section, findings from the bibliometric analysis have been used as the basis for the scientometric analysis. From the SLR, the most comprehensive paper on Industry 4.0 in construction was written by Oesterreich & Teuteberg, 2016, who have utilised a triangulation approach in discussing the implications of digitisation and automation, as well as the research agenda for the construction sector. This article has captured 14 elements of Industry 4.0 from the context of construction. The 14 elements have been used as the keyword search in the Scopus database, for this study. The study area is limited to the time frame between year 2011 until 2019 and only English-language publications were selected. The subject area searched for this study are "engineering" and "construction". After the refining process, a total of 2417 papers were found related to this study. Table 2 shows the resulting papers from the Scopus search.

The next stage involves the visualization process of the 2417 papers that have been transferred into the VOSviewer software. The purpose of this step is to analyse the bibliometric records directly from Scopus and generate maps from the network analysis (Hosseini et al., 2018). The types of analysis conducted were co-authorship, which identifies the authors, as well as country units and co-occurrence analysis, which analyses the author keywords based on the bibliometric data obtained. The network of author keywords will pinpoint the frequently studied topics, along with the inter-relatedness among publications (Jin et al., 2018). Furthermore, the author and country units illustrate a list of numbers where the adoption/adaption of Industry 4.0 applications were used the most. The VOSviewer provides three types of visualizations, which are network, overlay and density visualization. In this study, only network and density visualizations were used as both visualizations provide clearer results for this study. The network visualization indicates the weight of an item that set equally to the total strength of all links between the items, while the same colour on the circle shows the cluster of each item (van Eck & Waltman, 2013). The density visualization shows that the larger number of items are the higher weights of neighbouring items in contrast to the lowest which is the smaller size of items.

TABLE 2: Distribution of the keywords and articles for Industry 4.0 in construction

Keywords	Number of findings
Building Information Modelling (BIM)	1247
Internet of Things (IoT)/Internet of Services (IoS)	89
Product-Lifecycle-Management (PLM)	8
Cloud Computing	48
Mobile Computing	22
Augmented Reality (AR)/Virtual Reality (VR)/Mixed Reality (MR)	198
Robotics	484
Radio-Frequency Identification (RFID)	80
Big Data	53
3D-Printing/Additive Manufacturing	101
Smart Factory	0
Human-Computer-Interaction (HCI)	23
Modularisation	7
Cyber-Physical Systems (CPS)/Embedded system	57
Total	2417

3. DATA ANALYSIS

Quantitative descriptive analysis represents research patterns that answers the who, what, where, when and how questions in order to fulfil the capacities, needs, methods, practices, guidelines, data and classifications of the study (Loeb et al., 2017). There are three combinations of analyses utilised in this study, namely bibliometric analysis, content analysis and scientometric analysis.

3.1 Results of Bibliometric Analysis

The bibliometric analysis has been conducted based on the 299 Strongly Related findings, as given in Table 1.

3.1.1 Year-wise trend in publications

Fig. 6 shows the trend of publication-year for Industry 4.0 in construction engineering from year 2014 till June 2019. Exponential growth in publications on the subject matter is observed from year 2016 to 2018, from which 22 to 148 papers were published. This trend shows the greater interest from researches towards Industry 4.0 as a subject matter in construction engineering.

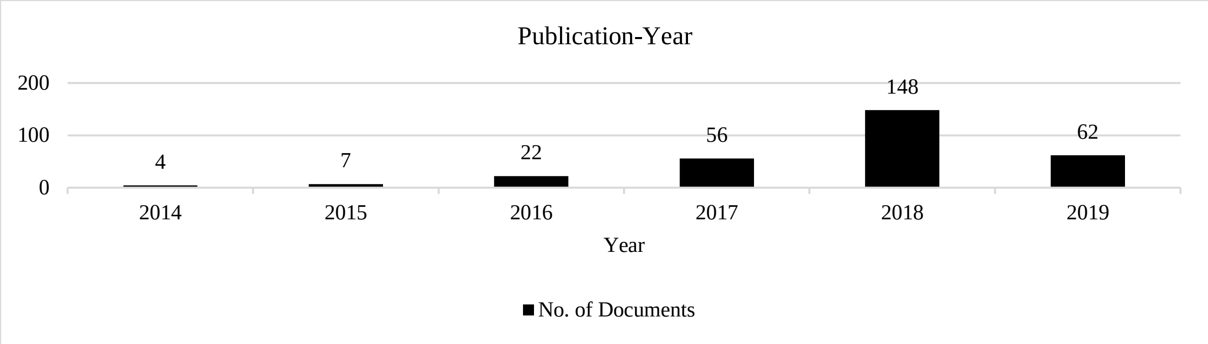

FIG.6: Year-wise trend in publications

3.1.2 Country-wise distribution of publications

In reference to Fig. 7, most of the publications were dominated by Germany, followed by Italy, the United Kingdom, China and the United States. The possible reason for German to top the publication is due to the country's public policy of Industrie 4.0, as it was deemed to be one of the earliest, if not the earliest policy established for navigating through Industrial Revolution 4.0. In addition, the Industrie 4.0 policy was also found to be the most popular/highest cited policy, as mentioned in Liao et al. (2018). The other early influential public policies of IR 4.0 for the top five countries were Fabbrica Intelligente (Italy), Future of Manufacturing (UK), Made in China 2025 (China), and Advanced Manufacturing Partnership (US) (Liao et al. 2018).

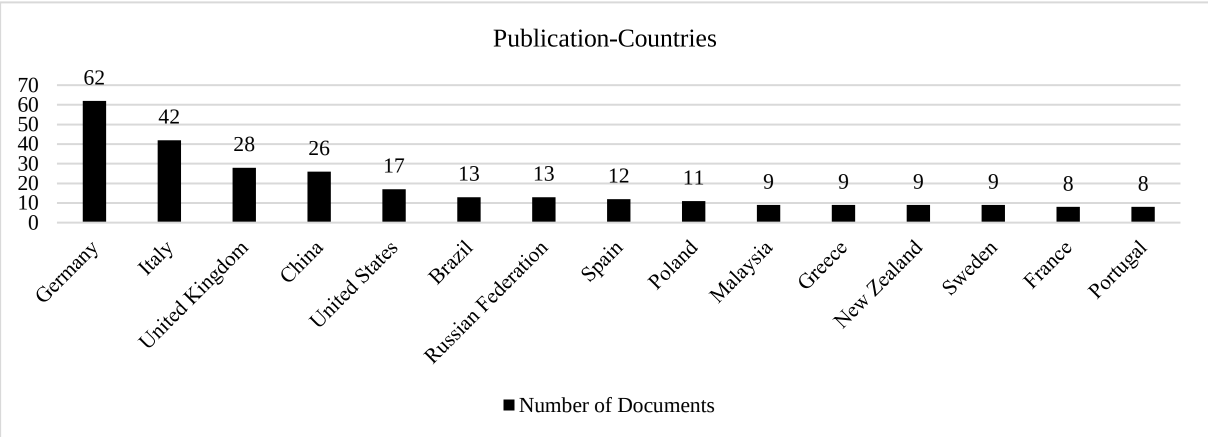

FIG.7: The trend of publication across different countries

**Note: Only the top 15 countries with the highest numbers of publication on Industry 4.0 in construction engineering are highlighted in Fig.7.*

3.1.3 Types of documents

Fig. 8 shows that from the 299 documents, 172 documents are journal articles, while the other 127 are conference papers.

