A Bibliometric Study of Industry 4.0 in Construction Industry Using Oesterreich and Teuteberg (2016) As A Key Marker

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Abstract: This study examines how Industry 4.0 has been discussed in the construction industry and construction management (CM) research over the past four years using Oesterreich and Teuteberg's (2016) article as a key marker. The techniques adopted in this paper were Bibliometric analysis. Citation, co-citation, and co-occurrence analyses were applied to the articles published between 2016-2019 in the WoS database. This study concluded that most CM research themes had been impacted by Industry 4.0. Also, CM scholars, journal editors, and decision-makers have expressed significant interest in Industry 4.0. Finally, this research has focused on research themes that have been less examined by scholars and have identified areas for future research on how CM literature may benefit from Industry 4.0. Twenty-one main research themes were identified, a co-occurrence network was constructed and examined. The results indicate that there are a sufficient number of references to Industry 4.0 in the themes of management, smart factory, and digitisation. On the other hand, other themes have received less scholarly attention, such as performance, simulation, and supply chain management. Those less explored themes possibly require additional studies.

1. Introduction

Over the past few years, Industry 4.0 has emerged as an essential research topic. Scholars from various disciplines have recently focused on understanding how Industry 4.0 could be integrated within the industry and examine its benefits. For construction management (CM) researchers, this has been a bountiful challenge to examine Industry 4.0 in the construction context due to the construction industry's extremely complex culture. Scholars have thus focused on examining the applications of Industry 4.0 technologies

within the construction industry, illustrating the benefits and challenges of Industry 4.0 integration, introducing project managers to the Industry 4.0 concepts, and examining industry readiness towards Industry 4.0 [2].

This study aims to analyse Industry 4.0 in CM research. With this purpose, this study investigates publications that examine Industry 4.0 in CM research and identify relationships between those publications. This study points out the impact of Industry 4.0-related research in CM and notes the fundamental CM works investigating Industry 4.0 technologies. Also, a network that illustrates the relationship between works was conducted. Finally, the main research themes and the way they are related were identified. Hence, in this literature review, a novel theory was not developed. Instead, this study delivers a rear-view of Industry 4.0 on CM; this study investigates the core of how Industry 4.0 and its technologies have spread inCM literature, contributing to point out research themes that scholars have less explored.

2. Industry 4.0 in Construction Research

The increased number of publications examining Industry 4.0 in the construction context has triggered many reviews, i.e. Maskuriy, Selamat [2] and Dallasega, Rauch [3]. According to Maskuriy, Selamat [2], only three reviews have a significant contribution related to Industry 4.0 and construction; [1], [3], and [4]. Among those three publications, [2] also identify Oesterreich and Teuteberg [1] work as the most frequently cited paper and the one with the whole discussion on the topic.

Similarly, bibliometric studies examining Industry 4.0 as a key research topic have been found in the literature. For instance, [5] and [2]. In a recent effort, [5] asserted the rapid increase in attention towards Industry 4.0 since its inception. Notably, they identified [1] work as one of the most highly cited papers on Industry 4.0.

[1] review the existing research efforts in Industry 4.0 and construction. In their research, they tried to find any scientific and peer-reviewed publications examining Industry 4.0 on construction. Their study concluded that scientific publications in Industry 4.0 and the construction domain did not exist in 2016. Thus, their research is considered the first scientific article published in a peer-review journal in the field of Industry 4.0 and the construction industry. [1] focused on the understanding state of the art and practice of Industry 4.0 technologies in the construction industry. In their research, [1] adopted a triangular approach to put forward a framework that illustrates the application and benefits of Industry 4.0 in construction. Fundamentally [1] grouped Industry 4.0 technologies, concepts and terms into three main clusters; ‘smart site’, ‘simulation and modelling’, and ‘digitisation and virtualisation’.

3. Methodology

Bibliometric studies are used to statistically analyse the patterns that arise in the publication of source documents. [6] provided a bibliometric dictionary that could be followed to examine connections among authors, theories, concepts, methods, and so forth. The methods and analysis of Ferreira, Serra [7] were followed.

