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Article

Sustainable Building Design Development Knowledge Map: A Visual Analysis Using CiteSpace

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Abstract: Based on the Web of Science (WoS) core collection database, this article compares the research results in this subject area since 2000 with the literature data on the theme of sustainable architectural design and conducts an in-depth investigation into the research themes, basic literature, development trends, and research frontiers. Qualitative and quantitative analyses were conducted through the CiteSpace scientific visualization software, and the degree of collaboration between authors, institutions, and countries was analysed through research power. The topical research hotspots and their evolution were explored through a word frequency analysis, cluster analysis, and timeline analysis; the origins and development of a particular issue in sustainable building design were explored in conjunction with mutation analysis; and the frontier hotspots were explored. The analysis of co-citations was used to identify important knowledge bases in the field; the flow of knowledge between disciplines was explored through biplot overlay analysis. By interpreting the scientific visualization knowledge map, it was concluded that the research trends in sustainable building design are mainly in the areas of resource control, energy consumption, renewable building materials, evaluation systems, and computer-aided tools, and so on. The major topics of future research related to sustainable building design are discussed and summarized.

Keywords: sustainable; architecture; design; visualization; knowledge mapping

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1. Introduction

The construction industry plays an important role in promoting social development, improving the quality of life, and driving national economic growth. However, in recent decades, a large number of construction activities have caused negative ecological impacts on a global scale [1]. Environmental issues, such as climate change caused by greenhouse gas emissions, are also gaining attention from researchers [2]. In addition to environmental factors, increasing competitive pressures in the construction industry are stimulating the industry to find new breakthroughs. As a result, various sectors are actively seeking solutions and recognizing the importance of sustainable building design.

There is ambiguity and uncertainty in the definition of sustainability [3,4]. However, environmental sustainability, social sustainability, and economic sustainability are its three pillars [5]. For sustainable building design, the U.S. Council on Environmental Quality (2011) proposes that sustainable building design (SBD) is the integration of environmental, economic, and social factors. Mater et al. [6] propose that sustainability refers to the interaction between ecological, economic, and social systems and their subsystems. Sharifi et al. [7] argue that in addition to the environmental, social, and economic aspects of sustainable building design, systems can exist as a fourth pillar. Organ [8] and Gharehbaghi [9] suggest that the implementation of sustainable building design will provide an additional competitive advantage to the construction industry. On the other hand, De Wilde [10] emphasizes the need to integrate sustainable building design into the complete life cycle of a building; SBD covers all aspects and phases of design and is a response to a range of environmental issues and industry crises. The aim is to create innovative, economical, and sustainable buildings that can effectively deliver economic, social, and environmental value.

In order to reduce the environmental impact of buildings while ensuring the meeting of the functional, health, and comfort needs of their human occupants, many countries and national organizations have started to research and use green rating systems (e.g., BREEAM, LEED, DGNB) to maximise the control of environmental pollution and reduce the consumption of natural resources. For example, Cheng and Ma used data mining techniques to study the relationship between LEED-attached scores and climate factors [11]. Lee and Burnett used HK-BEAM, BREEAM, and LEED to assess energy use [12]. However, as each country is in a different type of environment, their evaluation systems differ; still, they tend to give priority to certain sustainability indicators. These indicators encompass issues related to biodiversity, water resources, energy consumption, carbon emissions, air pollution, climate impacts, land degradation, materials and resources, and indoor environmental quality.

In addition to evaluation methods, research into computer-aided tools has been a major focus for researchers. For example, Building information modelling (BIM) has been used as an aid to digitally manage key information on building design and project data during the building life cycle [13], helping designers to anticipate risks and challenges during the different phases of sustainable building design, construction, and operation in order to make the right decisions, improve efficiency and quality, and reduce costs. The main areas of modelling are: building positioning (to potentially reduce project costs), building massing (to analyse building form and optimise the building envelope), light analysis and water harvesting (to reduce water demand in buildings), energy modelling (to reduce energy demand and analyse how renewable energy options can help reduce energy costs), sustainable materials (to reduce material demand through the use of recycled materials), and site and logistics management (reducing waste and carbon emissions) [14].