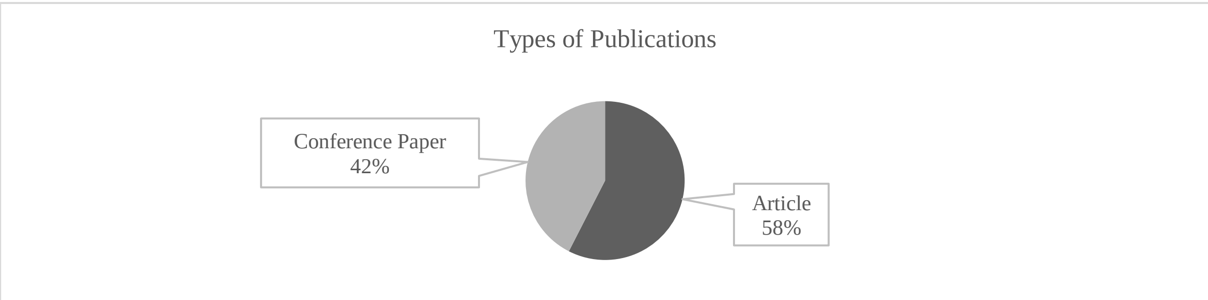

FIG. 8: The types of publications

3.1.4 Publication Details

Fig. 9 shows the number and details of the publications. Procedia manufacturing is the highest contributor to the publications, followed by Procedia CIRP, International Journal of Advanced Manufacturing and the least publication comes from Applied Energy.

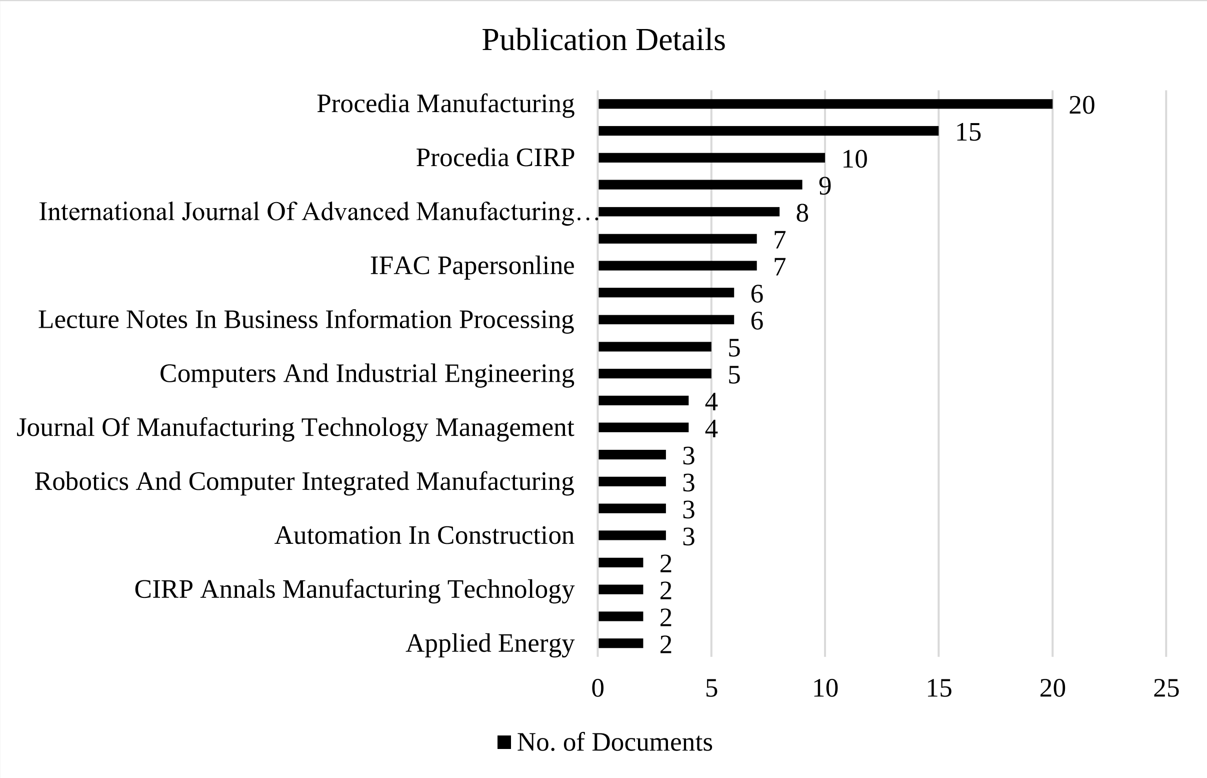

FIG.9: Details of the publications

**Note: Only the top 20 publications on Industry 4.0 in construction engineering are highlighted in Fig.9.*

Procedia manufacturing has published conference proceedings in the field of manufacturing engineering and a recent search (retrieved on 2 June 2019) on the source shows that the most downloaded papers were closely related to Industry 4.0, which are Industry 4.0-A Glimpse (Vaidya et al., 2018) and What does Industry 4.0 mean to Supply Chain? (Tjahjono et al., 2017). Similar trend was observed in Procedia CIRP, a production engineering publication and Computers in industry (an ICT related publication) that have featured all Industry 4.0 related papers in the most downloaded section.

3.2 Content Analysis Results

Findings based on the four main keywords used in the SLR ("Industrial Revolution 4.0", "IR 4.0", "Industry 4.0" and "Industrie 4.0") for construction engineering, are highlighted in Table 3. From the 299 publications, only 12 publications were selected after the exclusion and inclusion process.

TABLE 3: Findings in relation to Industry 4.0 in construction engineering

Keywords	"Keywords" + Engineering + Construction	Relevant Papers
Industrial Revolution 4.0	3	0
IR 4.0	2	1
Industry 4.0	277	11
Industrie 4.0	17	0
Total	299	12

Findings in Table 4 indicate that the most popular Industry 4.0 pillar used in construction engineering is simulation. Five out of twelve applications in construction have adopted simulation, with Internet of Things (IoT), System Integration and Autonomous System identified in the other publications.

TABLE 4: The applications of Industry 4.0 in construction engineering

No.	Title	Authors/ Year	Application
1.	Industry Revolution IR 4.0: Future Opportunities and Challenges in Construction Industry	(Alaloul et al., 2018)	Literature Review
2.	Automated design and modelling for mass-customized housing. A web-based design space catalogue for timber structures	(Bianconi et al., 2019)	Simulation
3.	Implications of Construction 4.0 to the workforce and organizational structures	(Soto et al., 2019)	Autonomous System
4.	Digital construction: From point solutions to IoT ecosystem	(Woodhead et al., 2018)	Internet of Things
5.	Internet of Things for Structural Health Monitoring	(Sciammarella & Olivito, 2018)	Internet of Things
6.	Cyber-physical systems for construction industry	(Correa, 2018)	Simulation
7.	Dynamic model of implementation efficiency of Building Information Modelling (BIM) in relation to the complexity of buildings and the level of their safety	(Hotový, 2018)	Simulation
8.	Industry 4.0 fostering construction supply chain management: Lessons learned from engineer-to-order suppliers	(Dallasega et al.,2018)	System Integration
9.	Can constructal law and exergy analysis produce a robust design method that couples with industry 4.0 paradigms? The case of a container house	(Trancossi et al., 2018)	Simulation
10.	Towards the generation of digital twins for facility management based on 3D point clouds	(Stojanovic et al., 2018)	Simulation
11.	Industry 4.0 Concept Introduction into Construction SMEs	(Nowotarski & Paslawski, 2017)	Literature Review
12.	A decentralized and pull-based control loop for on-demand delivery in ETO construction supply chains	(Dallasega et al., 2016)	System Integration

The existence of review papers also indicate that the subject matter is still at its infancy and researches are still keen to explore on what has been done in areas related to Industry 4.0 in construction engineering. It is worth highlighting that the shortlisted papers are mostly published in the recent years of 2018 and 2019, which signifies that the interest on Industry 4.0 has only been picked-up recently in construction.

