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Exploring Building Information Modeling (BIM) and Internet of Things (IoT) Integration for Sustainable Building

Yali Chen [1], Xiaozi Wang [1,*], Zhen Liu [1,*], Jia Cui [1], Mohamed Osmani [2] and Peter Demian [2]

1 School of Design, South China University of Technology, Guangzhou 510006, China
2 School of Architecture, Building and Civil Engineering, Loughborough University, Loughborough LE11 3TU, UK
* Correspondence: 202021055565@mail.scut.edu.cn (X.W.); liuzjames@scut.edu.cn (Z.L.)

Abstract: Sustainable development, which has become the priority study of architectural design, is receiving increasing attention with global climate change. At the same time, the building industry is urgently changing towards intelligent and digitalized tendencies. As a result, Building Information Modeling (BIM) and the Internet of Things (IoT) make crucial contributions to the transforming process. However, there is little knowledge of the integration of BIM–IoT in sustainable building from a macro perspective. Moreover, most existing research adopts a literature review method and lacks objective quantitative analysis. Few papers use bibliometric analysis to study the respective BIM and IoT research fields. Furthermore, few studies use Citespace software tools to analyze the integrated application of BIM–IoT. Therefore, this paper aims to investigate the research frontiers and knowledge structure in BIM–IoT integration and the relationship between BIM-IoT and sustainable building and explore the research hotspots, trends, and future research directions. A quick and objective method was proposed to understand the research status of these new and rapidly developing fields. This paper uses topic search in the web of science core collection to obtain relevant literature and then uses Citespace for bibliometric analysis based on the literature review. Controlled terms and subject terms statistics from the Engineering Index core database search results are also used to briefly examine the fields' research frontiers and hotspots as obtained from Citespace. The results show that: (1) The research on BIM–IoT integration focuses on building intelligence with BIM as the basis of application, and research on BIM–IoT integration within the field of sustainable building is currently focused on the first three phases of the life cycle. (2) The development of sustainable buildings needs to be considered on its human and social dimensions. BIM provides a platform for sharing information and communication among stakeholders involved in the building's entire life cycle. At the same time, IoT allows occupants to better participate in buildings' sustainable design and decision making. (3) In the future, more emerging technologies such as cloud computing and big data are required to better promote sustainable buildings and thus realize the construction of sustainable smart cities. At the same time, researchers should also pay attention to the sustainable transformation of existing buildings.

Keywords: Building Information Modeling (BIM); Internet of Things (IoT); sustainable building; smart cities; information management; building metaverse; life cycle; bibliometric

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1. Introduction

Sustainability is an essential pillar of smart city development [1]. As one of the main elements of the built environment of smart cities [2], smart buildings should implement sustainability throughout their life cycle [3]. Trends and concepts in building design and construction are similar to those in smart cities [2], from intelligent to digital to the sustainable intelligence that has been receiving huge attention recently. Smart buildings emphasize the need for automation [4] but in many cases incorporate sustainable features [2]. The pursuit of sustainability in building aims to meet the sustainable development of smart cities [5], which requires the promotion of technology [6]. Hence, the sustainable building defined in this paper is a smart building which considers sustainability. Most of the current studies on sustainable buildings have focused on energy, water, and carbon efficiency. However, the next giant leap in sustainable building design could come from integrating smart structural technologies [7].

Building Information Modeling (BIM) is a platform for keeping accurate and interoperable records of building information to enhance pre-planning, design construction, and maintenance throughout the life cycles of facilities [8,9]; it is also used for the delivery of integrated projects in buildings and infrastructure [10]. Research on BIM is still in a rapid growth phase. BIM is derived from the Building Description System (BDS) proposed by Charles Eastman et al. [11], which stores and manipulates building information consistently to prevent design changes. The United States National BIM Standard [12] defines BIM as "a digital representation of physical and functional characteristics of a facility; a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition". BIM is vital to facilitate the application of other technologies in the construction industry [13].

One potential use of BIM is to improve the current data capture technology for BIM model construction [14]. The Internet of Things (IoT) is capable of capturing massive numbers of data on facilities in real-time [15]. As an emerging technology, the definition of IoT is still unclear, with multiple interpretations. The term "Internet of Things" first appeared at the MIT Center for Automatic Identification Technology in 1999, and it was not until 2005 that the International Telecommunication Union (ITU) officially introduced it [16]. IoT in intelligent industrial IoT can be applied to production process control, production environment monitoring, manufacturing supply chain tracking, product whole life cycle monitoring, promoting safe production and energy saving, and emission reduction [17], in which the generated data are of a large volume, variety, speed, and accuracy [18]. However, BIM has also revealed shortcomings, such as only constructing the static models [19] without achieving dynamic detection, as well as insufficient interactivity [20]. Building digitization requires the optimization of data collection and management; therefore, the integration of BIM–IoT, which are two main pillars of building digitization, has gained in importance [19]. However, the current study is still pre-mature, and most of the work is at the conceptual stage. BIM and IoT technologies are emerging technologies that help the development of smart buildings. Although sustainable building emphasizes sustainability in every aspect of the building's life cycle [21] more so compared to smart building, it also needs the support and promotion of technology. Existing studies have used BIM and IoT devices in many areas such as energy management [22,23], construction monitoring, health and safety management, and building management [24]. The IoT has brought innovation in digital-based solutions in various industries, and the BIM approach allows for shareable, traceable data between stakeholders and integrated management of the building or infrastructure life cycle through virtual models of 3D information [25].

However, BIM–IoT integration is still in its early development, and the development of BIM–IoT integration for sustainable building, which is crucial for the development of current emerging technology for smart cities towards sustainability, is unclear. Additionally, the most recent studies in sustainable building and construction adopt the literature review method, which lacks the quantitative method to show a big picture objectively. Few studies use bibliometric analysis to explore BIM and the IoT. Therefore, this paper aims to explore the research frontiers and knowledge structure in BIM–IoT integration and the relationship between BIM–IoT and sustainable building with revealing the research hotspots, trends, and future directions of BIM–IoT integration for sustainable building.

2. Methods

This paper adopts mixed a research method, which comprised the use of the bibliometric method to quantitatively analyze the research frontiers in BIM–IoT integration and the research hotspots and trends of BIM–IoT for sustainable construction, and a follow-up qualitative review to reveal the research content of BIM–IoT integration on different topics in sustainable construction. Bibliometric analysis is widely used to analyze written publications [26]. Unlike traditional systematic reviews, visual analysis of the literature provides researchers with a timely, flexible, and repeatable method to track the development of emerging trends and identify key findings [27]. Therefore, in order to provide objective quantitative analysis, this paper proposes to use Citespace software for bibliometric analysis. Citesapce is a citation visualization and analysis software designed by professor Chaomei Chen.

Analyzing highly cited journals helps to understand the general background of the field [28]. It also prepares researchers for the subsequent analysis via Citespace software visualization. The method of bibliometric analysis does not require a complete review of all the literature but derives general findings quantitatively [29]. Co-citation and co-word analysis are the two main bibliometric methods for analyzing the development of topics in research areas [30]. Co-citation analysis is a typical research frontier detection method [31] to build and detect the knowledge structure of a scientific field over time [32]. The co-word analysis method is based on word frequency analysis, mainly through the use of co-keywords and subject terms, to explore the main knowledge structures and research hotspots in the subject area [33]. Each bibliometric technique has its theoretical basis, units of analysis, and limitations; the mixture of research methods is better when conducting a scientometric review [34]. This paper collects data from the Web of Science core collection (WoSc) [35] and imports it into Citespace software for co-citation, co-word, and cluster analysis, and then compares the Citespace results with the controlled terms frequency analysis included in the Engineering Index (EI) Compendex database [36] search results. However, the interpretation of the visualization results is a constructive exercise that still varies from person to person and is not entirely objective [37], which is one of its limitations. As such, it would be beneficial for the results from Citespace software to be reviewed by experts or verified in other ways. Hence, this paper also uses the statistics of controlled terms and subject terms in the search results of the EI core database to briefly compare the frontiers of field research and research hotspots obtained by Citespace. The WoSc contains high-quality literature from multiple disciplines in the search sciences, natural sciences, social sciences, humanities, and arts, which is an essential tool for academic analysis and evaluation. Furthermore, the WoS is one of Citespace's primary sources of analytical data. EI Compendex, the core database of EI, is the most comprehensive worldwide database of secondary literature in engineering, covering all engineering and applied sciences disciplines. Search results contain professionally organized controlled terms and subject terms that precisely summarize the content of the literature with word frequency statistics for controlled words, which can simply reflect the research hotspots and compare them side by side with the field research hotspots indicated by Citespace to illustrate the predictability of the reference results.