3.1 Data collection procedure

To examine the Industry 4.0 influence in the construction industry, we followed procedures to collect data. First, we selected [1] article, published in *Computers in Industry*, which has a great citation count in WoS, Scopus, and Google Scholar. In particular, [2] refer to [1] paper as the most cited paper in the domainof Industry 4.0 in CMR. Furthermore, [1] was among the top 40 most highly cited articles on industry 4.0 in WoS. Second, we identified the source from where to collect the data. We selected the WoS database asit represents the most relevant source for our purpose. Although Web of Science and Scopus are the two most used literature databases, and Scopus covers more journals than WoS, WoS was selected. Referencesstrings in Scopus may not have a consistent format; the co-citation analysis cannot be conducted using analytical software. There is also Google Scholar, which should not be used in a bibliometric research sourcedue to some deficiencies [8]. Third, the time span for the research was defined. The data collection was done in 2020. Therefore 2019 was identified as the last year; 2016 was identified as the starting year since [1] was published that year. Notably, the first references to [1] appeared in 2017. With these three decisions,we

narrowed down the WoS website search for articles cited [1] during 2016-2019. The identified data collection procedures resulted in 73 papers. The majority of our data were article papers, which presents 67% of the total sample

3.2 Analysis procedure

Three types of complementary analyses were conducted in this research. The classification evolved in steps using the application VOSviewer. First, Citation analysis to determine the most cited papers by the article in our sample were performed. According to [9], the more the article is cited, the more influential it is. Thus, citation analysis aims to establish a relationship between citing and cited work. Therefore, citationanalysis is commonly used to identify the impact of research on a specific domain. Second, a co-citation analysis was performed. The purpose of co-citation analysis is to identify the connection between research.Co-citation is conducted by analysing how multiple works are cited together. Co-citation analysis assumesthat the more the articles are cited together, the more they are considered connected [7]. Third, themes analysis. In this step, the themes in the selected articles were identified, and the relationship among them was analysed. Following [7] and [2] procedures, the author-supplied keywords were used to classify and identify the research themes.

4. RESULTS AND ANALYSIS

4.1 Evolution of citations

Figure 1 shows that the citation count to [1] has increased during the last three years (considering that the data was collected in 2020), reflecting the growing attention towards Industry 4.0 in the CMR domain.The most cited works for each year were examined to observe any shifts in the CMR agenda (Table 1).

Table 1. Most co-cited references with [1] by year

2017		2018		2019	
No cited	Reference	No cited	Reference	No cited	Reference
13	[1]	33	[1]	27	[1]
4	[10]	14	[11]	10	[12]
4	[13]	8	[14]	9	[14]
3	[15]	7	[16]	9	[17]
3	[18]	7	[18]	8	[19]
2	[20]	6	[21]	7	[22]
2	[14]	6	[23]	6	[23]
2	[24]	6	[22]	6	[3]
2	[25]	6	[10]	6	[10]
2	[11]	6	[13]	6	[13]

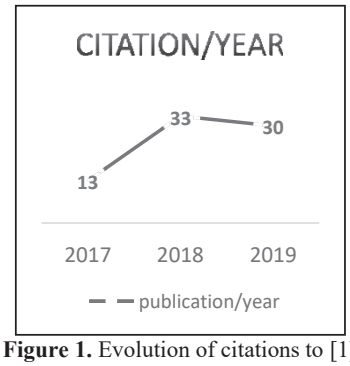

Figure 1. Evolution of citations to [1]

Table 1 indicated that the most cited publications are all recent efforts. That is because Industry 4.0 is a new field of research. In addition, in WoS, the first publication on Industry 4.0 came out in 2013 [5]. Table 1 also indicates some diversity of focus on Industry 4.0 related technologies within the CMR in the top-cited works. For instance, we observe a focus on IoT [21], big data, cyber-physical systems [13], and automation. Furthermore, reviews in their multiple forms, literature, systematic, and bibliometric review were cited the most, with 85% of papers citing a study [3, 12, 19].

Furthermore, by observing the three years, we may conclude a relative shift from citing publications about Industry 4.0 concept and definition in 2017 to focusing on Industry 4.0 applications in manufacturing and construction in 2018 and 2019. This shift indicated that the research attention is more related to the industry and the benefits of applying Industry 4.0 in multiple industries environments.

4.2 Intellectual Structure

Figure. 2 illustrates the co-citation network of the thirty most cited. Jointly, these papers used 4,759 references. The co-citation network concludes two phenomena; First, the lines that represent the connection between different publications and the strength of that connection. [1] is in the centre; the closer other papers are to the centre, the more they are co-cited with [1]. As illustrated in Fig. 2, the co-citation is higher with [18], [14], [12] articles on industry 4.0 concepts and challenges, [22], [26] articles on smart factory, and Lee jay works [13, 24]. These publications in the centre are the most relevant and more connected with all other articles.

