Blueprint for Construction 4.0 Technologies: A Bibliometric Analysis

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Abstract. To survive in an increasingly complex environment, the Architectural, Engineering and Construction (AEC) industry needs a game-changing innovation. As, the industrial sector has provided compelling evidence that Industry 4.0 gives the opportunity to gain competitive advantages, the construction industry started embracing what is now acknowledged as Construction 4.0. While Building Information modeling (BIM) has been extensively discussed and is perceived as a core enabler of Construction 4.0, this next revolution in the AEC industry goes beyond BIM. As Construction 4.0 is gaining momentum in the construction body of knowledge, there is still no consensus on what Construction 4.0 really means and what technologies it encompasses. Building on insights collected from the extant research corpus through a systematic literature review of the published scientific research in the last ten years, this paper proposes a blueprint for Construction 4.0. Bibliometric analysis was employed to map the currently discussed Construction 4.0 technologies, group them into clusters based on their occurrences, and determine the least researched ones. This blueprint sheds light on how well-defined the concept of Construction 4.0 is, detects the least researched technologies, and provides AEC stakeholders with a reference to better understand this transformation and where it stands today.

1. Introduction

As one of the oldest and most traditional industries, the Architectural, Engineering and Construction (AEC) industry has been recognized for its resistance to change and obstinacy to technology, leading to lagging productivity growth, limited digitization, frequent insolvencies, and low customer satisfaction [1]. However, influenced by the industrial sector and the gains that resulted from the fourth industrial revolution or what is known as Industry 4.0, the AEC industry began to follow suit and embraced this new transformation to improve its performance [2]. As a result, the term Construction 4.0 emerged in the construction research corpus [3].

Although Industry 4.0 is commonly and frequently used among practitioners and academics, there exists no clear definition of its concept [4]. The literature reveals more than 100 different definitions of Industry 4.0 [5]. Like its counterpart, there is also no consensus on the definition of Construction 4.0 and its elements [6]. Some authors refer to Construction 4.0 as the digitization of the AEC industry [7], others consider it a representation of a transformative framework towards a globally connected, smart, and active construction process integration [8].

Based on a recent report published by McKinsey & Company, 80% of the surveyed respondents believe that the AEC industry will change drastically in the next 20 years and that the COVID-19 pandemic will likely accelerate the transformation of the industry. Also, it is expected that the AEC
industry will harness new digital technologies to accelerate the transformation process [1]. In this context, it is critical to understand recent efforts undertaken toward achieving this transformation and investigate the current trends of adopting emerging technologies in the AEC industry.

Some implemented technologies are well investigated such as BIM [9] [10], modular and off-site construction [11] [12], virtual and augmented reality [13] [14]; however, they are not representative of all the recent efforts and trends toward digitizing the AEC industry. Moreover, most research efforts focus on the relatively mature technologies and ignore the least adopted ones. Thus, for a holistic understanding of Construction 4.0, it is vital to direct research toward investigating the less mature technologies to allow for a better forecast of future priorities. The work presented in this paper provides a review of the recent literature that investigated the technologies that are imbedded under the umbrella of Construction 4.0. A bibliometric analysis of the scientific literature since 2010 is presented to map out the currently discussed Construction 4.0 technologies and group them into clusters, forming the blueprint of Construction 4.0. Consequently, the findings of this paper shed light on the least addressed Construction 4.0 technologies, providing opportunities to further investigate this aspect of Construction 4.0. This paper assists both researchers and practitioners in directing their research efforts to accelerate the transformation of the AEC industry.

2. Recent Work on Construction 4.0

After the emergence of the concept of Construction 4.0, several researchers conducted a systematic literature review to investigate the efforts undertaken toward transforming the AEC industry by questing technologies that compose Construction 4.0. These research efforts and the identified Construction 4.0 technologies are summarized in Table 1.