This paper uses co-citation and co-word analysis in co-occurrence analysis via Citespace, a knowledge visualization software known for its co-citation analysis feature. Its features include the multiple, temporal, and dynamic presentation of knowledge graphs. Citespace also automatically identifies the research frontiers characterized by the citation node literature and co-citation clustering as on the graph; these features have led to the software's broad and rapid adoption, especially in the management field [38]. However, in recent years, Citespace has also proliferated and been used rapidly in engineering [38]. The network of cited reference nodes can be utilized to explore domain research frontiers, knowledge bases, hotspots, trends, and knowledge structures [37]. In addition, Prof. Chaomei Chen suggests communicating the clustering results of Citespace with experts for verification [39]. This paper also used cluster analysis and burst detection as extended analysis.

Since the lack of clarity of terminology within the construction industry will cause confusion rather than direction [4], it is necessary to clarify the key concepts in the subject of discussion. Building smart cities is a vast concept and interdisciplinary product containing many new development and research areas, in which there is the problem of the unclear definition of "smart building", "intelligent building", and "sustainable building". While some current studies have updated the concept of smart buildings to include "sustainability", earlier studies have not focused as much on sustainability in smart buildings as on adaptability [4]. Therefore, in the bibliometric analysis data preparation stage, only the term "sustainable building" has been used as a search term for this study to clarify the direction of the discussion and focus on the relationship between sustainable building as a crucial part of creating a sustainable environment within smart cities, and BIM–IoT integration in smart cities.

The research flow with method is shown in Figure 1 and encompasses five quantitative and qualitative data analysis steps: (1) Relevant publications in WoSc and EI Compendex database were collected by topic search with the topics "BIM–IoT" and "BIM–IoT and sustainable building". Only articles, reviews, and proceedings papers were selected. (2) A line graph was chosen to analyze the annual number of BIM–IoT-related articles issued to figure out the research trend. (3) Co-citation analysis, cluster analysis, and burst detection in Citespace were chosen for analysis of "BIM–IoT" to explore the frontiers of research in the field of BIM–IoT integration; keyword co-occurrence analysis, cluster analysis, and burst detection in Citespace were chosen for the analysis of "BIM–IoT-sustainable building" to explore the research hotspots and trends of BIM–IoT in the field of sustainable building for the subsequent micro-analysis. (4) Frequency analysis was performed on controlled words of papers in the fields of BIM–IoT integration and BIM-IoT and sustainable building obtained from EI Compendex database to examine the clustering results of Citespace. (5) Qualitative analysis of nine clusters of BIM–IoT and sustainable building obtained by co-word analysis was performed to obtain detailed information.

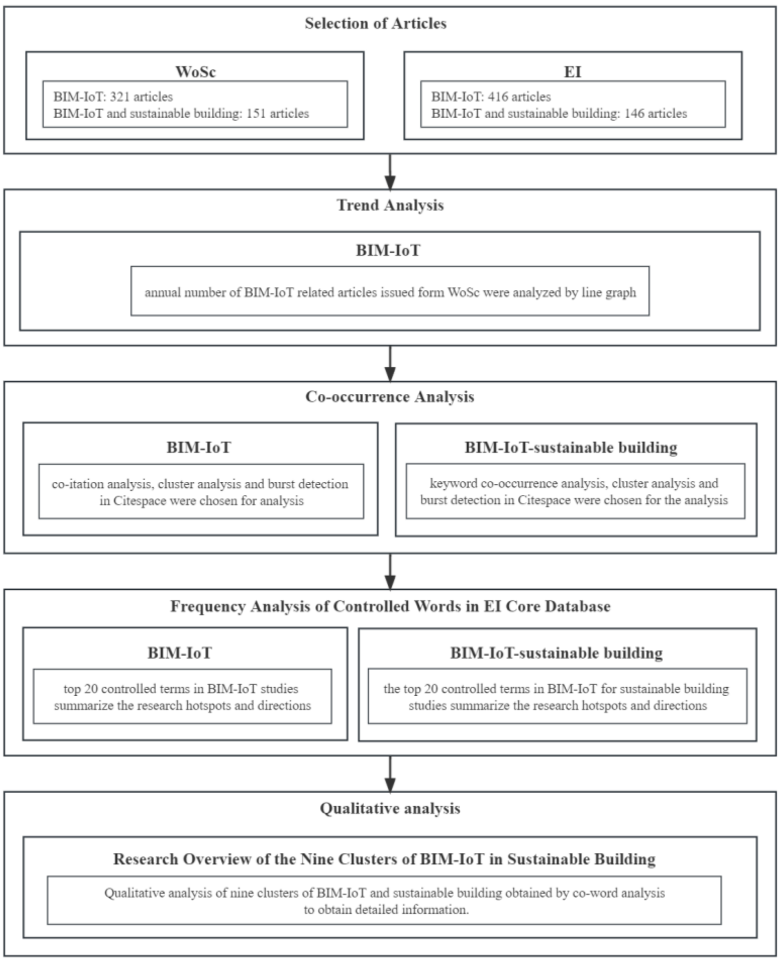

Figure 1. Research Methodology Flow Chart.

3. Results

This section shows the macro results of data analysis and the micro results of literature analysis. Firstly, the research status and knowledge base of BIM–IoT were obtained via Citespace analysis; the research direction of BIM–IoT in the field of sustainable building was also obtained through Citespace. Then, the word frequency analysis of EI controlled words was used to test the reliability of Citespace results. On the basis of Citespace analysis, the research direction of BIM–IoT in the field of sustainable building was analyzed microcosmically to reveal which life cycle stage the current research focuses on, and to outline the research direction.

3.1. Results of the Macro Quantitative Analysis of Bibliometrics

The results of the macro quantitative analysis of bibliometrics presented the trend and co-citation analysis of BIM–IoT integration and the co-word analysis of BIM–IoT sustainable building.

3.1.1. Trend Analysis and Co-Citation Analysis of Published Papers in WoSc Related to BIM–IoT Integration

- General Information

Figure 2 shows the number of published papers (the blue line) related to BIM–IoT integration in the WoS core database from the years 2015 to 2022, during which the field has gone through three periods: the first period of 2015 to 2017 is the early stage of development, with only six papers growth in the three years, which indicates that the field has not received much attention and the number of paper increases slowly; in the second period of the year 2017 to 2019, the growth rate of the number of papers has increased, and in particular the number of papers in 2018 is doubled compared to 2017; in the period of 2019 to 2022, the number of papers exceeds 50, entering a period of relatively rapid growth from 2019 onwards.

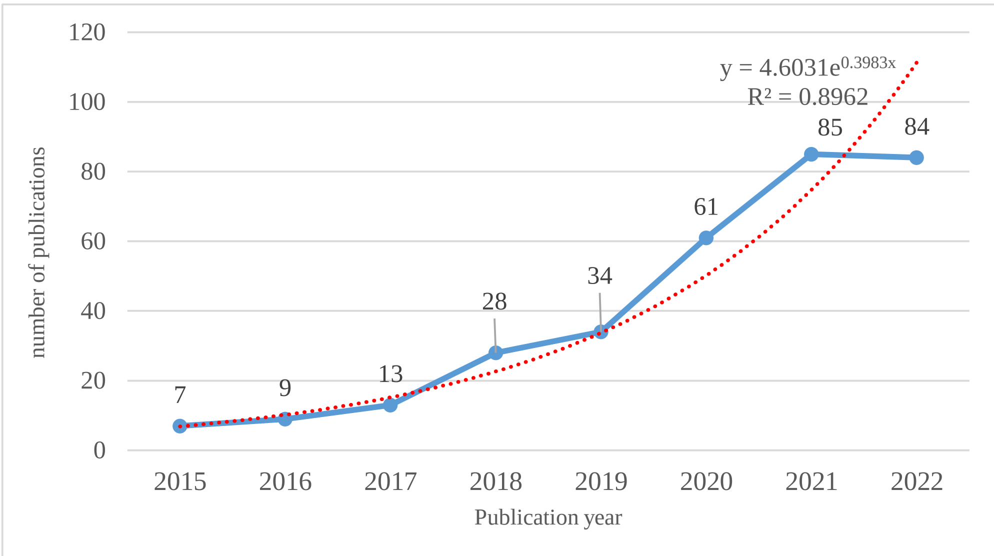

Figure 2. Number and trend of Building Information Modeling (BIM) and Internet of Things (IoT) related papers published from year 2015 to 2022 in the Web of Science core collection (WoSc) database (generated by the authors).

In general, BIM–IoT integration is a new field with a small number of publications, meaning that it is still in the early stage of development. However, the number of related paper publications is on the rise, in the past three years particularly rising sharply and approaching exponential growth in the red line in the Figure 2, indicating that the field is receiving more attention and has specific development prospects.

There are few studies that directly analyze the development of BIM and IoT integration, instead mostly discussing construction 4.0 [40,41], digital structure [14,18,42], and off-site construction [43], which are based on the application of BIM and IoT as emerging technologies [21]. Tang et al. explore common application areas and design patterns for BIM–IoT integration and predict future research directions; this is also the most cited paper, with 130 citations. Emerging technologies are mentioned separately [6,14,42], and the building life cycle receives much attention [6,14,42–44]. The years of publication of the highly cited literature are in the period 2019 to 2020, indicating the recent rapid development of the field.