3.2.1 Simulation

Construction industry is one of the many sectors that have adopted/adapted Industry 4.0 through simulation, in order to navigate towards the future direction of construction industrialization. Automated design and modelling enables mass-customisation of buildings through collaborative strategies, web-based catalogue and Building Information Modelling (BIM) that influences modern construction companies in embracing Industry 4.0 technologies (Bianconi et al., 2019). Besides that, a set of new processes for planning, design, and construction of buildings, which are based on virtual models has been implemented via Petri Nets and have been connected with BIM models and hardware (sensor and actuator) to provide real-time progression monitoring and information (Correa, 2018). Furthermore, the establishment of BIM enables efficiency by the implementation of the dynamical model as a tool in complex building industry towards Industry 4.0 (Hotový, 2018). Meanwhile, for the operation & maintenance stage of building lifecycle, BIM has been used for intensive process of labour data representation and 3D point cloud to represent the indoor environment as the basis data for a Digital Twin (DT) (Stojanovic et al., 2018). Digital Twin integrated with Constructal Law model in engineering and design process allows effective optimisation, through knowledge-based, holistic and evolutional perspectives in increasing the performance of low-cost container house (Trancossi et al., 2018). In general, the notion of Industry 4.0 in construction is heavily influenced by BIM.

3.2.2 Internet of Things

The construction industry is in a transformational stage of a larger evolutionary process, where the Internet of Things (IoT) and digital construction should disengage from focusing solely on "point solutions", and should move towards transcending digital layers (Woodhead et al., 2018). The adoption of IoT enables new digital services such as Structural Health Monitoring in order to identify, detect and characterize degradation and damages of all types of engineering structures by providing information about the quality and function of the raw material (Sciammarella & Olivito, 2018).

3.2.3 Systems Integration

A systems integration of several Industry 4.0 concepts for the construction industry supply chain could address the common issues of highly customised, with significant numbers of Engineer-To-Order (ETO) components, for a synchronized construction progress (Dallasega, 2018). Besides that, Dallasega et al., 2016 had earlier introduced the "Pitching" concepts and "Cyclical Planning" as an approach to break down job orders to synchronize ETO supply chains of construction progress and to handle unpredictable on-site demands in an efficient way. Hence, systems integration could potentially address the challenges and complexity inherent in ETO businesses.

3.2.4 Autonomous System

Soto et al., 2019 found that conventional construction with robotics technologies applied in different phases of project lifecycle have the potential to improve productivity and safety of a project, through the conduct of digital fabrication (DFAB), namely DFAB HOUSE process that consist of four sub-projects, such as the Mesh Mould Wall, Smart Slab, Smart Dynamic Casting and Spatial Timber Assemblies for the built of concrete wall.

3.2.5 Literature Review

The literature review papers represent the introduction, description and general idea of Industry 4.0 in construction. The evolution of construction industry in support of Industry 4.0 and digitisation, particularly over the last three years, has started to mature with various companies pointing out the actual and important concepts to achieve sustainable development (Alaloul et al., 2018). A general idea between Industry 4.0 and construction industry's Small Medium Enterprises is steadily increasing, particularly in European countries. Nonetheless, still limited amount of publications were found in this research field, even though numerous ranges of SMEs are affected by Industry 4.0 (Nowotarski & Paslawski, 2017).

3.2.6 Summary

In reference to Table 4, only 12 papers have the elements of Industry 4.0 in engineering and construction sector. Within that, the term Building Information Modelling (BIM) has consistently emerged and thus, suggest that the construction industry would have adapted technologies, which goes by other names, but with similar functions to the pillars of Industry 4.0. In order to truly understand the adaption of Industry 4.0 in construction, the keywords search in the Scopus database has been expanded to "Industry 4.0" and "construction". The extended search of the keywords is aimed to identify review papers that could have encapsulated Industry 4.0 applications adapted in the construction industry.

Findings from the search is shown in Table 5. Table 5 includes the two review papers identified in Table 4. From the findings, the top two applications mentioned in the reviews are BIM and 3D-printing. Oesterreich & Teuteberg, 2016, have identified the most applications of Industry 4.0 in construction. Thus, the scientometric analysis has been conducted based on the findings by Oesterreich & Teuteberg, 2016 (In reference to Section 2.4).

TABLE 5:Review papers of Industry 4.0 in construction engineering

No.	Authors/ Year	BIM	IoT/IoS	PLM	Cloud Computing	Mobile Computing	AR/ VR/ MR	Robotics	RFID	Big Data	3D- Printing	Smart Factory	HCI	Modularisation	CPS
1.	(Alaloul et al., 2018)	/													
2.	(Nowotarski & Paslawski, 2017)						/				/				
3.	(Böke, Knaack, & Hemmerling, 2018)														/
4.	(Oesterreich & Teuteberg, 2016)	/	/	/	/	/	/	/	/	/	/	/	/	/	/
5.	(Dallasega et al., 2018)	/			/						/				

NOTE:
BIM -Building Information Modelling
IoT/IoS -Internet of Things/ Internet of Services
PLM - Product-Lifecycle-Management
AR/VR/MR -Augmented Reality/Virtual Reality/Mixed Reality
RFID - Radio-Frequency Identification
HCI - Human-Computer-Interaction
CPS - Cyber-Physical Systems

3.3 Scientometric Analysis Results

As mentioned in Section 2.4, a scientometric analysis has been further established to expand the search on Industry 4.0 in construction. From the bibliometric results, it was found that the construction industry has different elements, or at least terms, associated with Industry 4.0, as compared to the nine common pillars of Industry 4.0, such as Building Information Modelling (BIM), modularisation, as well as product lifecycle management. The disaggregation has prompted the utilisation of scientometric analysis to extend the study on Industry 4.0 stemming from construction's perspective. The methodology adopted for this analysis could be referred in Section 2.4.

The scientometric analysis includes the analysis on co-authorship of countries, co-authorship of authors and co-occurrence of author keywords and visualisation of the networks. A total of 2417 publications were included in the science mapping analysis based on the fourteen (14) keywords identified in Table 2. The visualization mapping generated can provide valuable information from the network measures such as conceptual, intellectual, social evolution, patterns and trends of research fields (Hosseini et al., 2018). This technique also attempts to distinguish the intellectual connection within the structural and dynamically different systems of scientific knowledge by using pattern and data from online database (Cobo et al., 2011).

3.3.1 Co-authorship of Countries

A full-counting of the co-authorship's countries was conducted to investigate the most influential countries along with the degree of communication among the countries. There were 79 countries found in this study and 48 countries have met the threshold. The co-authorship of countries network is shown in Fig. 10. Multiple colours in the map shows the variation of research directions between the countries. The larger the nodes, the higher the country's influential factor. The top three influential countries adopting/adapting Industry 4.0 in the construction industry are the United States, China and United Kingdom. This might relate to the relevant governments' commitment, along with public policies that have been set in-place towards Industry 4.0, such as Advanced Manufacturing Partnership (US); Made in China 2025 (China) and Future of Manufacturing (UK). It is also observed that the links between these countries are very strong, which portrays strong cooperative relationships between the countries. A yield of 136 links between the United States and other network countries were found in this analysis, as presented in Table 6. Table 6 also indicates the total number of publications and the number of citations for the top 20 countries.