| Reference                     | Enabled Construction 4.0 technologies                                                                 |
|-------------------------------|--------------------------------------------------------------------------------------------------------|
| Oesterreich and Teuteberg     | Additive Manufacturing; Automation; Augmented/Virtual/Mixed Reality (AR/VR/MR); Big Data; BIM         |
| (2016)[15]                    | Cyber-Physical Systems (CPS)/Embedded systems; Cloud Computing; Digitization; Human-Computer Interaction (HCI); Internet of Services (IoS); Mobile Computing; Modularization/Prefabrication; Product-Lifecycle Management (PLM); Radio Frequency Identification (RFID); Robotics; Simulation tools/ Simulation models; Social Media |
| Dallasega et al. (2018)[16]   | BIM; Cloud Computing; Digitization; E-supply Chain Management; Tracking and Localization; 3D Printing  |
| Maskuriy et al. (2019)[17]    | Additive Manufacturing; AR/VR; Big Data; BIM; Cloud Computing; CPS; Geographic Information System (GIS); IoT; Mobile Computing; RFID |
| Boton et al. (2020)[18]       | Additive manufacturing; AR/VR; Big Data; BIM; Cloud computing; CPS; IoT; RFID; 3D Printing           |
| Forcael et al. (2020)[19]     | Technologies that are essential to understand Construction 4.0 at present time: Big Data; IoT; VR; 3D Printing Additive Manufacturing; AR/VR/MR; BIM; Blockchain; Cloud Computing; Drones; GIS; Laser Scanners/Point |
| Perrier et al. (2020)[20]     | Cloud/Photogrammetry; Sensors (RFID-Infrared- data transfer sensors); Machine Learning /Neural Networks; Mobile Robotic Units Actuators; Additive manufacturing; Artificial Intelligence (AI); AR/VR; Big Data and Analytics; BIM; Blockchain; Cloud-based Common Data Environment (CDE); Cloud-based Project Management; Cybersecurity; IoT/equipment |
| Sawhney et al. (2020)[8]      | BIM; Blockchain; Cloud-based Common Data Environment (CDE); Cloud-based Project Management; Cybersecurity; IoT/equipment |
3. Research approach

This research paper is part of an ongoing effort to investigate the least discussed Construction 4.0, their requirements, and potential integration with other Construction 4.0 technologies. This overarching objective is achieved through a series of intermediate objectives: (1) identify the existing research work that categorized Construction 4.0 technologies; (2) find the most common technologies from the work identified in task 1; (3) conduct a systematic literature review of the detected technologies and provide a bibliometric analysis to cluster the technologies based on their occurrences; (4) identify the least researched technologies, extract the requirements of their implementations divided into three tiers: people, process, and technology i.e. who are the people who will use this technology and what are their needs, the process of implementing the technology, and the required technologies; (5) identify the challenges that hinder the implementation of the least researched technology; and (6) investigate if the technology can be implemented to both vertical and horizontal construction. This paper only covers the first three tasks.

3.1. Data collection

As outlined in Table 1, different research efforts resulted in different sets of Construction 4.0 technologies. Based on the results in Table 1, the most frequently mentioned technologies, sorted in alphabetical order, are listed as follows: AI, Additive Manufacturing, AR/VR, Automation and Robotics, Big Data, BIM, Cloud Computing, CPS, Digital Twin, GIS, IoT, Laser Scanners, Modular Construction, Offsite construction, Prefabrication, Sensors, and UAVs/Drones. This list of Construction 4.0 technologies was then used to conduct a systematic literature review to develop the blueprint of Construction 4.0.

Web of science was considered as the data collection source. The unit of analysis used was “term extracted from title or abstract” which is considered one of the most used bibliometric techniques [23]. Based on the Web of Science settings, all research written in English from 2010 to 2021 were selected. To ensure a good representative selection of the collected data, different queries were used. Moreover, to better focus the scope of the search and limit unnecessary burden, the focus was on articles that contained the searched query term in their title. Table 2 summarizes the queries used for the data collection.

| Table 2. Summary of the queries used for the data collection |
|-------------------------------------------------------------|
| “Construction” AND | "Additive Manufacturing"; "Artificial Intelligence"; "AI"; "Augmented Reality"; "AR"; "Automation"; "Robotics"; "Building Information Modeling"; "BIM"; "Big Data"; "Cyber-Physical System"; "CPS"; "Cloud Computing"; "Digital twin"; "Geographic information System"; "GIS"; "Internet of Things"; "IoT"; "Laser scanners"; "Laser Scanning"; "Offsite Construction"; "Sensors"; "Drones"; "UAV"; "Unmanned Aerial System"; "Unmanned Aerial Vehicle"; "Virtual Reality"; "VR" |
3.2. Quality assessment and normalization

Each query search was conducted separately to ensure better quality assessment and quality control. After each query search, the abstracts were investigated, and, if the topic of the research was found to be relevant to the current study, the research was selected. This selective process enabled the selection of the research work that is only specific to the construction industry and one of the selected Construction 4.0 technologies. As a result, a total of 2204 articles were collected.