- Co-citation analysis

Co-citation analysis revealed the research frontiers within the knowledge domain [38], in which the research frontiers refer to emerging theoretical trends and new topics that arise and can be represented in Citespace software by the cluster names of co-cited literature. First, 321 papers in the BIM–IoT obtained from the WoS core dataset were imported into Citespace software for co-citation analysis and cluster analysis, from which results are shown in Figure 3 and Table 1. Figure 3 identifies the seven main clusters, i.e., #0 'rfid-based computer system', #1 'devices integration', #2 'virtual reality', #3 'digital technology adoption', #4 'smart construction', #5 'construction management ', and #6 'sensing information' in the BIM-IoT domain, using the headline terms and the log-likelihood ratio (LLR) weighting algorithm to label the clusters. The top left corner of the Figure 3 reveals the cluster structure information, in which the Q value (modularity) = 0.875 > 0.3 and S = 0.9483 > 0.7, convincingly indicating that the clustering structure is significant and efficient, since a Q value (modularity) > 0.3 for cluster mapping means that the cluster structure is significant, while an S value (silhouette) > 0.7 indicates that the clusters are convincing [39]. Modularity is a metric proposed by M.E.J. Newman to evaluate the equality of association recognition; Silhouette is another parameter, proposed by L Ksufmsnhe and Peter J. Rousseeuw, to evaluate the equality of clustering. The colors of the clusters reflect the old and new changes in the field of study, and the color block in the lower right corner of Figure 3 indicates the different years, with yellow representing the most recent year. As shown in Figure 3, #4 'smart construction' and #5 'construction management' are two of the newer research sub-topics in the field in recent years, while #6 'sensing information' is a relatively old research topic. A smaller number of labels suggests that the cluster is more massive and contains more literature; the nodes in the graph represent the cited literature; and the node size indicates the citation frequency. The more frequently cited, the larger the node. The most cited papers are often milestones due to their seminal contributions [24]. These literature nodes are larger and are among the more cited literature including open standards BIM–IoT integration framework [45], the current status and future trends of BIM–IoT integration [24], BIM–IoT integration and prefabricated construction [46], the current status and future needs of BIM [8], BIM–IoT enhanced digital twins [44], BIM for facility management [47], the status and future of big data technology in the construction industry [48], multidimensional BIM–IoT platform [49], the importance of information synchronization between BIM and buildings [50], and integration of BIM and GIS [51]. In addition, Figure 3 shows that the clusters #0 'rfid-based computer system', #1 'devices integration', #2 'virtual reality', and #3 'digital technology adoption' are more connected to each other and more closely linked. The link between the #2 'virtual reality' and #3 'digital technology adoption' is closer and thicker, which implies a stronger degree of co-citation in the literature in these two clusters [38].

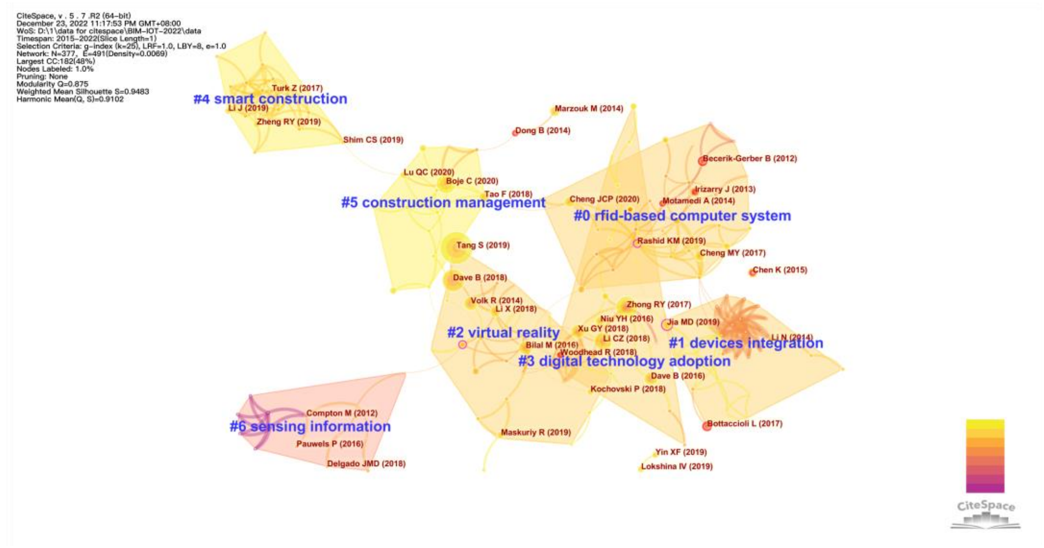

Figure 3. The network visualization on co-citation analysis of BIM–IoT integration literatures in the WoSc database via Citespace (generated by the authors).

Table 1. Major clusters of co-cited literatures of BIM–IoT integration in the WoSc database via Citespace (generated by the authors).

Cluster	Size	Silhouette	Mean (Cited Year)	Label (LSI)	Label (LLR)	Label (MI)
0	33	0.951	2016	building information modeling	rfid-based computer system	facility management
1	23	0.969	2015	future trends	devices integration	sustainable environment
2	27	0.918	2017	virtual reality	virtual reality	airport project delivery
3	22	0.944	2017	Internet	digital technology adoption	wearable sensing device
4	19	0.967	2019	smart construction	smart construction	construction information flow
5	15	0.922	2018	Integration	construction management	advanced project management
6	14	0.94	2013	sensing information	sensing information	semantic construction

In this paper, LLR naming is chosen for the cluster names.

Figure 4 is the timeline diagram to the Figure 3 clustering, in which BIM–IoT integration is closely related to digital technology and smart buildings. Figure 4 shows that the two research topics #0 'rfid-based computer system' and #1 'devices integration' have received significant attention since year 2012, indicating that the connection and control of various devices is a research topic that has been continuously concerned with the development of BIM–IoT integration technology. Additionally, the timelines of #2 'virtual reality'and #3 'digital technology adoption' show that the integration of other digital technologies also attract attention. #4 'smart construction' and #5 'construction management' show that the application of BIM–IoT integration in the whole intelligent building attracts attention from 2016 onwards. The topic #6 'sensing information' gained attention back in 2009 with heat-cooling off since 2016. The red dots are burst references, the appearance of which often indicates changes in the subject of the study [38,39]. The more burst nodes a cluster contains, the more active the domain, indicating an emerging trend [38]. There are five burst references in Figure 4, 'Becerik-Gerber B, 2012' [47], 'Irizarry J, 2013' [51] and 'Motamedi A, 2014' (exploring the use of BIM visualization function for failure root cause detection in facilities management) [52] in cluster #0 'rfid-based computer system', 'Bottaccioli L, 2017' (presenting a model based on BIM and IoT integration for management and simulation of energy behaviours in buildings) [53] in the clsuter #1 'devices integration', and 'Woodhead R, 2018' (exploring the impact of an IoT-based ecosystem on the construction industry) [54] in cluster #4 'smart construction'.

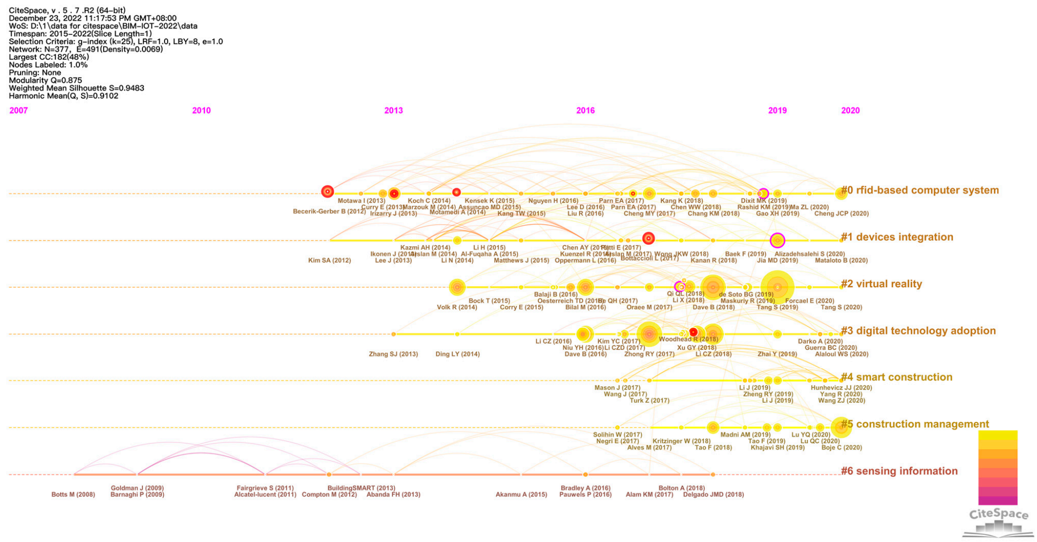

Figure 4. Timelines of co-citation clusters in Figure 3 (generated by the authors).