**Both Figure 10 and Table 6 contains various countries, except for Hong Kong, which is known as a special administrative region of China.*

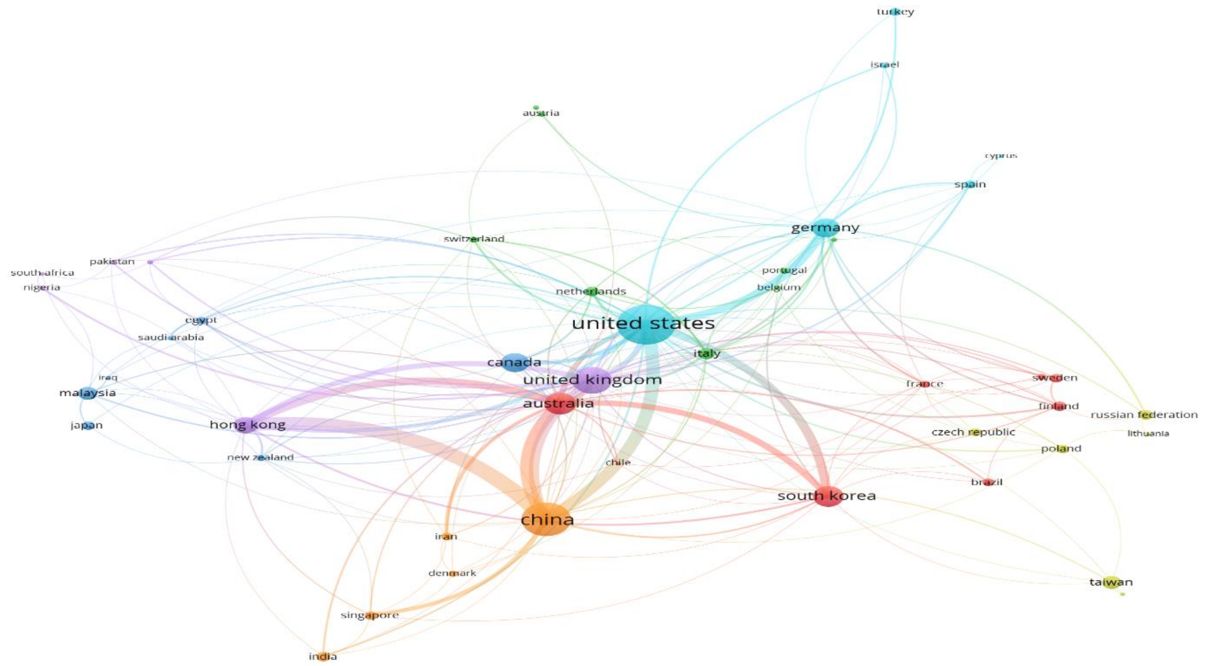

FIG. 10: Co-authorship of countries mapping

TABLE 6: Top 20 co-authorship countries with the most publication

Country	Documents	Citations	Link Strength
United States	432	4245	136
China	318	1443	112
United Kingdom	218	2391	107
Australia	152	1790	96
Hong Kong	93	1192	80
Germany	115	750	59
South Korea	139	1910	47
Italy	50	303	28
Canada	117	733	25
Netherlands	38	727	20
Singapore	28	298	17
Finland	38	374	16

Country	Documents	Citations	Link Strength
Switzerland	17	170	16
France	20	83	15
New Zealand	17	66	15
Egypt	22	115	14
Iran	25	145	14
Malaysia	60	182	14
Spain	26	105	12
Belgium	9	158	11

**Note: Not all of the 79 countries are listed in this table. This table only portrays the top 20 countries with most influential publications on the applications of Industry 4.0 in construction.*

3.3.2 Co-authorship of Authors

From the 4179 authors and co-authors found in the VOSviewer, 150 authors who have met the threshold of five (5) minimum numbers of document per author were shortlisted. Fig. 11 illustrates the authors' networks on the application of Industry 4.0 in the construction industry. Bigger circle and larger font size of an author indicates the larger numbers of papers published by the author. Meanwhile, the largest citations network in Fig. 12 is located at the centre of the network and other authors are indicated at a minimum distance. The findings indicate that the most influential author is Li H., who has the highest numbers of publications as well as citations. Table 7 shows the most influential publications and citations by the authors. In reference to Table 7, productive authors that have published the most are Li H., Lu W., and Teizer J., while the authors with the most citations are Teizer J., Zhang S. and Wang X.