3.3. Data analysis

The collected data was exported to both text files and CSV files. The selected research data was imported to VOSviewer, an open-source network visualization software application, which allows for the visualization of research work based on their occurrences and separates them into clusters. The VOSviewer setting of “creating a map based on text data” was employed where terms are extracted from the title and the abstract. Moreover, to filter the extracted terms, a VOSviewer thesaurus file was applied. For instance, the terms “BIM”, “Building Information Modeling”, “Building Information Modelling”, and “BIM Models” were replaced by Building Information Modeling. Also, binary counting (i.e., only the presence or the absence of the term is counted and the number of occurrences of a term in the document is not considered) was selected. This selected option allowed for the reliable analysis of the data occurrences. Finally, only terms that represent Construction 4.0 technologies were selected to allow a better visualization of the results. The resulting map is presented in Figure 1.

![Network of normalized Construction 4.0 technologies’ occurrences](image)

Each cluster is identified by a color and relative technologies/points are grouped together based on highly connected terms that share similar fields. A total of five clusters were identified. The total number of occurrences and the resulting clusters are summarized in Table 3.

The first cluster includes a wide range of technologies available in Construction 4.0 which represent automation of the construction production, the second cluster represents storing and processing of construction data, the third cluster refers to construction data analysis and visualization, while the fourth cluster defines construction information modeling and design, and finally the fifth cluster depicts construction surveying and photogrammetry. According to the results, the most
researched technology in the construction industry is BIM with 1289 occurrences. On the other hand, the least researched Construction 4.0 technologies are Digital Twin with 13 occurrences and Cyber-Physical Systems with 15 occurrences.

| Table 3. Construction 4.0 technologies clusters and occurrences (n=number of occurrences) |
|------------------------------------------|----------------------------------|----------------|----------------|----------------|
| Cluster 1                                | Cluster 2                        | Cluster 3      | Cluster 4      | Cluster 5      |
| *Additive Manufacturing (n=28)           | *Big Data (n=74)                 | *AI (n=28)     | *BIM (n=1289)  | *Laser Scanning (n=46) |
| *Automation (n=98)                       | *Cloud Computing (n=33)          | *AR (n=69)     | *GIS (n=74)    | *UAV (n=47)    |
| *Offsite Construction (n=32)             | *IoT (n=55)                      | *CPS (n=15)    | *VR (n=79)     |                |
| *Modular Construction (n=59)             | *Sensors (n=73)                  | *Digital Twin (n=13) |                |                |
| *Prefabication (n=41)                    |                                   |                |                |                |
| *Robotics (n=51)                         |                                   |                |                |                |

Based on the data analysis the least occurring technologies are Digital Twin and CPS and they are both clustered together (Cluster 3) with AI and AR. This observation is supported by findings of [23] who stated that the concept of Digital Twin emphasizes a holistic characterization of the operating facility by contributing with CPS to optimize bidirectional data flow and data interoperability. Moreover, the concept of Digital Twin in the AEC industry goes beyond BIM [24]. It integrates with several technologies, positioning it as the hub of all other technologies that are encompassed within the concept of Construction 4.0, including autonomous construction vehicles, aerial drones, sensors, BIM models, IoT, semantic web technologies, and AI [23] [25].

4. Conclusion, limitations, and further studies
This paper investigated the research corpus to categorize the technologies that encompass Construction 4.0. Bibliometric analysis and clustering of technologies based on their occurrences were conducted. Results showed that Digital Twin and CPS are the least investigated technologies and they were clustered with AI and AR. It should be noted that the results presented in this paper are limited to the web science database. Additional databases could be added to the conducted analysis.

Based on the findings of this paper, and part of the ongoing research effort, future work will investigate the requirements of Digital Twin (people, process, and technology) with a focus on the technologies that were clustered with Digital Twin. The use of Digital Twin in the AEC industry will be demonstrated through case studies in the vertical and horizontal construction sector. Providing an understanding of a promising technology that is key to connectivity in Construction 4.0 will help direct research toward investigating the interrelations between the technologies and better forecast of the digital future of the AEC industry.

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