This study is intended to provide a detailed understanding of the trends in sustainable building design, to better promote the development of sustainable building design and research, and to help architects and architectural researchers quickly access relevant research trends and research information. It is important to understand which institutions are making outstanding contributions to the field, which countries are doing the best research in the field, what specific aspects of sustainable building design are contributing, and what the trends are in the field of sustainable building design. This study uses the CiteSpace software to present the research trends related to sustainable building design in a clear and introductory way using scientific knowledge mapping visualization to promote the development of sustainable building design.

2. Research Methodology and Data Sources

2.1. Research Methodology

CiteSpace, developed by Professor Chaomei Chen and his team, is an information visualization software for literature data mining in a Java-based environment. The basic principle is to analyse the similarity and measurement of research units (e.g., keywords, authors, and institutions), which is essentially an information visualization technique for macro knowledge measurement and, therefore, has its own unique measurement indicators and implications [15]. It is mainly based on co-citation analysis theory, pathfinding network algorithms, minimum spanning tree algorithms, and so on, to measure specific literature and detect the core themes, development history, frontier areas, and disciplinary basis of the field through visualization.

2.2. Data Sources

The Web of Science (hereafter, WoS) core collection database was used as the search platform for this study. The search criteria were ‘TS = sustainable building design’, the search period was from 2000 to 2021, the types of literature were ‘thesis’ and ‘review’, the research directions selected were 'engineering' and 'building technology', and a total of 7492 English language documents were retrieved. The search results were exported as plain text files, and the output was selected as 'full record with references cited' to obtain the full literature information.

2.3. Data Processing

These data were analysed using the information visualization tool in CiteSpace.5.8.R3. We analysed the co-occurrence, clustering, and emergence of thematic keywords. The graphs analysed are referred to as 'scientific knowledge graphs' because they present the structure, patterns, and distribution of scientific knowledge in a visual way.

Based on the temporal mapping $\Phi(t)$ from the research frontier $\Psi(t)$ to the underlying knowledge $\Omega(t)$ (i.e., $\Phi(t)$:$\Psi(t) \rightarrow \Omega(t)$), CiteSpace is able to identify and display new trends and changes in research topics in $\Phi(t)$. $\Psi(t)$ is a set of terms that are closely related to the new trends and mutations at moment T. These terms are called boundary terms. $\Omega(t)$ contains the articles that are cited within the articles with the frontier terms, and the relationship between them is summarized as [16].

$$\Phi(t) : \Psi(t) \rightarrow \Omega(t) \quad (1)$$

$$\Psi(t) = \{\ term \backslash term \in S_{Title} \cup S_{Abstract} \cup S_{Descriptior} \cup S_{Indentifier} \wedge IsHotTopic\ (term, t)\} \quad (2)$$

$$\Omega(t) = \{\ term \backslash term \in \Psi(t) \wedge term \in article_0 \wedge article_0 \rightarrow article\} \quad (3)$$

CiteSpace has three algorithms for calculating the strength of network connections, namely, cos, Jaccard, and Dice. In this paper, we used the default cosine algorithm:

$$Cosine(C_{ij}, S_{ij}, S_j = \frac{C_{ij}}{\sqrt{S_i S_j}}) \quad (4)$$

The range of cosine is 0~1, C_{ij} denotes the number of co-occurrences of i and j, S_i denotes the frequency of occurrence of i, and S_j denotes the frequency of occurrence of j.

The complete record of the WoS-related research data was downloaded and imported into CiteSpace.5.8.R3, with the time span set to 2000–2021 and the time slice set to 1 year. The threshold was selected as Top N, set to 50 (i.e., the top 50 high-frequency nodes within a year were selected). Due to the large amount of data selected for this paper, the pruning was chosen as Pathfinder, pruning sliced networks, and pruning the merged network, which were used to simplify the data information and highlight the most important construct features for graph interpretation [17]. The number of publications remained at 7492 after filtering by a software check.