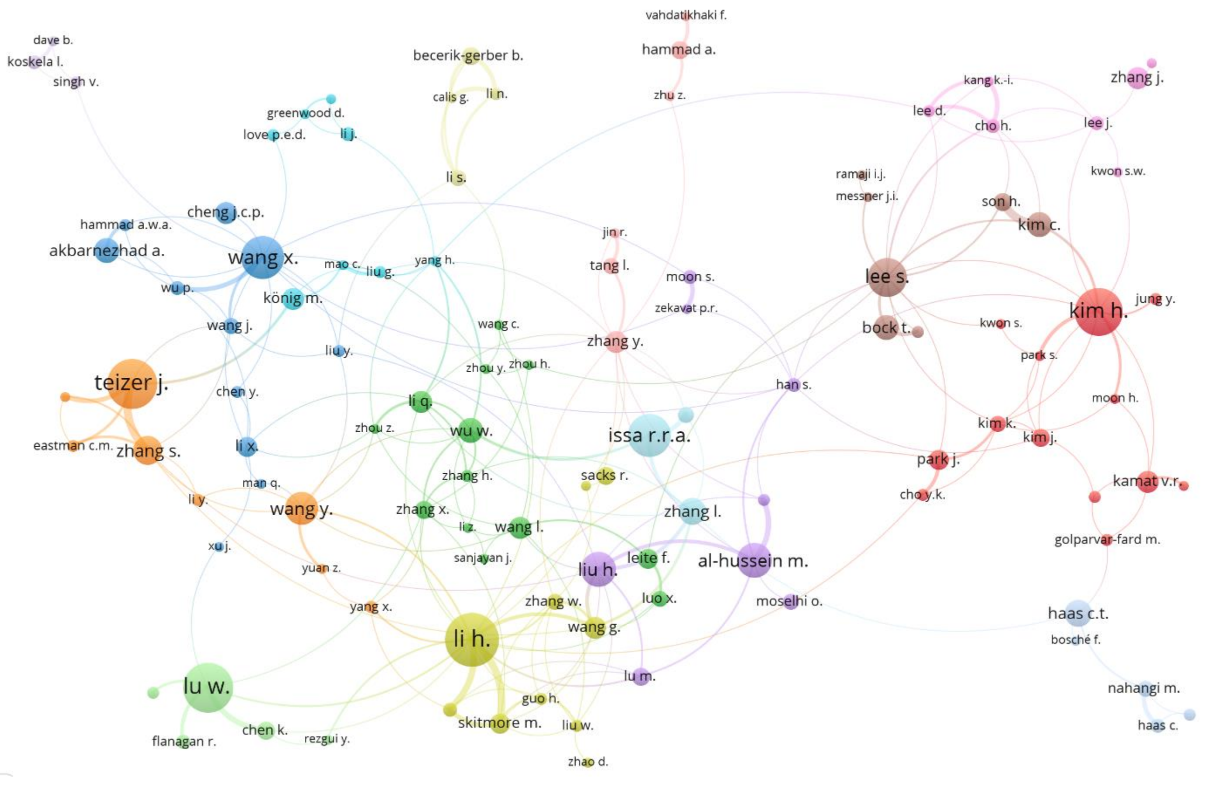

FIG. 11: Co-authorship of author network mapping

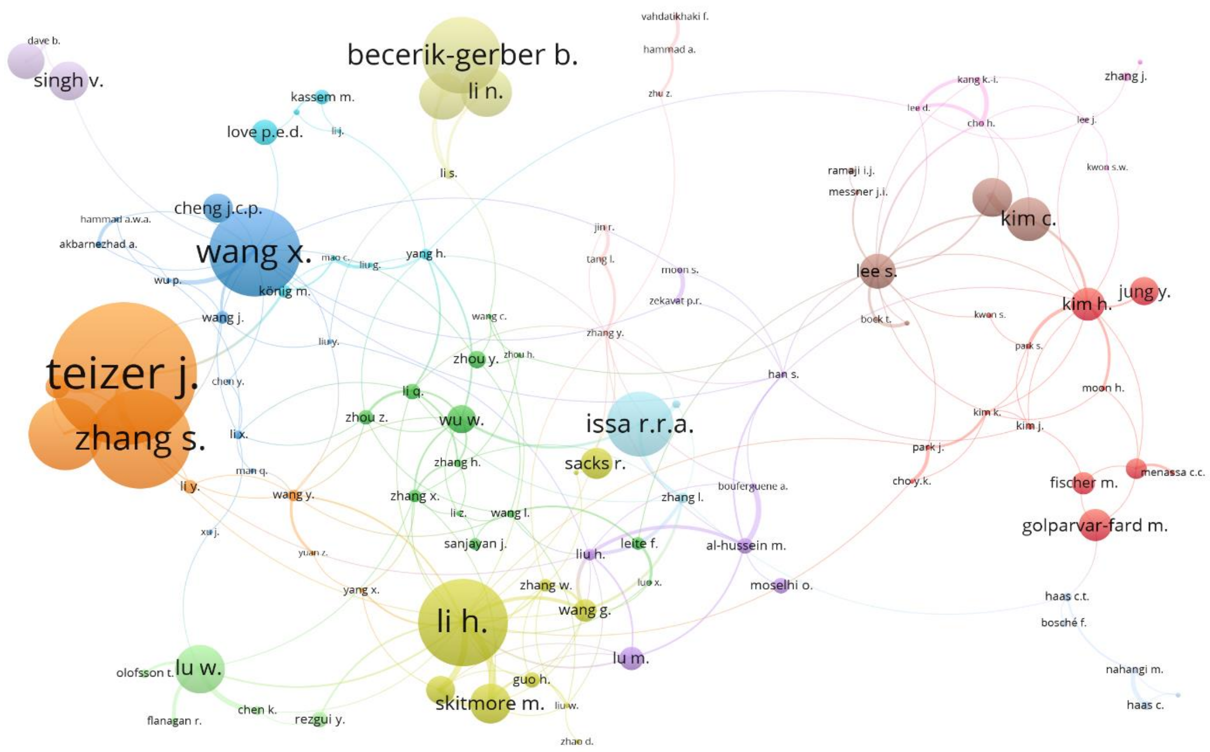

FIG.12: Co-authorship of authors' citations network mapping

TABLE 7: Top 10 authors list of Industry 4.0 in construction industry publications and citations

Authors	Total Publications	Authors	Total Citations
Li H.	26	Teizer J.	922
Lu W.	24	Zhang S.	640
Teizer J.	24	Wang X.	583
Kim H.	23	Li H.	569
Issa R.R.A	21	Becerik-Gerber B.	498
Wang X.	21	Eastman C.M.	468
Lee S.	19	Issa R.R. A	425
Al – Hussein M.	17	Li N.	325
Liu H.	17	Lu W.	317
Wang Y.	16	Calis G.	305

**Note: Not all of the 150 authors are listed in this table, but only the top 10 authors with the most influential publications on the applications of IR 4.0 in construction.*

3.3.3 Co-occurrence of author keywords

An analysis has been conducted to discover the co-occurrence of author keywords for the applications of Industry 4.0 in construction. From the total of 2417 related publications for this study, 4451 keywords have resulted, where all keywords met the threshold of one (1) number of keyword occurrences. Figure 13 shows the link between author keywords and the closest keywords that have connected the authors are BIM, Augmented Reality, Virtual Reality, Simulation and Cloud Computing.

Based on Fig. 14 and Fig. 15, the lightest (yellow) colour indicates the most periodically mentioned keywords, while the darker colour (green-blue) is the least mentioned keywords for this study. The other co-occurrence of author keywords is shown in Table 8 and Table 9, which presents the top 20 subject areas of the author keywords occurrence. Based on the science mapping in Table 8, it can be observed that the most popular keywords for Industry 4.0 are BIM (459 occurrences) and the least applied is Cyber-Physical Systems (3 occurrences).

Meanwhile, the highest occurrence of subject area is as illustrated in Fig. 15, which is the study on construction (415 occurrences). This finding is expected as the study has been focused on the area of construction throughout the literature search. Nonetheless, it is worth highlighting that the following most mentioned subject area is information and communication technology (ICT) that suggest the influence of ICT successful Industry 4.0 adoption/adaption. In addition, other subject areas that have been influenced by Industry 4.0 are safety, sustainability and also education.