Table 1 lists the details of clusters #0 'rfid-based computer system', #1 'devices integration', #2 'virtual reality', #3 'digital technology adoption', #4 'smart construction', #5 'construction management ', and #6 'sensing information' by cluster size. The higher the silhouette, the more similar the content of the literature within the cluster, the higher the quality of the cluster, and the more focused the research interest in the issue. As shown in Table 1, the silhouette of all the clusters is greater than 0.9. The average publication years of the clusters are relatively close, concentrated in the years 2015 to 2017, illustrating that BIM–IoT integration is a rapidly growing and emerging field. Citespace provides three algorithms for tag word extraction, with different algorithms having different focuses, and researchers can choose a form of tag presentation at their discretion [38]. This paper adopts the tag words extracted by the Log-likelihood rate (LLR) algorithm that extracts tags focusing on the study characteristics [38], in which the principle is to assume that for the category Cj words Wi, the frequency (α), concentration (β), and dispersion (γ) metrics form the vector Vij (α,β,γ), and the selection of the clustering label is based on Vij to determine whether Wi can be used as a feature word of category Cj [55].

Citation burst can find emergent citations, i.e., papers with sudden changes in the number of citations, which to some extent reflect the research frontiers of the corresponding emergent time interval [39]. Figure 5 states the ten citations with the strongest citation burst, i.e., 'Chen K, 2015' [50], 'Gubbi J, 2013' [56], 'Azhar S, 2011' [57], 'Azhar S, 2012' [58], 'Riaz Z, 2014' [59], 'Becerik-Gerber B, 2012' [47], 'Bottaccioli L, 2017' [53], 'Motamedi A, 2014' [52], 'Irizarry, 2013' [51], and 'Woodhead R, 2018' [54]. The earliest emergent citation is 'Chen K, 2015' [50], which started in 2016. This study is about the use of BIM to address the information synchronization problem. From 2017 to 2022, with the exception of 'Gubbi J, 2013' (research about the future direction and architectural elements of IoT) [56] attracting attention, the focus of early studies has been skewed toward BIM and gradually became the integration of BIM with other technologies, such as the concept of BIM and the development trend, possible risks, and future challenges of BIM [57,58], BIM-wireless sensors for solving the problem of worker safety in confined spaces [59], potential application areas for BIM in facilities management practices [47,52,53], integrating GIS–BIM models to improve construction supply chain management [51], and the impact of an ecosystem built on IoT for the transformation process of the construction industry [54]. Although 'Riaz Z, 2014' [59] does not use the concept of IoT, the idea of wireless sensor applications mentioned is similar to IoT. 'Bottaccioli L, 2017' [53], 'Motamedi A, 2014' [52], 'Becerik-Gerber B, 2012' [47] and 'Woodhead R, 2018' [54] are the relatively new burst papers, which indicates that the integration of BIM and FM and the integration of BIM and IoT are receiving more attention and are two major research hot topics.

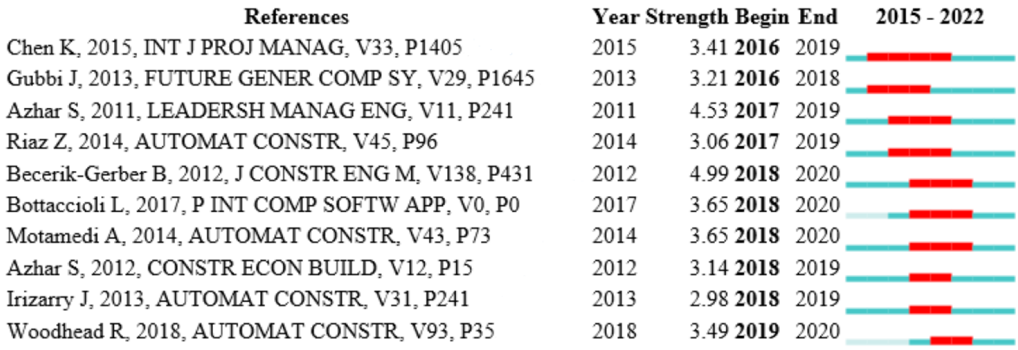

Figure 5. The highest burst literatures of BIM–IoT integration in the WoSc database via Citespace (generated by the authors).

3.1.2. Co-Word Analysis of Published Papers in WoSc Related to BIM–IoT for Sustainable Building

The 151 papers in the field of BIM–IoT for sustainable building obtained from the WoS core database were imported into Citespace software for keyword analysis, cluster analysis, and burst detection. Table 2 shows the 10 keywords with intermediary centrality greater than 0.1, sorted by the size of intermediary centrality that measures the ability of nodes to exchange information in a network [60]. These keywords are considered influential in shifting the research direction and represent research topics and directions that have received more attention in the field [37]. As shown in Table 2, in different periods, basic construction, framework, and optimization of buildings issues attracted more attention in BIM-IoT for sustainable building. And building metaverse may be a new research hotspot in 2022.

Table 2. Keywords with structural significance in the field of BIM–IoT-sustainable building via Citespace, whose centrality is greater than 0.1 (generated by the authors).

Centrality	Count	Year	Keywords
0.20	25	2012	Construction
0.19	16	2015	Framework
0.18	11	2012	Optimization
0.15	4	2015	Construction project
0.12	1	2022	Building Metaverse
0.11	2	2015	Decision Making
0.11	4	2015	Construction Industry
0.10	3	2019	Building Design
0.10	5	2019	Benefit
0.10	21	2013	Design

The life cycle of a building can be divided into four stages [43,61–64]: (i) Preparation Stage (design, decision-making, manufacturing, procurement); (ii) Construction Stage (construction, transport); (iii) Usage Stage (operation, maintenance, refurbishment); and (iv) End stage (deconstruction, disposal, reuse, or recycling). As shown in Table 2, the keywords are related to the first three phases of the building life cycle stages:

(1) Preparation Stage: optimization, framework, decision making, design, building design
(2) Construction Stage: construction, construction project
(3) Usage Stage: building metaverse, benefit

The keyword burst detection is performed to obtain burst words that reflect the hotspots and trends of research in a specific time interval [38]. As shown in Figure 6, there are 12 words whose burst period occurs in year 2017 to 2021 (in red color), indicating how fast the research development changed during this period. The burst period of management, IoT, sustainability, and challenge is 2021 to 2022, indicating that they are the four latest research hotspots. The sustainable design, simulation, and leed bursts last for more than three years, indicating that there are a relatively high number of studies on these three issues.

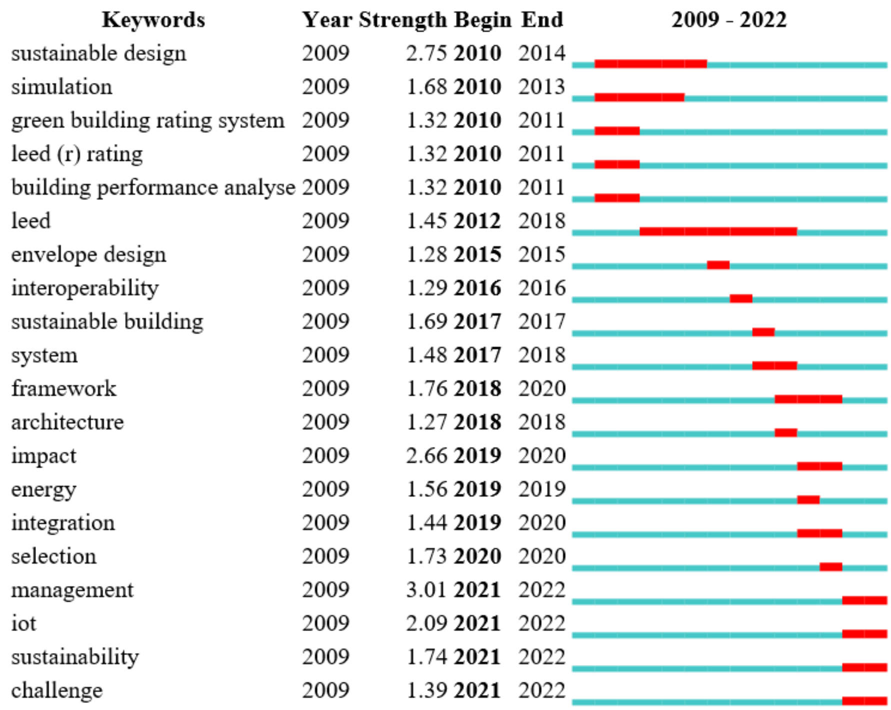

Figure 6. Top 20 emergent words in the field of BIM–IoT-sustainable building via Citespace (generated by the authors).