3. Data Analysis

3.1. Analysis of the Distribution of the Number of Publications

From the total number of publications, the number of articles published in the field of sustainable architectural design has increased rapidly (Figure 1). In terms of development stages, there have been three stages: slow development, steady growth, and rapid growth. The first stage was the slow development stage (2000–2009), in which the total number of articles published in those 10 years was 491, accounting for 6.5% of the total number of articles, indicating that research was not very strong and was in the initial development stage of this research field. The second stage was the steady growth stage (2010–2014), during which a total of 1266 articles were published, accounting for 16.8% of the total number of articles, indicating that the academic community has gradually paid attention to this research area, and relevant research has been steadily increasing. The third stage was the rapid growth stage (2015–2021), with the number of publications accounting for 76.7% of all articles in this research area, reaching a peak in 2021, accounting for 19% of all articles, with 95 times the number of publications in 2000. This reflects the interest of the academic community in the field of sustainable building design research and also implies a pressing need to address the issues arising in the field.

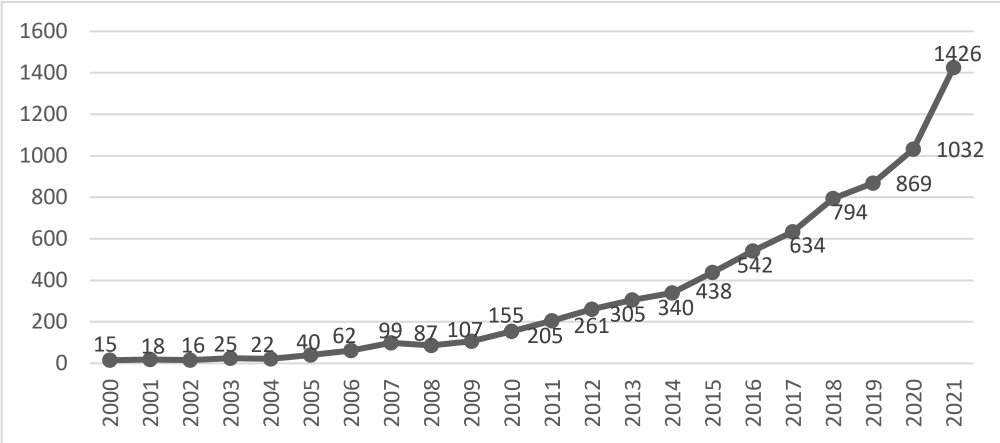

Figure 1. WoS core ensemble source sustainable building design annual volume mapping.

The reasons for the steady increase in the number of articles published and the high level of publications are as follows: (1) Environmental and energy factors: Along with economic development, the world is now facing increasingly prominent environmental problems, including the greenhouse effect, global warming, ozone layer depletion, waste accumulation, toxic pollution, and so on. In the past few decades, studies have shown that the global climate is changing rapidly. (2) Policy implications: In 2002, the European Union established the near-zero energy building (nZEB) standard to reduce energy consumption in buildings. E.U. member states adapted their local legislation to the directive and updated national building codes to ensure that new buildings, when authorized for construction, met local nZEB targets to reduce energy consumption and environmental damage. (3) Economic factors: Environmental factors increase environmental costs, energy costs, pollution remediation costs, and so on, due to, for example, greenhouse gas emission (GHG) costs set by the EU.

3.2. Analysis of Research Power

3.2.1. Analysis of Research Authorship

The authors are the basis of scientific research. By analysing research authorship and the collaboration structure, the core authors in a research field and their collaborations can be visually identified. The node type was set to Author, the number of research authors and their collaboration structure were calculated, the collaboration class diagram was restricted to 10, and the author collaboration network diagram was drawn, as shown in Figure 2 (the nodes and connecting lines are only part of the diagram). The top 15 research authors were extracted according to the number of articles they published, as shown in Table 1. Each node represents the number of articles published by an author, and the links represent the collaboration and strength of the authors. As can be seen from Figure 2, there were 886 research authors, 512 lines, and a collaboration density of 0.0013, indicating that the degree of author collaboration in this research area was low; there were mostly independent research results, and there was no research collaboration team of a certain scale. As can be seen from Table 1, the highest number of articles published by one author was 26. The core author calculation formula M = 0.749(Nmax)1/2 proposed by the American bibliographer Price gives M = 9.737, and taking the whole number, the minimum number of articles issued by the core authors in this research field was 10.

Figure 2. WoS core collection source sustainable building design research author collaboration network diagram.

Table 1. Power distribution of sustainable building design research authors from the WoS core collection sources.