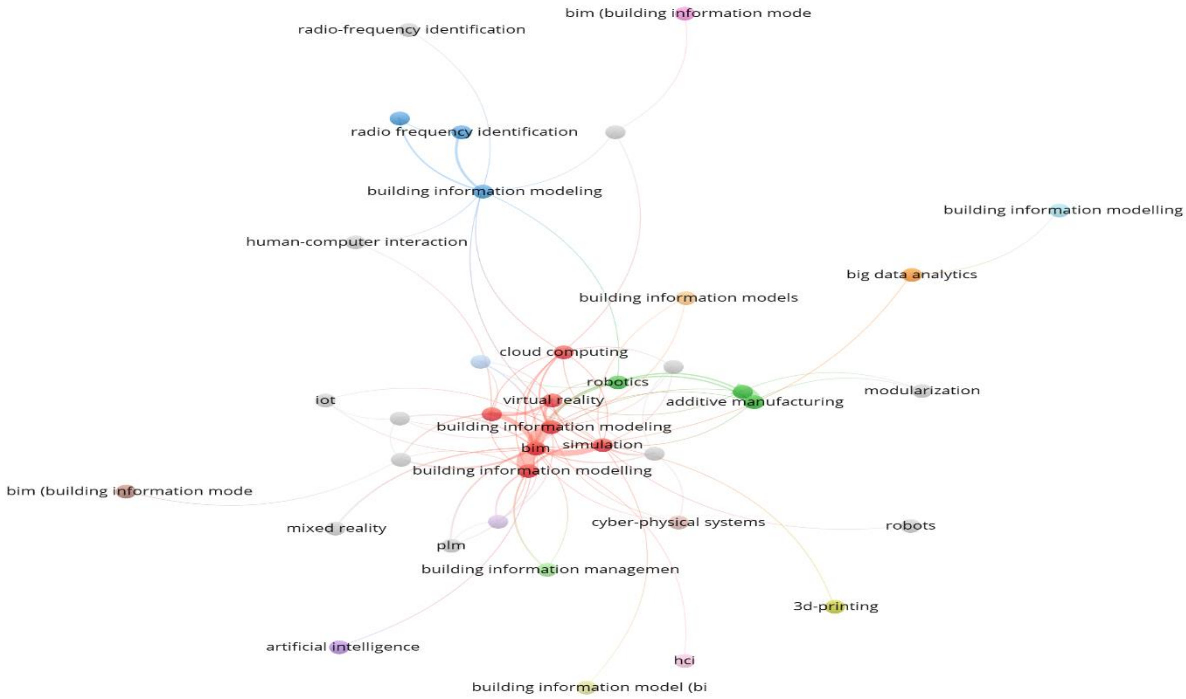

FIG.13: Co-occurrences for author keywords

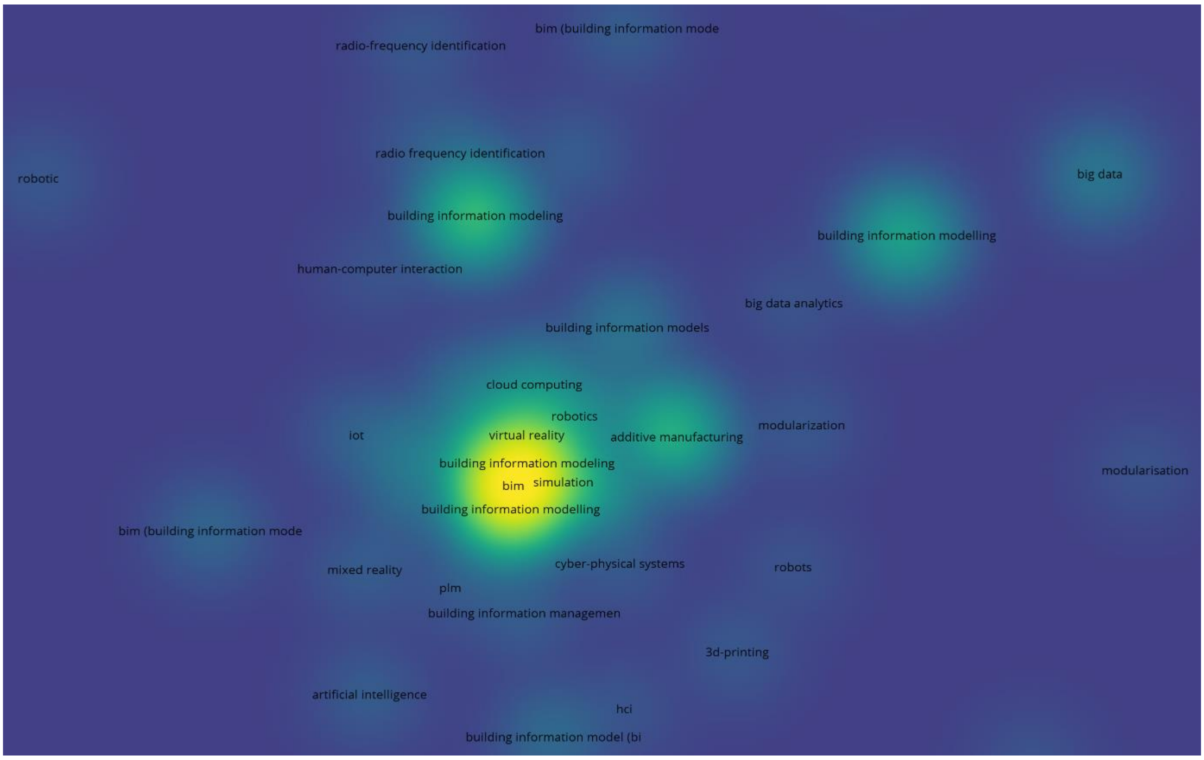

FIG.14: Co-occurrences for author keywords

TABLE 8: List of co-occurrences for author keywords

Keywords	Occurrence	Keywords	Occurrence
BIM	459	Big Data	16
Virtual Reality (VR)/ Augmented Reality (AR)/ Mixed Reality (MR)	78	Radio-Frequency Identification (RFID)	15
Simulation	43	Mobile Computing	7
Additive Manufacturing	42	Product Lifecycle Management (PLM)	5
3d-Printing	39	Human-Computer-Interface (HCI)	5
Robotics	28	Modularisation	5
Internet of Things (IOT)	24	Artificial Intelligence	4
Cloud Computing	23	Cyber-Physical Systems	3

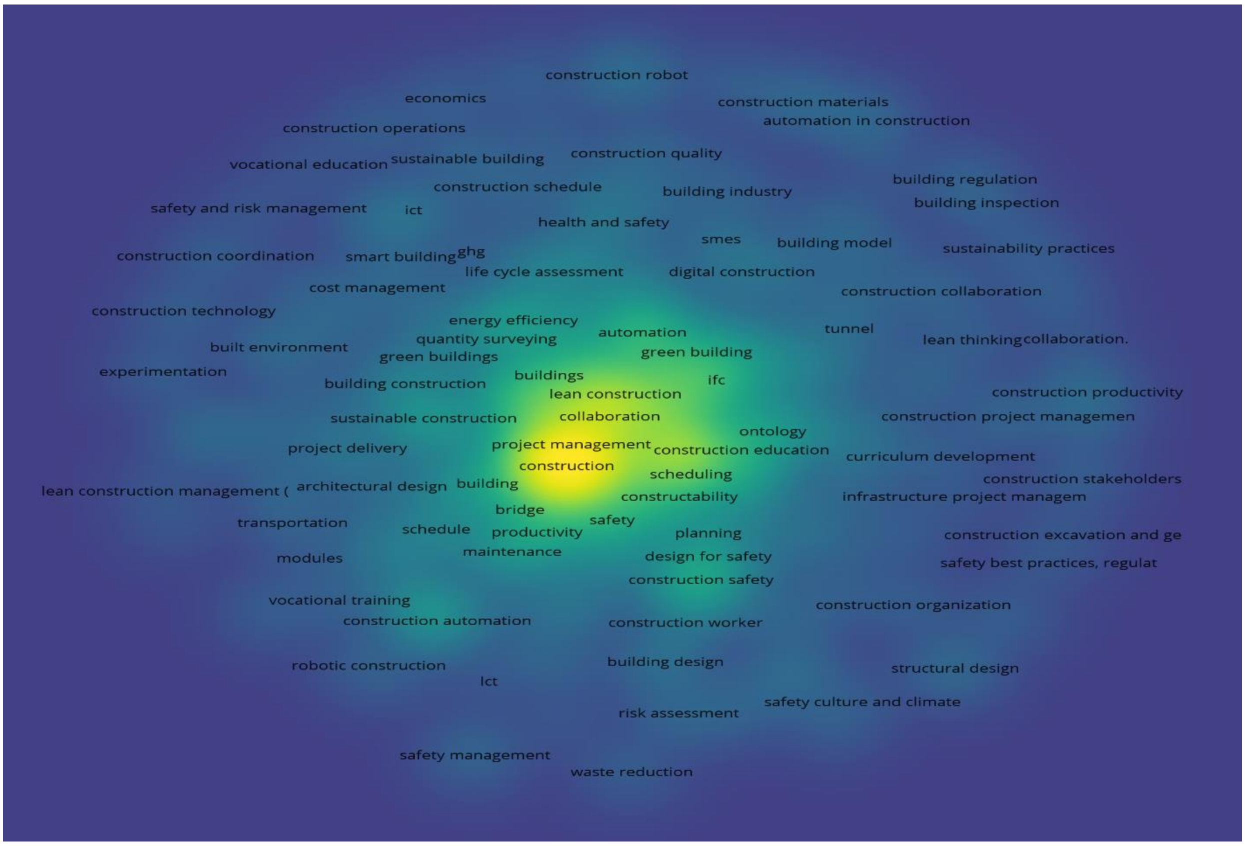

FIG. 15: Co-occurrences for author keywords for Industry 4.0 subject area

TABLE 9: List of co-occurrences for author keywords for IR 4.0 subject area

Keywords	Occurrence
Construction	415
Information and Communication Technology	80
Construction Safety	71
Sustainable Construction	61
Construction Education	60
Automation in Construction	54
Project Management	52

Keywords	Occurrence
Building Construction	51
Lean Construction	51
Collaboration	47

**Note: Not all 200 subject areas are listed in this table. Only the top 10 most influential publications of Industry 4.0 in construction are given here.*

4. DISCUSSIONS

The dynamic and complex nature of the construction industry would benefit from the adoption and adaption of Industry 4.0, as it provides opportunities to improve construction processes and productivity, which is currently lacking behind other sectors such as manufacturing and services (Holt & Kearney, 2015). In order to bridge the gap between construction and the other sectors, this study has been conducted to identify the current state of Industry 4.0 applications in construction, through a combination of systematic literature review, bibliometric, content and scientometric analysis techniques.

Findings from the bibliometric analysis that have focused on the adoption of Industry 4.0 in construction has resulted in a total of 3004 papers from the keywords of Industry 4.0 and engineering, and when narrowed down to construction, only 299 papers were found. The top five contributors were from Germany, Italy, UK, China and the US. From those publications, most focus was given on the Industry 4.0 pillar of simulation. Several other applications from the Industry 4.0 pillars have been captured in construction, but frequent occurrences mentioned in the applications was Building Information Modelling (BIM). The scientometric analysis that has been applied to complement findings from bibliometric and content analysis has provided another spectrum of Industry 4.0 in construction, by exhibiting the construction version of Industry 4.0. The analysis that has been conducted to evaluate specific elements/ terms related to Industry 4.0 from the construction perspective (the adaptation of Industry 4.0 in construction) has resulted in 2417 findings using keywords such as Building Information Modelling, cloud computing, robotic, etc (Refer to Table 2). The top five contributing countries were from the US, China, UK, Australia and Hong Kong. As expected, and aligned with findings from the earlier analysis, the keyword most mentioned was BIM, while the subject matter most mentioned was construction, as well as other areas such as information and communication technology, safety, sustainability and education that made it to the top 20 most influential areas that have adapted Industry 4.0 in construction. Based on the top five countries identified from the bibliometric and scientometric, most countries ranked in the top positions are similar, such as the US, UK and China. Meanwhile, Germany that ranked top in Industry 4.0 has resulted lower, at the 6th position in the scientometric findings. The reason for German to be at the top for Industry 4.0 might be influenced by the German government's public policy of *Industrie 4.0*, which can be considered as the pioneer policy established in riding the wave of Industrial Revolution 4.0 (Liao et al., 2018). Meanwhile, since the keywords used for the scientometric analysis was based on the specific elements of 4.0, associated to construction, the results might be lower as terms such as BIM has been more popular in countries such as the US. Therefore, the three competing countries (US, UK and China) have shown consistent progress in the adoption as well as the adaption of Industry 4.0 in construction.

