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Synergies Between Construction 4.0 Technologies and Sustainable Construction: A Bibliometric Analysis

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Abstract

In November of 2021, world leaders united in the 26th UN Climate Change Conference (COP26), and they set a Building Vision for a Zero Emission and Resilient Built Environment, Regions and Cities. The Architectural, Engineering, and Construction industry (AEC) is responsible for the design, planning, construction, and maintenance of the built environment- thus, playing a critical role in supporting and leading these endeavors. With the ongoing efforts to digitize the AEC industry by implementing and integrating innovative technologies in the industry's main practices, the aim of this research is to investigate the contribution of three major technologies that are considered under the umbrella of Construction 4.0 namely Building Information Modeling (BIM), advanced manufacturing (including 3D printing, modular construction, offsite construction, and prefabrication) and Digital Twins. Building on insights collected from the extant research corpus through a systematic literature review of the published scientific research, this paper proposes a blueprint for the three Construction 4.0 technologies and their overarching influence on the achievement of Sustainable Development Goals (SDGs). Bibliometric analysis was employed to map the currently discussed technologies, and group them into themes based on their "combat capabilities" and contribution to sustainability. The analysis resulted in three major clusters: (1) Sustainable Design and Modelling lead by BIM, (2) Lifecycle Sustainability Assessment led by prefabrication, modular construction, and offsite construction, and (3) Sustainable Construction and Performance led by Digital Twins and 3D printing. Findings of the paper will serve as the foundation for future work that will map the expand on the clusters and mark their respective technologies to the SDGs.

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Keywords: 3D printing, building information modeling, digital twins, offsite construction, sustainable Development Goals (SDGs)

1. Introduction and Background

As of November 4, 2016, actions resulting from the Paris Agreement on Climate change was commenced after 55 countries responsible for 55% of the total greenhouse gas emission agreed to work toward limiting the global temperature rise to below 2 degrees Celsius. The Paris Agreement aligned with the efforts initiated by the United Nations (UN) in 2015 toward achieving the 17 Sustainable Development Goals (SDGs), initiating a global roadmap to achieve an essential transformation of energy access and transition by 2030, and contributing to net zero emission by 2050 [1]. However, in 2019, the COVID-19 crisis was an inflection point which changed the course toward sustainable development. While progress toward the 2030 target goals has been made before the pandemic, the pace of change toward the 17 SDGs was not as desired [2]

[3]. The authors of [4] showcased how the pandemic disrupted the progress toward SDGs especially in developing countries. Moreover, [3] highlighted that SDGs' priorities will shift due to funding disruptions. The pandemic crisis provided clear evidence that the lack of focus on SDGs, especially the ones related to people and the environment, played an important role in the emergence and spread of infectious diseases, including COVID-19 [5]. Consequently, the chaotic environment that was caused by the pandemic has spurred a shift in goals and investments towards health and infrastructure [6]. The pandemic has accelerated the shift toward social infrastructure projects that will target urbanization, healthcare, infrastructure, and Global Water, Sanitation, & Hygiene (WASH) projects which will help cities to face future pandemics [7] [8].

However, regardless of the challenges facing the SDGs, various publications have highlighted the important role SDGs have in recovery. The authors of [2] [5] [9] argued that SDGs can be the blueprint of response and recovery. Moreover, United Nations Environment Programme (UNEP) listed four SDGs that are anticipated to help in the post-pandemic recovery, including Responsible Consumption and Production, Climate Action, Life on Land, and Life Below Water [10]. Also, the authors of [11] explained how SDGs such as Climate Action Partnerships and Reduced Inequality are considered the cornerstone for a successful recovery and transition to sustainability. In addition to being an important aspect of strong sustainable recovery, previous work highlighted how SDGs are beneficial for various industries including the Architectural, Engineering and Construction (AEC) industry. Corporate Citizenship provided a detailed overview of how different SDGs benefit different businesses. For instance, the Architectural, Engineering, and Construction (AEC) industry can benefit from affordable and clean energy goal, a benefit that is becoming critical for the future market, and for improving operational efficiency in addition to the benefits for the environment [12]. Other goals such as Industry Innovation and Infrastructure, Life on Land, and Life Below Water will aid in the prevention of adverse environmental incidents, proactively manage operational health and safety, and help to maintain trust with key stakeholders which can have a long-term positive effect on future projects.