Cluster analysis was performed based on keyword co-occurrence to obtain cluster mapping (Figure 7) and a timeline diagram (Figure 8) was created for mapping further the research hotspots and trend changes in integrating BIM–IoT and sustainable building. Because the data in year 2022 cannot form effective clustering, the data up to 2021 are selected for clustering information. The research hotspots and trends in 2022 are analyzed according to the above mentioned emergent words in Figure 6 and high centrality words in Table 2. The cluster profile as shown in Figure 7, Q = 0.7519 > 0.3 and S = 0.8783 > 0.7, indicates that the clustering structure is convincingly significant and efficient. As shown in Figure 7, the largest cluster is #0 'building information', which is associated with cluster #6 'knowledge-based building management system', cluster #7 'modern challenge', and cluster #1 'sustainable building design'. The most recent cluster is cluster #7 'modern challenge', which is not overly related to the other clusters. Cluster #2 'digital twin technology' is closely related to cluster #4 'integrated life-cycle analysis' and cluster #1 'sustainable building design'. Cluster #1 'sustainable building design' is also associated with Cluster #8 'decision support' and Cluster #5 'conceptual framework'. Moreover, Figure 8 shows that cluster #0 'building information' from 2012 to date and cluster #4 'integrated life-cycle analysis' from 2014 to date have demonstrated good trends. Cluster #1 'sustainable building design', cluster #2 'digital twin technology', and cluster #5 'conceptual framework research fever' have decreased since year 2018. Additionally, Cluster #6 'knowledge-based building management system', cluster #7 'modern challenge', cluster #8 'decision support', and cluster #13 'green building information modeling lifecycle' are small in scale. The clusters are small in size, "fleeting" in the years 2017, 2019, and 2015, have little connection with other groups, and have not formed an inevitable development trend, which could be of future potential research value.

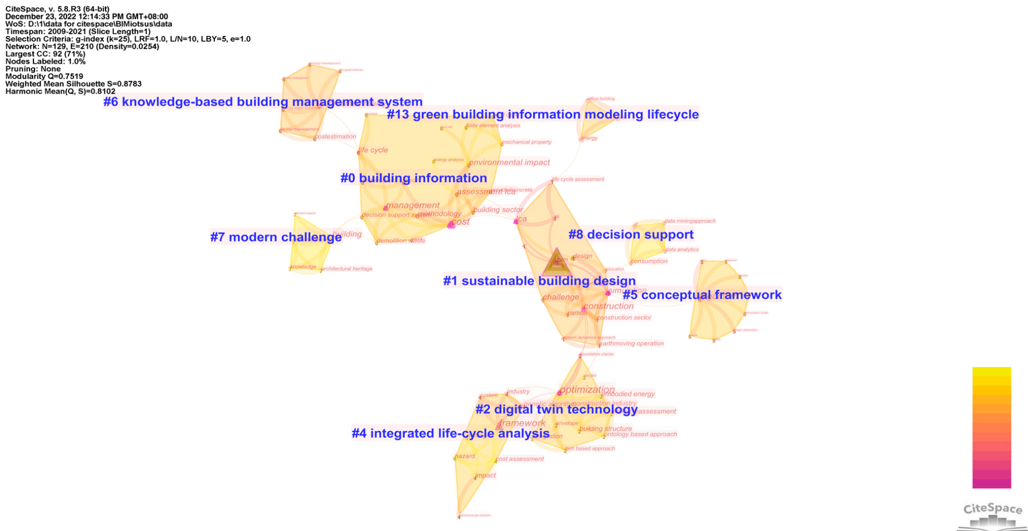

Figure 7. The network visualization on keyword co-word analysis of BIM–IoT sustainable building literatures in the WoSc database via Citespace (generated by the authors).

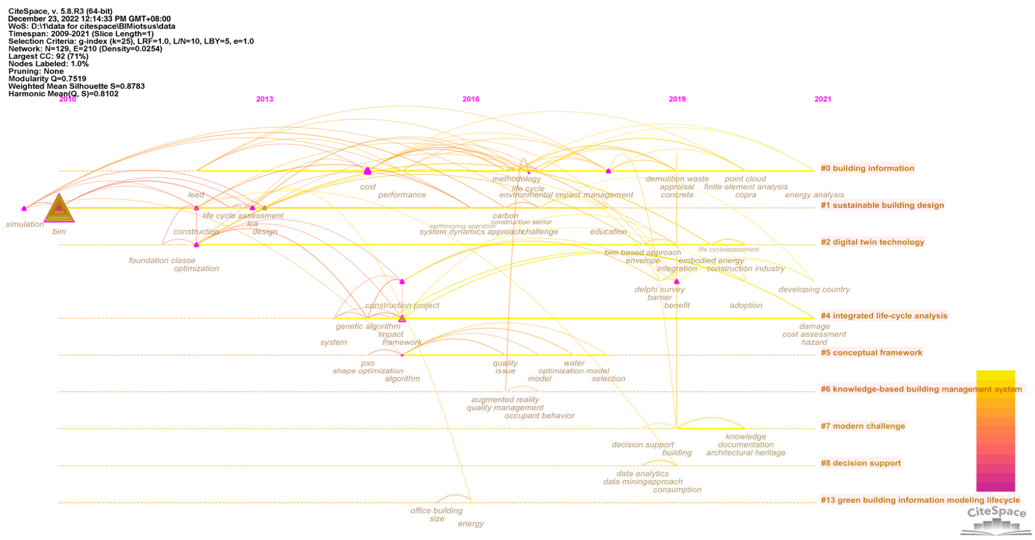

Figure 8. Keyword co-occurrence timeline of co-citation clusters in Figure 7 (generated by the authors).

3.2. *Frequency Analysis of Controlled Words in Engineering Index (EI) Core Database*

Word frequency analysis explores the research hotspots and trends in the research field, in which keywords or subject terms are the condensation of the core content of the literature [65]. It is necessary to process the data before starting word frequency analysis, but the natural frequency of normalized subject words' occurrences can be directly used as the basis and foundation of the study [66].

One of the advantages of the EI database is that the search results provide controlled term frequency statistics directly, and each document in the EI core database is tagged with a specific controlled term that is a word in professionals' standard for expressing the content of documents. In order to keep in line with the process in WoSc database, this paper selects "subject/title/abstract" in the EI Compendex core database, uses the same search formula, selects only conference articles and journal articles, and obtains the corresponding statistical ranking of controlled terms as shown in Table 3. Table 3 lists the top 20 controlled terms in BIM–IoT studies and the top 20 controlled terms in BIM–IoT for sustainable building studies. The top 20 controlled terms summarize the research hotspots and directions and illustrate the credibility of the primary descriptive results obtained by Citespace software.

Table 3. Top 20 controlled terms under the topic BIM–IoT (left) and BIM–IoT-sustainable building (right) in the Engineering Index (EI) Compendex core database (generated by the authors).

BIM-IoT		BIM-IoT-Sustainable Building	
Controlled Vocabulary	**Count**	**Controlled Vocabulary**	**Count**
Architectural Design	312	Architectural Design	162
Internet of Things	271	Intelligent Buildings	135
Information Management	128	Sustainable Development	134
Information Theory	97	Information Theory	65
Construction Industry	78	Life Cycle	49
Project Management	69	Energy Efficiency	43
Life Cycle	68	Construction Industry	40
Construction	57	Eco-design	38
Intelligent Buildings	54	Decision Making	34
Office Buildings	43	Construction	28
Decision Making	41	Energy Utilization	24
Smart City	28	Office Buildings	22
Data Visualization	23	Project Management	20
Data Integration	22	Environmental Impact	16
Visualization	21	Structural Design	16
Semantics	20	Environmental Design	13
Digital Storage	19	Information Management	13
Energy Utilization	19	Energy Conservation	12
Human Resource Management	19	Environmental Management	12
Three Dimensional Computer Graphics	19	Apartment Houses	8

In Section 3.1.1, the BIM–IoT research frontiers derived from the results of co-citation analysis of 321 papers in WoSc via Citespace software are cluster #0 'rfid-based computer system', cluster #1 'devices integration', cluster #2 'virtual reality', cluster #3 'digital technology adoption ', cluster #4 'smart construction', cluster #5 'construction management' and cluster #6 'sensing information'; additionally, the 20 controlled terms obtained from the EI search reflect scattered research hotspots, which can be further summarized into four categories of frontier research directions. If the inductively classified topics are close to the results obtained by citespace, the results of citespace can be proved to be credible and referable. The four categories are:

(1) Life Cycle: Life Cycle, Project Management, Decision Making, Energy Utilization, and Human Resource Management.
(2) Smart City and Architecture: Architectural Design, Construction Industry (Construction), Office Buildings, Intelligent Buildings, and Smart City.
(3) Internet of Things and other digital technologies: Internet of Things, Data Visualization(Visualization), Data Integration, Digital Storage, Semantics, and Three Dimensional Computer Graphics.
(4) Information Management: Information Management and Information Theory.