The collation of findings between the bibliometric and scientometric analysis resulted in several similarities and differences between the adoption/adaption of Industry 4.0 in construction. It was found that the construction industry has adopted Industry 4.0 pillars such as the Internet of Things (IoT), Simulation, Augmented Reality, Autonomous System, Systems Integration, Augmented Reality, Big Data and Additive Manufacturing. The pillar that have not been adopted by construction is cyber-security. On the other hand, the industry's own version of Industry 4.0 consists of Building Information Modelling (BIM), Product Lifecycle Management (PLM), mobile computing, RFID, 3D-Printing, robotics, human-computer interaction and modularisation. These applications are specific to construction and are not listed within the pillars of Industry 4.0. Nonetheless, elements such as BIM does fit well into the functionalities within the pillars of Industry 4.0, such as simulation. Therefore, it is observed that the construction sector has also adapted, rather than only adopted the notion of Industry 4.0 within the sector. Even so, there is also elements of Industry 4.0 in construction, which does not fit into the pillars of Industry 4.0, such as modularisation, particularly due to the nature (peculiar and complex) of the industry itself. However, in order to progress towards Industry 4.0, the industry should both adopt, adapt as well as integrate the different elements of Industry 4.0 (pillars and construction version), as the reliance on a single element would only limit the opportunities for expansion.

This would give way to systems beyond BIM, such as Digital Twins for buildings. In general, the construction industry has acknowledged BIM as construction's version of Industry 4.0, without realising that there would be loss of potential when these elements are applied in isolation from the pillars of Industry 4.0. Nonetheless, in order for construction to move towards Industry 4.0, BIM could be a key input data for a more conclusive system such as the built of a Digital Twin for building (Savian, 2019). Digital Twin provides a near-real-time comprehensive linkage between the physical and digital world that enables the inclusion of behaviour patterns of people and space design, which could not be done by BIM alone, but only possible through the integration with the other pillars in Industry 4.0, such as the IoT. An integration between BIM and IoT could present cyber-physical system that allows bi-directional information that can be used to monitor the performance of assets in real-time and alert system for any problems before they arise in the physical environment. The immersion of construction into Industry 4.0 would enable the industry to move towards construction industrialisation (component-prefabricated; construction-packaging) so that construction industry and manufacturing industry could develop together, while promoting the reform of the industry (Li & Yang, 2016). Even though construction industry and manufacturing industry belong to two different categories, with the construction industry being slow to adopt manufacturing processes and principles, the highly dependent relationship between each other has even regarded construction as a special kind of manufacturing. Therefore, the integration between elements, such as modularisation (construction version of Industry 4.0) with IoT (pillar of Industry 4.0) allows optimised supply chain, whereas the integration with cyber-physical systems enables the monitoring of physical processes, creating virtual models of physical processes and decentralizing decision-making. Cyber-physical systems can also intercommunicate in real time over IoT, allowing participants to offer and share internal and cross-organizational services across the whole value chain. Therefore, in order to truly advance construction towards construction industrialisation and Industry 4.0, a thorough understanding on the functions, pillars and potential integration between the elements (both within and beyond construction) of Industry 4.0 is inevitable.

5. CONCLUSIONS

The purpose of this study was to explore the current state and nature of Industry 4.0 in construction. The findings suggest that the construction engineering field has adopted the nine pillars of Industry 4.0, except for cyber-security, while the adaption lies upon the industry's own version of Industry 4.0, namely Building Information Modelling (BIM), Product Lifecycle Management (PLM), mobile computing, RFID, 3D-Printing, robotics, human-computer interaction and modularisation. It is envisioned that such efforts of incorporating digitisation into this field would push the industry towards positioning itself at the same level as other sectors such as manufacturing (Nolling, 2016).

This study has been conducted meticulously and has been presented through several complementing analyses, such as bibliometric, content and scientometric analysis. Even so, the limitation lies within the constraints set in the inclusion/exclusion criteria in the conduct of the SLR. Future studies could widen the research area by expanding the boundaries, as well as the range of keywords used. In contrast, future researchers could also narrow down the study by focusing to research on each pillar and the elements of IR 4.0 in construction. This would provide a more specific perspective on how each pillar/element has been applied in construction.

This study has served as the basis for researchers to carry out future studies in the field of Industry 4.0 in construction. The findings from this study has highlighted current gaps to be filled, such as the applications as well as the integrations between the elements of Industry 4.0 in construction. Along with that, subject areas such as collaboration and lean construction are recognised as crucial areas of improvement in construction.

ACKNOWLEDGEMENT

This research was supported by the Faculty of Civil Engineering and Bestari Perdana grant, Universiti Teknologi MARA [Grant No: 600-IRMI/PERDANA 5/3 BESTARI (065/2018)].

REFERENCES

Alaloul, W. S., Liew, M. S., Amila, N., Abdullah, W., & Mohammed, B. S. (2018). Industry Revolution IR 4.0 : Future Challenges in Construction Industry Opportunities and Challenges in Construction Industry, *02010*, 1–7.

Bahrin, M. A. K., Othman, M. F., Azli, N. H. N., & Talib, M. F. (2016). Industry 4.0: A review on industrial automation and robotic. *Jurnal Teknologi*, *78*(6–13), 137–143. https://doi.org/10.11113/jt.v78.9285

Bianconi, F., Filippucci, M., & Bu, A. (2019). Automated design and modeling for mass-customized housing . A web-based design space catalog for timber structures, *Automation in Construction*, *103 (July 2019)*, 13–25. https://doi.org/10.1016/j.autcon.2019.03.002

Böke, J., Knaack, U., & Hemmerling, M. (2018). State-of-the-art of intelligent building envelopes in the context of intelligent technical systems. *Intelligent Buildings International*, *11(1)*, 27-45. https://doi.org/10.1080/17508975.2018.1447437

Cobo, M. J., López-Herrera, A. G., Herrera-Viedma, E., & Herrera, F. (2011). Science mapping software tools: Review, analysis, and cooperative study among tools. *Journal of the American Society for Information Science and Technology*, *62(7)*, 1382–1402. https://doi.org/10.1002/asi

Comerio, N., & Strozzi, F. (2018). Tourism and its economic impact: A literature review using bibliometric tools. *Tourism Economics, 25(1),* 109–131. https://doi.org/10.1177/1354816618793762

Correa, F. R. (2018). Cyber-physical systems for construction industry. *2018 IEEE Industrial Cyber-Physical Systems (ICPS)*, 392–397. https://doi.org/10.1109/ICPHYS.2018.8387690

Dallasega, P. (2018). Industry 4.0 Fostering Construction Supply Chain Management: Lessons Learned From Engineer-to-Order Suppliers, *46*(3), 49–55. https://doi.org/10.1109/EMR.2018.2861389

Dallasega, P., Marcher, C., Marengo, E., Rauch, E., Matt, T., & Nutt, W. (2016). A Decentralized and Pull - Based Control Loop for on - Demand Delivery in Eto Construction Supply Chains. *International Group for Lean Construction*, (November), 33–42.