By the same token, governments around the world are considering several actions to address the sustainable issues of the AEC industry, including high carbon emission, health and safety risks, low productivity, and increasing costs. Thus, implementing and adopting Construction 4.0 technologies within the AEC industry was considered as a potential solution to address and overcome the industry's sustainable challenges [13] [14]. [15] investigated the existing research work that categorized Construction 4.0 technologies and identified 17 different technologies that are considered under the umbrella of Construction 4.0, namely: Artificial Intelligence (AI), Additive Manufacturing, Augmented Reality/Virtual reality, Automation and Robotics, Big Data, Building Information Modelling (BIM), Cloud Computing, Cypher Physical Systems (CPS), Digital Twins, Geographic Information System (GIS), Internet of Thing (IoT), Laser scanners, Modular Construction, Offsite Construction, Prefabrication, Sensors, and Unmanned Aerial Vehicles/Drones.

The authors of [16] conducted a bibliometric analysis of the construction education studies published between 1983 and 2017 to highlight the current trends in the construction education research. This study found that emerging concepts like BIM and sustainability are trending. This finding indicates the increasing interest of researchers in investigating sustainable construction. Similarly, [17] conducted a bibliometric review to document the trending research in the field of sustainable construction over the last 25 years and determined that the dominant topics were alternative materials for sustainable construction, sustainable construction management, recycling and waste reduction, and social sustainability in construction management. Moreover, [13] further discussed that understanding the implementation of Construction 4.0 technologies in the AEC industry and its contribution to sustainability is not clear yet, however, the authors found that positive impact of Construction 4.0 technologies on the environmental and economic sustainability surmounts its negative effect, but its impact on social sustainability is still questionable. Thus, it is critical to upskill the level of knowledge about the capabilities of Construction 4.0 technologies, investigate the different applications for trending technologies, and consider technologies that are expected to have a significant impact in the future. This knowledge and understanding will increase the awareness of the potential of Construction 4.0 technologies in addressing the sustainable concerns facing the industry and will enable the stipulation of policy interventions that would mitigate the negative impacts related to sustainability. Therefore, the aim of this paper is to further investigate the contribution of adopting Construction 4.0 technologies in the AEC industry toward achieving the overarching SDGs and supporting the post-pandemic recovery.

2. Research Approach

This research paper is part of an ongoing effort to investigate the influence of Construction 4.0 technologies on the achievement of the Sustainable Development Goals (SDG). This overarching objective is achieved through a series of intermediate objectives: (1) conduct a bibliometric review of research aimed to document and articulate research trends in the integrated domain of sustainable construction and the implementation of Construction 4.0 technologies; (2) cluster the technologies based on their keyword co-occurrences and identify existing themes; (3) identify the contribution of the investigated Construction 4.0 technologies toward sustainability by extracting empirical evidences of this contribution from literature; (4) map the influence of Construction 4.0 technologies to the SDGs; and (5) develop a quantitative measure to quantify the direction of influence of the investigated Construction 4.0 technology toward achieving SDGs (i.e., no influence, positive influence, or negative influence) and the aggregated influence of all investigated technologies toward the achievement of the SDGs. This paper only covers the first three tasks and investigates the major technologies that are considered under the umbrella of Construction 4.0, namely Building Information Modelling (BIM); advanced manufacturing including the following technologies: 3D printing, modular construction, additive manufacturing, offsite construction, and pre-fabrication; and Digital Twins.

2.1. *Data collection*

Web of science (WOS) 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 [18]. Based on the Web of Science settings, all research written in English 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(s) in their title or abstract. Table 13 summarizes the queries used for the data collection. The collected data was exported to both text and CSV files.

Table 13. Summary of the queries used for the data collection

First Search	((TS=("Construction") OR TS=("AEC") OR TS= ("Architecture Engineering Construction") OR TS= ("Built Environment")) AND	(TS= ("Building information Modeling") OR TS=("BIM")) AND (TS=("Sustainability")))
Second Search	((TS=("Construction") OR TS=("AEC") OR TS= ("Architecture Engineering Construction") OR TS= ("Built Environment")) AND	(TS= ("Modular Construction") OR TS= ("3D Printing") OR TS= ("Additive Manufacturing") OR TS= ("three-dimensional printing") OR TS= ("Offsite Construction") OR TS=("Prefabrication")) AND (TS=("Sustainability")))
Third Search	((TS=("Construction") OR TS=("AEC") OR TS= ("Architecture Engineering Construction") OR TS= ("Built Environment")) AND	(TS= ("Digital Twin*) AND (TS=("Sustainability")))

2.2. *Quality assessment and normalization*

A total of three searches were conducted as shown in Table 1. Each query search was conducted separately to ensure better quality assessment and quality control. The search resulted in a total of 979 papers, distributed as follows: 651 papers resulted from the first search, 302 papers were obtained from the second search, and 26 papers were gathered from the third search (refer to Table 1). 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 sustainable construction in the AEC industry and the selected Construction 4.0 technologies. As such, 358 papers were selected from the first search, 174 papers from the second search, and 24 from the third search. Therefore, a total of 556 papers were considered for further data analysis.