The categories indicate that the main focus is on digital technologies in relation to IoT, smart building life cycle, data visualization, and construction management. This grouping result is similar to the grouping result obtained by Citespace, which proves the credibility and referenceability of results from Citespace.

Moreover, in Section 3.1.2, the research hotspots of BIM–IoT for sustainable building derived from the results of co-word analysis of 151 papers in WoSc via Citespace software are cluster #0 'building information', cluster #1 'sustainable building design', cluster #2 'digital twin technology', cluster #4 'integrated life-cycle analysis', cluster #5 'conceptual framework', cluster #6 'knowledge-based management system', cluster #7 'modern challenge', cluster #8 'decision support', and cluster #13 'green building information modeling lifecycle'.

Furthermore, the controlled terms of BIM–IoT for sustainable building from Table 3 have been sorted and classified into four hot research directions:

(1) Construction industry and building types: Construction Industry, Construction, Intelligent Buildings, Apartment Houses, and Office Buildings.
(2) Design Related: Architectural Design, Structural Design, Eco-design, and Environmental Design.
(3) Building Information Management and Decision Making: Decision Making, Information Theory, and Information Management.
(4) Life Cycle and Sustainability: Life Cycle, Energy Efficiency, Environmental Impact, Sustainable Development, Project Management, Energy Utilization, Environmental Management, and Energy Conservation.

The categories indicate that the main focus is on architectural design, information management and decision making, and life cycle. Their closeness to the categories of conclusions drawn by Citespace software verifies the credibility of the results obtained by Citespace.

3.3. Results of the Micro Qualitative Analysis

The micro qualitative analysis results reveal the topics of BIM–IoT and sustainability, including the lifecycle involved and the overview of the nine clusters.

3.3.1. The Lifecycle Involved in The Nine Clusters in BIM–IoT-Sustainable Building

The results in Section 3.1.2 indicate that the keywords have been obtained from WoSc on BIM–IoT for sustainable building filed into nine clusters via Citespace software, representing nine research hotspots, which provides further insight into each research hotspot and the life cycle stages, as shown in Table 4, which includes:

(1) Preparation Stage (design and decision making): cluster #0 'building information', cluster #1 'sustainable building design', cluster #2 'digital twin technology', cluster #4 'integrated life-cycle analysis', cluster #5 'conceptual framework', cluster #8 'decision support', and cluster #13 'green building information modeling lifecycle';
(2) Construction Stage (construction): cluster #0 'building information', cluster #2 'digital twin technology', cluster #4 'integrated life-cycle analysis', and cluster #13 'green building information modeling lifecycle';
(3) Usage Stage (operation, maintenance and refurbishment): cluster #1 'sustainable building design', cluster #2 'digital twin technology', cluster #4 'integrated life-cycle analysis', cluster #6 'knowledge-based management system', cluster #7 'modern challenge', cluster #8 'decision support', and cluster #13 'green building information modeling lifecycle';
(4) End Stage (deconstruction): cluster #2 'digital twin technology', and cluster #13 'green building information modeling lifecycle'; and
(5) Complete life cycle: cluster #2 'digital twin technology', and cluster #13 'green building information modeling lifecycle'.

Table 4. Life cycle stages involved in each clustering study (generated by the authors).

Cluster Name	Life Cycle Stages											
	Preparation Stage				Construction Stage		Usage Stage			End Stage		
	Design	Decision-Making	Manufacturing	Procurement	Construction	Transport	Operations	Maintenance	Refurbishment	Deconstruction	Disposal	Reuse or Recycling
#0 building information	1				1							
#1 sustainable building design		1					1					
#2 digital twin technology	1	1			1		1	1		1		
#4 integrated life-cycle analysis	1	1			1		1	1				
#5 conceptual framework	1	1										
#6 knowledge-based management system							1	1	1			
#7 modern challenge									1			
#8 decision support		1					1					
#13 green building information modeling lifecycle	1				1		1	1		1		

The collated results show that the current research focuses on the design and decision-making aspects of the preparation stage and the operation and maintenance aspects of the usage stage. The construction stage and the end stage have not been receiving much attention.

3.3.2. Research Overview of the Nine Clusters of BIM–IoT in Sustainable Building

- Cluster 0 building information

As shown in Table 4, this cluster involves the preparation stage (design and decision making) and construction stage (construction). Building information is one of the largest clusters, indicating that it has received much research attention. As shown in Figure 8, the research fervor of this cluster has remained unabated from year 2012 to the present. In addition, three high centrality keywords are included, arranged chronologically as follows: cost, life cycle, and management, of which high centrality indicates that they are more associated with other keywords and dominate the studies on the cluster. In the current rapid development of the construction industry toward digitalization, building information is essential to building a digital building model. The BIM technology bears the closest relationship with building information. The most important use of BIM technology in construction projects is to obtain reliable information and make the right decisions during the implementation phase of any construction project [67]. Studies mainly consider collecting and using building-related information for sustainability and improving the different life cycle stages. For example, Lorenzo and Mimendi [68] introduce a non-destructive 3D scanning and modeling workflow to capture and process relevant digital information describing the geometric properties of bamboo poles, allowing a new material, bamboo poles, to be effectively digitized and integrated into the architectural structure. Additionally, Khalesi et al. [69] proposed to integrate the Stepwise Weight Assessment Ratio Analysis method with BIM technology to identify and reduce time delays caused by rework in construction projects from a time perspective to enhance the delivery of sustainable construction projects. Furthermore, Borja et al. [70] used a cost database in the construction sector facilitated with environmental information to generate environmental indicators to aid decision making. The emergence of BIM has turned the architecture, engineering, and construction (AEC) industry into an information management industry, managing buildings through information [71,72].

- Cluster 1 sustainable building design

As shown in Table 4, this cluster involves the preparation stage (decision making) and usage stage (operation). The construction industry is increasingly interested in sustainable buildings with low environmental impact, high performance, and high cost savings. Important decisions affecting building life cycle energy needs must be made in the early stages of building design [73]. Using BIM and other technologies to assist decision making can help achieve true building sustainability [74,75]. The integration of BIM and parametric modeling is a new trend in building modeling that can significantly contribute to sustainable building design [76]. J. Starynina and L. Ustinovichius [77] proposed a sustainable building modernization model that estimates the energy demand and the relevant parameters for reconstructing old public buildings. The development of prefabricated building elements, the integration of Life Cycle Assessment (LCA) and BIM, and multi-objective optimization methods can also be used to help achieve sustainability in the built environment [78]. Liu et al. [79] proposed an improved particle swarm optimization algorithm for finding a balance between the life-cycle cost of building design and life-cycle carbon emissions to improve the sustainability of buildings. In general, this cluster focuses on using BIM with other technologies such as IoT and LCA in the design phase to select sustainable building design solutions for reliable building sustainability.

- Cluster 2 digital twin technology

As shown in Table 4, this cluster involves the preparation stage (design and decision making), construction stage (construction), usage stage (operation and maintenance) and end stage (deconstruction). The digital twin is not a brand-new concept, having been published first in the aerospace sector, then in product manufacturing, and in recent years in the smart city sector [44]. It is a powerful example of an integrated application of BIM and IoT [80], which maps physical assets in the physical world to the virtual world, enabling real-time recording and analysis of the physical assets' real-time structural and environmental parameters from which existing buildings can benefit [81,82]. In addition, the digital twin can predict a building's future state [83], reduce maintenance costs, improve tenant comfort, and reduce the building's overall management and operating costs [84]. There has been research on building sensor networks on facades to create digital twin models of buildings [84]. However, how to build sensor networks inside buildings to better utilize the Internet of Things remains to be researched.

- Cluster 4 integrated life-cycle analysis

As shown in Table 4, this cluster involves the preparation stage (design and decision making), construction stage (construction) and usage stage (operation and maintenance). Life Cycle Assessment (LCA) introduces an explicit temporal dimension and metabolic links to social quality and energy flow and is now more commonly used in the design of new buildings [85]. However, to improve the design process and effectively build a sustainable future, data on the diversity of the existing building stock needs to be transformed to discover new knowledge and inform future design decisions in an evidence-based manner [86]. Angeles et al. [87] proposed an integrated life cycle assessment (iLCA) to achieve a comprehensive, in-depth review of the environmental impact of a building, including a full accounting of its operation and contained energy, as well as of the effect of damage and maintenance due to hazards. Marzouk et al. [88] propose a framework that facilitates the implementation of stochastic whole life cycle cost (LCC) models to select optimal building material alternatives and discover the most effective building systems in each cost element from initial cost to complete life cost. Focusing on the well-being of a building's occupants during the building's life cycle may also impact sustainable building design and operational decision-making processes. IoT technology enables a connected and interactive platform that helps occupants express their feelings more efficiently and participate in the design and construction of sustainable buildings. Tao et al. [89] proposes a framework to define the types of data that can be measured or obtained that will enable building designers and operators to use a well-being-centered life-cycle assessment for decision making and help improve the energy efficiency of buildings related to human well-being and socio-economic aspects.