Dallasega, P., Rauch, E., & Linder, C. (2018). Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review. *Computers in Industry*, *99*(April), 205–225. https://doi.org/10.1016/j.compind.2018.03.039

Glas, A. H., & Kleemann, F. C. (2016). The Impact of Industry 4.0 on Procurement and Supply Management: A Conceptual and Qualitative Analysis. *International Journal of Business and Management Invention ISSN Online*, *5*(6), 2319–8028. https://doi.org/10.1016/j.procir.2016.03.162

He, Q., Wang, G., Luo, L., Shi, Q., Xie, J., & Meng, X. (2017). Mapping the managerial areas of Building Information Modeling (BIM) using scientometric analysis. *International Journal of Project Management*, *35*(4), 670–685. https://doi.org/10.1016/j.ijproman.2016.08.001

Holt, P. E. A., & Kearney, N. (2015). Emerging Technology in the Construction Industry: Perceptions from Construction Industry Professionals Emerging Technology in the Construction Industry: Perceptions from. *122nd ASSEE Annual Conference & Exposition*.

Hosseini, M. R., Martek, I., Zavadskas, E. K., Aibinu, A. A., Arashpour, M., & Chileshe, N. (2018). Critical evaluation of off-site construction research: A Scientometric analysis. *Automation in Construction*, *87*(January), 235–247. https://doi.org/10.1016/j.autcon.2017.12.002

Hotový, M. (2018). Dynamic model of implementation efficiency of Building Information Modelling (BIM) in relation to the complexity of buildings and the level of their safety. *MATEC Web of Conferences*, *146*, 01010. https://doi.org/10.1051/matecconf/201814601010

Jin, R., Gao, S., Cheshmehzangi, A., & Aboagye-Nimo, E. (2018). A holistic review of off-site construction literature published between 2008 and 2018. *Journal of Cleaner Production*, *202*, 1202–1219. https://doi.org/10.1016/j.jclepro.2018.08.195

Kamble, S. S., Gunasekaran, A., & Gawankar, S. A. (2018). Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives. *Process Safety and Environmental Protection*, *117*, 408–425. https://doi.org/10.1016/j.psep.2018.05.009

Klinc, R., & Turk, Z. (2019). Construction 4.0 – Digital transformation of one of the oldest industries. *Economic and Business Review*, 21 (3), 393-410. https://doi.org/10.15458/ebr.92

Li, J., & Yang, H. (2017). A research on development of construction industrialization based on BIM technology under the background of industry 4.0. *MATEC Web of Conferences*, 100, 02046. https://doi.org/10.1051/matecconf/201710002046

Liao, Y., Deschamps, F., Loures, E. de F. R., & Ramos, L. F. P. (2017). Past, present and future of Industry 4.0 - a systematic literature review and research agenda proposal. *International Journal of Production Research*, *55*(12), 3609–3629. https://doi.org/10.1080/00207543.2017.1308576

Liao, Y., Loures, E. R., Deschamps, F., Brezinski, G., & Venâncio, A. (2018). The impact of the fourth industrial revolution: a cross-country/region comparison. *Production*, 28, e20180061. DOI: 10.1590/0103-6513.20180061

Loeb, S., Dynarski, S., McFarland, D., Morris, P., Reardon, S., & Reber, S. (2017). Descriptive Analysis in Education: A Guide for Researchers. *(NCEE 2017-4023). U.S Department of Education, Institute of Education Sciences. National Center for Education Evaluation and Regional Assistance*, (March), 1–40. Retrieved from https://eric.ed.gov/?id=ED573325

Lu, Y. (2017). Industry 4.0: A survey on technologies, applications and open research issues. *Journal of Industrial Information Integration*, *6*, 1–10. https://doi.org/10.1016/j.jii.2017.04.005

Mayring, P. (2000). Qualitative Content Analysis Philipp Mayring 3. Basic Ideas of Content Analysis. *Forum Qualitative Social Research*, *1*(2), 10. https://doi.org/10.1016/S1479-3709(07)11003-7

Nolling, K. (2016). Think act: Digitization in the construction industry, Roland Berger GMBH.

Nowotarski, P., & Paslawski, J. (2017). Industry 4.0 Concept Introduction into Construction SMEs. *IOP Conference Series: Materials Science and Engineering*, *245*(5), 0–10. https://doi.org/10.1088/1757-899X/245/5/052043

Oesterreich, T. D., & Teuteberg, F. (2016). Understanding the implications of digitisation 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*, *83*, 121–139. https://doi.org/10.1016/j.compind.2016.09.006

Olawumi, T. O., Chan, D. W. M., & Wong, J. K. W. (2017). Evolution in the intellectual structure of BIM research: a bibliometric analysis. *Journal of Civil Engineering and Management*, *23*(8), 1060–1081. https://doi.org/10.3846/13923730.2017.1374301

Osunsanmi, T. O., Aigbavboa, C., & Oke, A. (2018). Construction 4 . 0 : The Future of South Africa Construction Industry. *International Scholarly and Scientific Research & Innovation*, *12*(January), 2017–2018.

Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., & Harnisch, M. (2015). Industry 4.0. *The Boston Consulting Group*, 20. https://doi.org/10.1007/s12599-014-0334-4

Saunders, M., Lewis, P., & Thornhill, A. (2007). *Research Methods for Business Students 5^th^ Edition*. https://doi.org/10.1007/s13398-014-0173-7.2

Savian, C. (2019). Potential to use BIM data in digital twins is being overlooked. CIOB. Retrieved from: http://www.bimplus.co.uk/analysis/potential-use-bim-data-digital-twins-being-overloo

Sciammarella, P. F., & Olivito, R. S. (2018). Internet of Things for Structural Health Monitoring, 95–100.

Soto, B. G. De, Agustí-juan, I., Joss, S., & Hunhevicz, J. (2019). Implications of Construction 4.0 to the workforce and organizational structures. *International Journal of Construction Management*, 1–13. https://doi.org/10.1080/15623599.2019.1616414

Stojanovic, V., Trapp, M., Richter, R., & Hagedorn, B. (2018). Towards The Generation of Digital Twins for Facility Management Based on 3D Point Clouds, In: Gorse, C and Neilson, C J (Eds) Proceeding of the 34th

Annual ARCOM Conference, 3-5 September 2018, Belfast, UK, Association of Researchers in Construction Management, 270-279.

Tjahjono, B., Esplugues, C., Ares, E., & Pelaez, G. (2017). What does industry 4.0 mean to supply Chain? *Procedia Manufacturing*, 13, 1175–1182, https://doi.org/10.1016/j.promfg.2017.09.191.

Trancossi, M., Cannistraro, M., & Pascoa, J. (2018). Can constructal law and exergy analysis produce a robust design method that couples with industry 4.0 paradigms ? The case of a container house, *Mathematical Modelling of Engineering Problems, 5(*4), 303–312.

Vaidya, S., Ambad, P., & Bhosle, S. (2018). Industry 4.0 - A Glimpse. *Procedia Manufacturing*, *20*, 233–238. https://doi.org/10.1016/j.promfg.2018.02.034

van Eck, N. J., & Waltman, L. (2013). {VOSviewer} manual. *Leiden: Univeristeit Leiden*, (January), 1–29. Retrieved from http://www.vosviewer.com/documentation/Manual_VOSviewer_1.6.1.pdf

van Eck, N. J., & Waltman, L. (2014). *Visualizing Bibliometric Networks*. *Measuring Scholarly Impact*. https://doi.org/10.1007/978-3-319-10377-8_13

Woodhead, R., Stephenson, P., & Morrey, D. (2018). Digital construction: From point solutions to IoT ecosystem. *Automation in Construction*, *93*(May), 35–46. https://doi.org/10.1016/j.autcon.2018.05.004

Zhao, D., & Strotmann, A. (2015). Analysis and Visualization of Citation Networks, Morgan & Claypool Publishers. https://doi.org/10.2200/S00624ED1V01Y201501ICR039