The final set of 556 papers was then categorized according to the type of technology adopted. Moreover, to ensure a required level of quality control, the Document Type (DT) as identified by WOS [19] was further investigated. As shown in Fig. 14., most of the selected papers for the different technologies were articles (i.e., a published research paper), followed by proceedings paper (papers that have been presented in full at a conference, meeting, symposium or similar gathering, generally published in a book of conference proceedings), then followed by review (i.e., a renewed study or survey of previously published literature providing new analysis or summarization of the research topic).

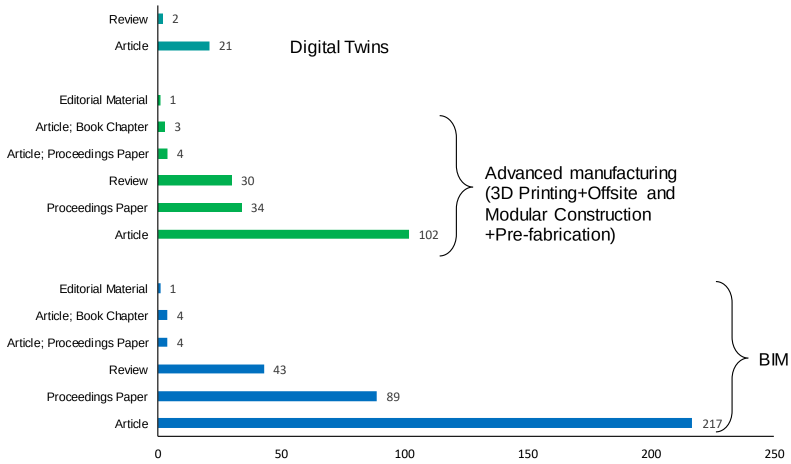

Fig. 14. Distribution of Document Types of the selected papers across different technologies.

3. Results

3.1. Bibliometric analysis

The annual scientific production presented in Fig. 15. shows that the interest in implementing BIM, advanced manufacturing and Digital Twins for sustainable construction fluctuated in early years until 2018. After 2018, the interest in implementing these technologies and their contribution to achieve sustainability continued to increase and peaked in 2021 for all technologies considered in this study. Thus, these trends support the argument that, after the COVID-19 pandemic, awareness of the criticality of achieving sustainable construction by adopting and implementing emerging technologies became evident.

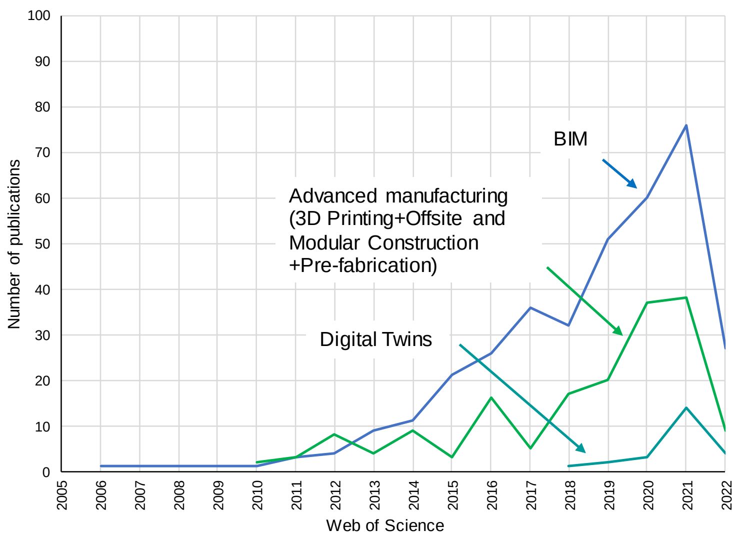

Fig. 15. Published scientific literature (2005-2022)

Moreover, to highlight how the research field is structured, topical analysis was employed. A co-word map was generated in VOSviewer using a threshold of 15 keyword co-occurrences as presented in Fig. 16. Three clusters were identified, each represented by a color and with a minimum size of five keywords. The map in Fig. 16. reveals three themes (1) Sustainable Design and Modelling, (2) Lifecycle Sustainability Assessment, and (3) Sustainable Construction and Performance. As shown in Fig. 3. BIM is in the middle of theme 1 of Sustainable Design and Modelling. This finding is also evident in the work of [20] who investigated the synergies between BIM and sustainability where BIM is said to be mainly associated with sustainability through its capabilities of design optimization, data management and data integration, analysis and simulation. Moreover, for the second theme of Lifecycle Sustainability Assessment, technologies such as off-site construction, prefabrication, and modular construction were included in this theme. This grouping aligns with the capabilities of these technologies that aim to enable the concept of circular economy and reduce the greenhouse gas emission and waste generation [21] [22]. Also, the authors of [23] found that the sustainability performance indicators of these technologies are very important for evaluating lifecycle sustainability of construction. Furthermore, for the third theme of Sustainable Construction and Performance, technologies such as Digital Twins and 3D printing were clustered together. Digital Twins can contribute to sustainability by optimizing performance through its capability of conducting what-if simulations [24] [25]. Additionally, [26] investigated how 3D printing can improve the thermal performance of structures and how it can contribute to waste minimization.