- Cluster 5 conceptual framework

As shown in Table 4, this cluster involves the preparation stage (design and decision making). The three papers [74,79,88] involved in this cluster all propose a conceptual framework for the BIM-based optimization of building design solutions for building sustainability, verifying the feasibility of this with examples and discussions. Liu et al. [79] proposes a BIM-based building design optimization method that can help designers optimize the design from economic and environmental perspectives and improve the sustainability of the building. Ahmad et al. [74] investigated a conceptual framework for a BIM-based design iteration (BIM-DIT) tool for selecting sustainable PSTM (processes, systems, technologies, and materials) combinations during the design process to support the decision-making process in the residential building design phase. Marzouk et al. [88] presents a framework that integrates building information modeling (BIM), genetic algorithm optimization, and Monte Carlo simulation to select the best building solution from the perspective of sustainability. Although the conceptual models have all been validated in a specific instance, there are still technical or cost issues to be overcome for large-scale replication. In addition to the continuous innovation of conceptual frameworks in the future, the feasibility of landing existing conceptual frameworks can be studied from the perspective of practical applications. These conceptual frameworks all have data collection needs, and the IoT sensor network can generate a large number of real-time data, which again reflects the necessity of BIM–IoT integration.

- Cluster 6 knowledge-based management system

As shown in Table 4, this cluster involves the usage stage (operation, maintenance and refurbishment). The cluster is concerned with achieving energy savings in the operation and maintenance phase of the building through efficient methods. A knowledge-based management system is critical for sustainable post-construction performance [90]. Building maintenance decisions involve the collaboration of multiple departments and require the support of various types of knowledge and information; therefore, ineffective decisions will likely result in significant cost losses and energy consumption. Knowledge-based management is an artificial intelligence (AI) approach to reasoning and learning from experience [91]. A knowledge-based management system can provide good collection experience, history, and operations, making it easy for maintenance teams to take practical action in certain situations [92]. The advent of knowledge-based management systems, with an emphasis on automation, compensates for the inaccuracy of manual inspections and the lack of real-time dynamic factor input, ensuring the continued comfort of occupants through efficient building maintenance and reducing energy consumption by providing adequate controls [90]. However, the advantages of this aspect currently remain in the theoretical stage, and in future it needs to be verified in practical applications to improve cost barriers and automation weaknesses. BIM–IoT integration can build a data-based platform to meet the above automation and efficiency needs, and more landing attempts can be made in the future to promote buildings' sustainable and digital transformation.

- Cluster 7 modern challenge

As shown in Table 4, this cluster involves the usage stage (refurbishment). The cluster is concerned with the renovation and maintenance of historic buildings, i.e., the use phase of the life cycle. One of the current challenges is the sustainable renovation of existing buildings, especially the renovation of historic buildings. Each historic building has a certain uniqueness, and finding a suitable reference is difficult, making the renovation task more difficult. However, Diara and Rinaudo [93] pointed out that the sheer number of Heritage assets makes it difficult to achieve a unique solution for each asset, thus requiring a relational database. Historic Building Information Modeling (HBIM) was proposed to address the abovementioned problem. Finding commonalities in historic buildings and creating a database that can be shared to record information gives a referable solution for the future renovation of other landmark buildings and helps rapidly expand expertise, allowing people from various disciplines to acquire knowledge of the building as a whole quickly. HBIM is a quest to bridge the knowledge gap through the potential commonality of historic buildings, thus achieving some degree of efficiency [94]. Essentially, the problem is similar to that mentioned in Cluster 6, i.e., the rational use of building information to assist in renovation decisions to reduce energy consumption during renovation and maintenance. As in Cluster 6, these needs are precisely what can be solved using BIM–IoT integration.

- Cluster 8 decision support

As shown in Table 4, this cluster involves the preparation stage (decision making) and usage stage (operation). Cluster 8 still revolves around how building information obtained during the operations phase can be used in the future. Current design decisions still rely heavily on experience [95], but the diversity of data from the existing building stock can effectively build a sustainable future and reduce knowledge evaporation and uncertainty [86]. Researchers are no longer concerned with acquiring building information but are instead concerned with how to transform it into new knowledge to further aid design decisions. The research on this issue can be seen as exploring the development of BIM platform applications. It also faces the same challenge as Cluster 2, i.e., how to build a sensor network inside the building to better utilize the data collected by the IoT, which remains to be researched in the future.

- Cluster 13 green building information modeling lifecycle

As shown in Table 4, this cluster involves the preparation stage (design), construction stage (construction), usage stage (operation and maintenance), and end stage (deconstruction). In today's building industry, which is moving towards digitalization and sustainability, ensuring the sustainability of buildings requires a focus not only on digital information model or green building itself but also on the entire life cycles of buildings [96,97]. Muller [96] found that interoperability and sustainability are intrinsically linked. The efficient interoperability throughout the life cycle by BIM allows for better overall management and improved project sustainability. Garcia et al. [97] proposed that data mining can effectively help handle the large amount of data generated throughout the building lifecycle process to be applied to support the refinement of future projects. Therefore, BIM–IoT integration is not a finished state and still needs to be considered in conjunction with more new technologies to further contribute to building sustainability and digital transformation.

4. Discussion

This section further explores the necessity of a clear definition and scope of sustainable building, the change and the future development directions in the BIM–IoT integration field, and the impact brought by emerging information technology and the research gap in sustainable building.

4.1. The Necessity of Clarifying the Scope of the Definition of Sustainable Building

In this paper, "sustainable building" was chosen as one of the the search keywords for the topic "BIM–IoT and sustainable building". According to the results of Sections 3.1.2 and 3.3, the development of BIM–IoT integration in the field of sustainable building includes both humanity and technology. In conducting the search and starting the discussion, it is necessary and helpful to clarify the concept of sustainable building so that only focusing on a single aspect of the research problem can be avoided. The lack of clarity of terminology within the construction industry will cause confusion [4]. At present, the concepts of smart, intelligent, sustainable, and green buildings are confused. Few of the retrieved papers use the label "sustainable building" directly only to study the sustainability of smart building. The definition of sustainable building is indeed uncertain and subject to constant change as society evolves. However, it is still necessary to clarify the definition and scope of the subject when discussing the description. Green building is more narrowly defined, focusing on the building itself. Sustainable building considers the impact on the physical and psychological health of the occupants and the social-economic aspects [20]. Intelligent building emphasizes buildings' responsiveness to the environment and automation. Smart building integrates and exemplifies intelligence, entrepreneurship, control, materials, and construction as a whole system with adaptability at its core [4]. Today, the definitions of smart and sustainable building overlap significantly, especially as climate change and sustainability receive more attention. However, it is recommended to explicitly include the sustainable building label in the discussion. It is important to pay attention to the changes in concept definitions during the research process in order to prevent confusion caused by the split of the research topic and to be clear about the definition of the concept under discussion.

4.2. Change of Research Topics in the BIM-IoT Integration Field in the Timeline

According to the results in Section 3.1.1, the field of BIM–IoT integration is in a period of rapid development, with some connection to the construction industry and building intelligence. The research frontiers in order of attention are as follows: rfid-based computer system, devices integration, virtual reality, digital technology adoption, smart construction, construction management, and sensing information. Regarding the timeline, "sensing information" was the first topic that attracted attention. However, while this is the case, research on that topic has slowed down in recent years. Sensing technology is a key enabler of IoT [98]. The sensor network is one of the end networks for data collection, which can only realize signal collection and transmission in a small local area [99]. IoT is seen as a ubiquitous global computing network that can automatically organize and share information, data, and resources [100]. IoT uses sensors and connected devices to monitor real-time parameters and provide visualizations of information using information collected through technologies such as big data analysis and data mining [80]; additionally, the IoT infrastructure of smart buildings can be integrated into the BIM model through IFC technology [101]. The emergence of the IoT has made smart cities more attainable and attracted more researchers' attention.

The results in Table 1 and Figures 2 and 5 indicate that the field of BIM–IoT integration entered a period of rapid development in the period 2017–2021, with research topics starting to be focused on and targeted. This shift in the research frontier can be seen from the ten most cited literature with the greatest burst of citations shown in Figure 5: In the period 2017–2019, the focus of researchers was still on exploring the concepts, trends, and applications of BIM itself. Furthermore, after 2019, discussions started focusing on the feasibility of combining BIM with other technologies to manage buildings. 'Motamedi A, 2014' [52], 'Bottaccioli L, 2017' [53], 'Becerik-Gerber B, 2012' [47], and 'Woodhead R, 2018' [54] burst in recently from 2018 to 2020, introducing the application of BIM in facilities management practices and the impact of IoT on the transformation of the construction industry. It can be seen that the research on BIM–IoT integration is based on BIM as an application. As Wang et al. [13] said, BIM is central to connecting other new technologies emerging from Industry 4.0. Therefore, this change in trend is related to the development of BIM itself. Wen et al. [10] showed that the development process of BIM is away from data collection and information integration and towards knowledge management. One of the changes in the development trend is to pay more attention to the harmonious coexistence of building and environment, sustainability, green building, and prefabrication. In researching and applying BIM, new challenges will be faced continually.