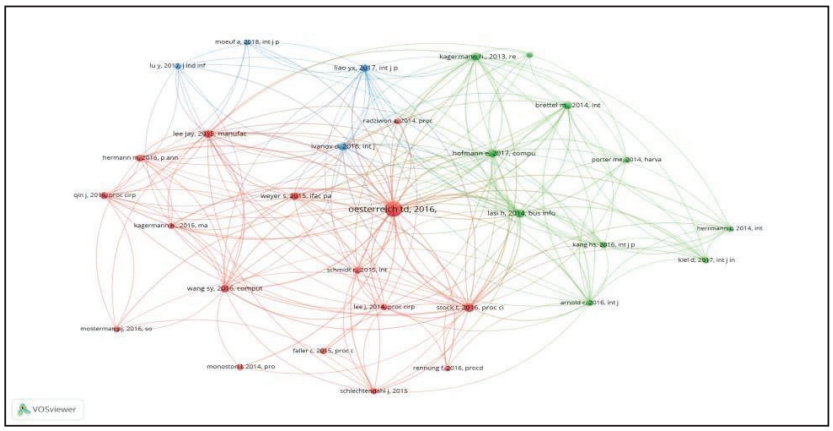

Figure 2. Co-citation network of the 30 most cited with Oesterreich and Teuteberg [1]

Second, the thickness of the connecting lines indicated the strength of the connections. VOSviewer places each reference on the network so that it pushes to the outer layer articles that, despite being frequentlyco-cited with [1], are usually less often cited by all other publications. For instance, [12] work on the currentand future status of Industry 4.0, and [26] article on Industry 4.0 potentials are often co-cited with [1]. Still,they are rarely cited together in our sample

4.3 Research Themes

This paper aims to understand how and in which context [1] is cited. For this endeavour, the authors-keywords of the articles citing [1] were coded into main research themes, following the described procedures. Table 2 summarises the main research themes; the most current themes are ‘the fourth industrial revolution’ (71 times), ‘methodology, data analysis, and review’ (51 times), and ‘Decision making, management, and performance’ (46 times). This analysis illustrates how Industry 4.0 was merged in CMR, that is, how Industry 4.0 was researched in the construction industry context

Table 2. Main research themes

Research theme	Frequency	Research theme	Frequency
The fourth industrial revolution (Industry 4.0)	71	Supply chain management	11
Methodology, data analysis, and review	51	Skills and workers	9
Management, applications, and concept	46	Sustainability	9
Smart factory*	37	Performance and impact	9
Digitisation and virtualisation*	23	BIM	8
Collaborative engineering and innovation	23	Business intelligence	7
External and internal environment	20	Regional and geography	7
Manufacturing industry	17	IT	7
Enterprise, industry, and discipline	16	Simulation and modelling*	5
Construction industry	15	Theory	5
Cyber-physical system	12		

*Note: Frequency is the sum of author-supplied keywords. The * indicated the themes that were drawn from [1].*

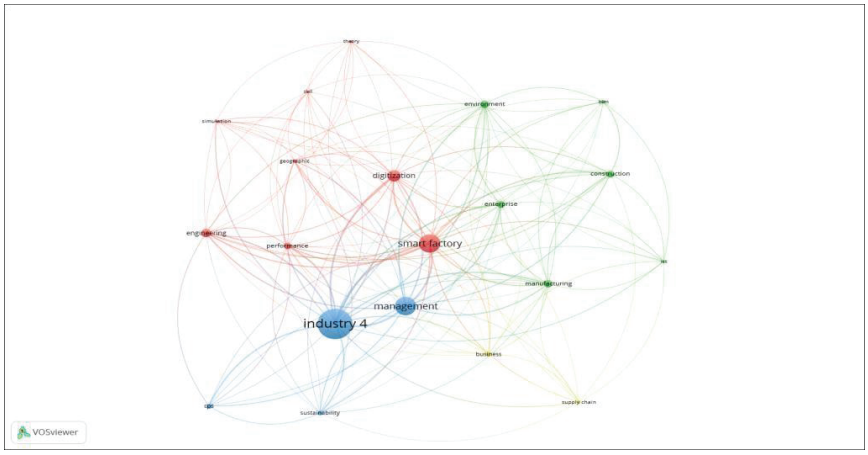

Figure 3. Co-occurrence network of the main research theme

Figure 3 illustrates the co-occurrence network with the connections between the 20 main themes identified in our sample (methodology theme was excluded). This network aims to identify the significant issues examined in the works citing [1]. The network is also considered dynamic; that is, the size and position of the theme in the network are based on its frequency count and its co-occurrence count with otherthemes. In this type of network, the closer the theme to the centre, the more prevalent it is and has a high impact.