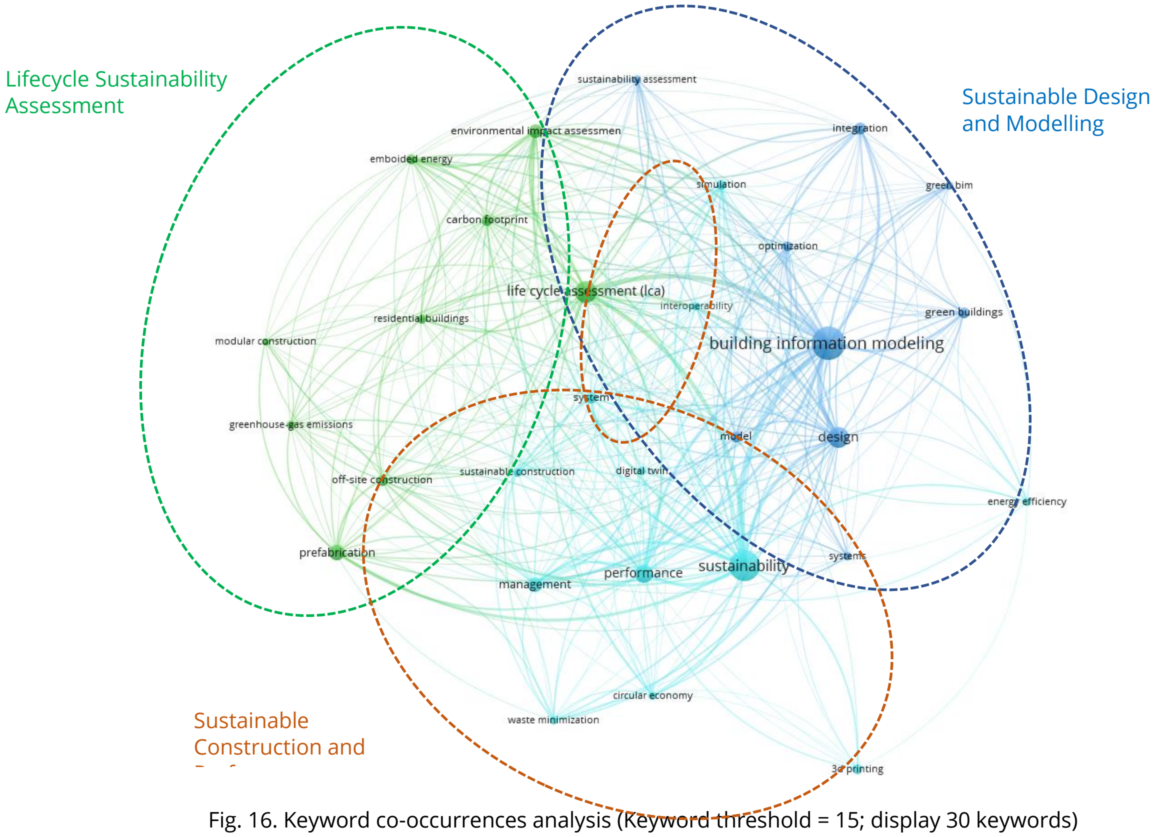

Fig. 16. Keyword co-occurrences analysis (Keyword threshold = 15; display 30 keywords)

Note: Size of node represents the frequency of occurrences of the keyword, proximity of nodes (line width) is based on the frequency of the co-occurrences of two keywords in the selected document, and clustering (by color) is based on the pattern of co-occurrences among multiple keywords in the review document (minimum cluster size = 5 keywords).

4. Conclusion, limitations, and further studies

This paper investigated the construction research corpus to investigate major Construction 4.0 technologies and their contribution to sustainability. A bibliometric analysis and clustering on keyword co-occurrences were conducted. Results showed the distinction of three themes (1) *Sustainable Design and Modelling* lead by BIM, (2) *Lifecycle Sustainability Assessment* where technologies such as prefabrication, modular construction, and offsite construction impacted the direction of this theme, and (3) Sustainable Construction and Performance, where technologies such as Digital Twins and 3D printing are the main contributors to this theme.

Based on the findings of this paper, and part of the ongoing research effort, future work will map the influence of Construction 4.0 technologies onto the Sustainable Development Goals (SDGs) and will quantify the direction of influence towards achieving each goal.

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