As such, the role of IoT in "BIM–IoT integration" is to join the platform of BIM as an "auxiliary plug-in" bringing new solutions to address the need to collect, synchronize, and manage the massive number of data needed to build smart, sustainable buildings. In general, the analysis results in Sections 3.1.1 and 3.2 indicate that BIM will combine with not only IoT but more digital technologies to promote the digital development of the construction industry in the future.

4.3. Impact of Emerging Information Technology on Sustainable Building

Based on the results in Section 3.1.2, basic construction issues are of more interest, followed by framework and optimization issues in the field of BIM–IoT-sustainable building. In addition, management, IoT, sustainability, challenge, building metaverse is the new research hotspot in 2022, and building metaverse is also one of the emergent words in 2022, indicating that BIM–IoT integration for meta-cosmic architecture has begun to receive attention. This could be a turning point in the digital process of sustainable building. The nine clusters obtained after applying Citespace show the research hotspots in the field of BIM–IoT-sustainable building, and the cluster sizes are all relatively small, indicating that the field of BIM–IoT-sustainable building is comparatively new and has not yet been able to form a specific scale. The development trend of clusters #0 building information and #4 integrated life-cycle analysis are good. Clusters #6 knowledge-based building management system, #7 modern challenge, #8 decision support, and #13 green building information modeling lifecycle are small in scale and not well connected to other clusters. They do not form a particular development trend. However, the core of these clusters is how to explore the valuable knowledge behind building information and better use this knowledge to manage buildings, which has potential research value and development space. According to the results of 3.3.1, the research focus of BIM–IoT within sustainable construction involves all phases of the building life cycle. However, it concentrates on the first three phases, i.e., the preparation stage (design, decision-making, manufacturing, procurement), the construction stage (construction, transport), and the usage stage (operation, maintenance, refurbishment). Yet few studies have addressed the end-stage (deconstruction, disposal, reuse, or recycling). BIM can reduce construction waste throughout the life cycle of building design projects and better contribute to SDG 11 from the perspective of waste management for urban environmental impact [102]. In the future, IoT can be added to supervise the building components using sensor networks to facilitate the disposal of construction waste and recycling. This is also in line with the requirements of the new ten principles of sustainable building proposed by the International Council for Sustainable Building (CIB) [21], namely managing waste to reduce environmental impact.

Sustainable architecture involves social, economic, and human elements. Still, the results in Section 3.3.2 reveal that the current research content is not sufficient in focusing on the social and human aspects and should focus more on technical development and economic impact. Furthermore, as also understood from the content of the discussion of cluster #4 integrated life-cycle analysis in Section 3.3.1, user involvement is critical for sustainable buildings, but few studies have collected real-time data involving asset users in building use and management. Participatory sensing emphasizes the involvement of citizens and community groups in sensing and recording the processes by which they live, work, and play [98], and IoT [103] and mobile devices enhance the ability of people to engage in participatory sensing to gather information about their environment [104]. Nevertheless, simultaneously, how to couple dynamic real-time data to the model database is also one of the main challenges of BIM–IoT integration [19]. There are already studies on building facades with sensor networks to create digital twin models of buildings [84]. However, how to build a sensor network inside the building to utilize the IoT better is still to be researched. This also points to a future research direction for researchers on how to make BIM–IoT integrated technology to achieve the social and human sustainability of buildings.

In addition, from the analysis of clusters #6 knowledge-based building management system, #7 modern challenge, #8 decision support, and #13 green building information modeling lifecycle, the importance of analyzing and mining the deep information behind the huge amount of data can be recognized. The actual implementation of smart cities faces challenges such as design and operational costs, heterogeneity among devices, massive data collection and analysis, information security, and sustainability [105]. IoT technology enables the collection, tracking, and transmission of multiple data, greatly expanding the information sources of BIM and solving the problems of authority and timeliness of BIM information [106,107]. BIM enables easy data exchange and real-time collaboration among stakeholders [108]. This is important for the development of smart cities. BIM–IoT integration facilitates not only the realization of sustainable buildings but also that of smart cities. However, these two technologies alone are not enough to cope with the demand of smart cities for mining and applying data. Other emerging technologies are still needed to support them—for example, cloud computing, big data, and AI technologies. Cloud computing is used in all levels of IoT; it is one of the fundamental technologies of IoT and has a strong capability of carrying this data; big data can mine and analyze massive data, turning data into information; artificial intelligence can learn and understand data, turning data into knowledge [109].

In addition, the content of cluster #7 modern challenge illustrates that people are starting to realize that retrofitting existing buildings is also a research point that cannot only focus on building new structures. How to transform existing buildings into sustainable buildings through IoT sensors will also be a popular research direction in the future, because, as Carl Elefante says [110], the most environmentally friendly building is the one that already exists, and any new construction will, to a greater or lesser extent, result in a waste of new resources. Pavon et al. [111] have proved through a case that BIM combined with IoT and FM can transform existing buildings to be more intelligent and sustainable at a low cost, so how to make existing buildings more sustainable deserves more attention. In general, the analysis results in Sections 3.1.2 and 3.3 indicate that BIM–IoT integration still has a relatively large research gap in the field of sustainable buildings, especially in the humanities and data processing. At the same time, BIM–IoT integration is growing rapidly in the field of sustainable buildings, with research on multiple building types and different building life cycles.

5. Conclusions

This paper aims to understand the research frontiers and knowledge base structure in the field of BIM–IoT integration and the relationship between BIM–IoT and sustainable building and to explore the research hotspots, trends, and future research directions of BIM–IoT integration technology for sustainable building. This paper has three main contributions: (1) In terms of research content, this paper explores the current research status and research frontiers of BIM–IoT integration through macro-quantitative and micro-qualitative analysis via bibliometrics, as well as the research hotspots and future research directions of BIM–IoT integration in sustainable building. Future sustainable building needs to consider the user's feelings, in which the IoT enables the user to participate in sustainable design and decision making. Additionally, sustainable building involves social, economic, and human dimensions. However, current research in the field has paid less attention to the social and human aspects than to the technical and economic impacts of development. For instance, the aging population is currently facing the issue of community aging and retrofitting the existing built environment to meet the needs of the elderly for a healthy, safe, and comfortable living environment requires much cost. It may even generate much waste. Perhaps the BIM–IoT integration model may solve this problem. Another issue is how to focus on the psychological health and comfort of people in isolation while ensuring sustainability in the current COVID-19 context, which is also an issue worth studying. In addition, it would be better to explicitly bring the "sustainable buildings" label into the discussion to prevent confusion caused by splitting the research topic. (2) The research value aspect illustrates the necessity of IoT as an "auxiliary plug-in" to join the platform of BIM and the importance of analyzing and mining the deep information behind the massive data. BIM–IoT integration can facilitate the development of digital sustainable buildings, making full use of building information. BIM–IoT integration is meant not only to promote the sustainable transformation of buildings but also to help the construction of smart cities. In the future, more emerging technologies, such as cloud computing and big data, can be integrated with BIM-IoT integration to address the demand for mining and environmental data in smart cities, thus realizing the construction of sustainable smart cities. (3) In terms of research method, this paper provides a quick and objective method of understanding the research status of new and rapidly developing fields. The data from the EI core database were introduced for word frequency analysis to corroborate further the results obtained by Citespace. Knowledge mapping interpretation is a constructive task. Although expert interpretation can improve the science of interpretation, the rapid development of emerging fields means that experts do not have a good grasp on the whole or individual parts of the field. Using the controlled word statistics that come with the search results of the EI core database to perform word frequency analysis provides a more objective and quantitative method to assist in interpreting the mapping. The study only selected WoS as the primary database and EI as the control auxiliary reference database, and future studies may consider using other databases to increase the research paradigm. Thus, BIM–IoT integration currently contributes to the intelligence and digitization of buildings, while its impact on sustainable building is an emerging field. Implementing BIM–IoT integration in sustainable building seems complicated, but it results from a wide range of detailed directions for several specific issues. The lack of research has not yet established a set of standard paradigms, an early problem in the emerging field. In addition, the combined application of BIM–IoT needs the assistance of other technologies, such as big data and cloud computing, to tap and utilize the information carried by the massive amount of data to achieve intelligent and sustainable future city construction. Future research can also: (1) focus more on the application of BIM-IoT integration technology in the construction stage and end stage of the building life cycle; (2) explore the application of BIM-IoT integration in building metaverse or the integration of other digital technology.

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