Examining Figure 3, the theme '(Industry 4.0)' was identified in the network's core at the centre. Industry 4.0 was the central theme in [1], and it is a new field of research within which most scholars and journals are focusing. Similarly, the theme 'Management, applications, and concept' was also identified in the core, amplifying the focus on Industry 4.0 applications, technologies, and concepts in multiple disciplines. Theme 'Performance, KPIs, and impact' is also close to the core, and this type of research aims to help decision-makers managers adopt such technologies by identifying their impact on performance. For the themes 'Smart factory', 'Simulation and modelling', and 'Digitization and virtualisation' adopted from [4], the connection with Industry 4.0 are well identified in the network. Additionally, its frequencies are in proportion with the number of technologies under each theme.

5. DISCUSSION AND CONCLUSIONS

In this research, bibliometric analysis was used to capture a broad understanding of Industry 4.0 in the extant research in construction management studies over the past three years. A group of bibliometric techniques was conducted including citation, co-citation, and co-occurrence. The aim of those techniques was identifying the core works with the more significant impact and identifying the research themes in CMR. Moreover, Industry 4.0 opens a pathway to different context of research. The emergence of Industry 4.0 in the industry disciplines has been widespread, and the construction industry has not been immune. Industry 4.0 has already earned its print in CMR, and contributed to creating much novel research by putting forward its various technologies and its alternative applications, challenges, benefits, and so forth. Virtually all CM top journals are moving towards Industry 4.0 in construction. That is easily observable in citations to Industry 4.0 in the extant CM research.

Undoubtedly, the decision to use [1] is a simplification. Also, Oesterreich and Teuteberg are not the only contributors, as many other scholars have been contributing to examine Industry 4.0 in the CM context. Nevertheless, the argument is not that Oesterreich and Teuteberg are the only contributors, but that their research has been used as a key marker to understand Industry 4.0 in the construction context in any article examining those two fields.

The evolution of citation was identified in the past four years, indicating the importance of Industry 4.0 applications in the construction industry. The most co-cited references were from other industry, especially manufacturing industry. That is because Industry 4.0 was applied in the manufacturing sector at the very beginning of Industry 4.0 emerging back in 2012. On the other hand, Industry 4.0 was slowly integrated into the construction industry due to its complex environment and project wise culture [1]. Notably, the cited references were for recent works, which indicates the rising importance of Industry 4.0 research and is in line with the fact that Industry 4.0 term was originated in 2012 [5]

Considering the interactions and relationship between top-cited references, it was noticed that [1] has a strong relationship with papers examining smart factory and bigdata; [22] and [26] papers. That could be related to Oesterreich and Teuteberg's broad definition of smart factories and their technologies. Second observation is that when examining [3] paper, it was noticed that it has a weak connection with the top-cited works, despite the fact that it is also about Industry 4.0 in construction context, which strengthens the assumption of the importance of [1] which has a strong connection with all other Industry 4.0 works.

Twenty-one main research themes were identified, a co-occurrence network was constructed and examined. In the core of that network was the fourth industrial revolution theme, which is in line with the aim of this paper. Also, for the smart factory to be in the core supports the finding from the co-citation network. Similarly, the management and performance themes have a great importance and influence, which indicate the recent tendency towards examining Industry 4.0 application and benefits to the construction industry among authors.

This paper could be useful to identify the current knowledge and identify gaps in research to create a better understanding of how Industry 4.0 has contributed to CM literature. The path for integrating Industry 4.0 in the construction industry is still munificent – see, for example, [2] paper. The results indicate that some research themes seem to have more research attention. Figure 4 illustrates a sufficient number of references to Industry 4.0 in the themes of management, smart factory, and digitisation. On the other hand, other themes have received less scholarly attention, such as performance, simulation, and supply chain management. Those less explored themes possibly require additional studies.

Understanding and integration Industry 4.0 within the construction industry may be evolved by targeting various countries. It was noticed that much of the research was conducted in developed countries such as Germany, Japan and China, while a larger group of emerging economies is rising. Therefore, research in less developed countries is encouraged.

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