Serial No.	Author Name	Year of Debut	Number of Articles
1	Mounir El Asmar	2013	26
2	H J H Brouwers	2014	25
3	Gian Paolo Cimellaro	2017	20
4	Zhenjun Ma	2018	18
5	Shady Attia	2017	17
6	Hongxing Yang	2015	15
7	Jeong Tai Kim	2010	14
8	Srinivas Garimella	2018	14
9	Arul Arulrajah	2017	13
10	Wei Wang	2020	11
11	P Spiesz	2014	10
12	Melissa M Bilec	2014	10
13	Guillaume Habert	2019	10
14	Suksun Horpibulsuk	2017	10
15	Amos Darko	2017	9

Mounir El Asmar, together with Elie Azar and Tianzhang Hong, presented the shortcomings of existing building performance simulation tools for the integration of occupant behaviour modelling and complementing building design practices and discussing future directions, including large-scale international data collection, improved building performance indicators, and industry practices, in the hope of achieving a two-way interaction between people and buildings to achieve sustainable zero-energy or carbon-neutral buildings and so on [18]. H J H Brouwers, with P Spiesz and R Yu, focused on the impact resistance of the building material, Sustainable Ultra High Performance Fibre Concrete [19,20]. With Zhenjun Ma as the core and Georgios Kokogiannakis, Paul Cooper, Yi Guo, and Ali Aljubainawi as a collaborative group, Zhenjun Ma and Georgios Kokogiannakis proposed a model-based optimization of a ground source heat pump system design strategy that may also be applicable to design optimization strategies for other building energy systems [21]; Zhenjun Ma and Paul Cooper's research aimed primarily to create a stochastic model for determining the environmental and other driving conditions associated with the behaviour of residential buildings in relation to air conditioning use and the energy consumption of air conditioning operations [22]. Hongxing Yang, with Xi Chen, Gang Pei, Lin Lu, and Jinqing Peng, proposed the application of building information modelling (BIM) to the green building assessment scheme (GBA) [23] and a new passive design assessment system for a green building label [24]. A study by Jeong Tai Kim and Gon Kim, Robert Lopez, and others identified key factors affecting the cost of design errors and proposed that BIM and 3D modelling could reduce the cost of errors due to lack of design coordination, among others.

3.2.2. Analysis of Research Institution Profiles

In this analysis, we used research institution cooperation network mapping to identify the research institutions at the forefront of the sustainable architectural design research field. The node type was set to Institution, and the number of publications and collaboration structure of research institutions were calculated to obtain the power distribution map of research institutions, as shown in Figure 3; the top 20 research institutions were extracted, as shown in Table 2. As can be seen from Figure 3, there were 626 research institutions with 592 links, and the collaboration density was 0.003, which was relatively high compared with the collaboration of the research authors. From the analysis of Table 2, in the order of the number of publications, it can be seen that there were nine core institutions with more than 70 publications in the field of sustainable architectural design research, in the order of Hong Kong Polytech Univ, Arizona State Univ, Tech Univ Denmark, Delft Univ Technol, and so on; Hong Kong Polytech Univ was the oldest, with the highest number of publications. The number of articles published by institutions with 70 or more articles accounted for 58% of the top 20 institutions, which indicates that there was a relatively high concentration of sustainable architectural design research institutions and a large difference in research capacity between institutions. In terms of institution type, the top 20 research institutions were all universities, indicating a single type of research institution. From a regional perspective, the main output areas were Asia (China, Singapore), Europe (Netherlands, Denmark), and North America (USA), indicating that the research field of sustainable building design was closely related to the degree of economic development.

The interinstitutional cooperation is shown in Figure 3: Hong Kong Polytech Univ (13 articles), Arizona State Univ (10 articles), and Natl Univ Singapore (8 articles) had a high number of articles and more links with other institutions, indicating that interinstitutional cooperation and exchange played a greater role in improving the research level and academic influence of institutions. The Hong Kong Polytechnic University had a wide range of research interests, including research related to intelligent tools, such as building information modelling (BIM) and geographic information systems (GISs) in sustainable building design [25,26]; the integration of energy and environmental design (LEED) and green design build (DB) projects, which provides an effective means for owners and contractors to communicate sustainability messages [27,28]; adaptive reuse of historic buildings; and a range of other research studies [29]. Arizona State Univ proposed a new technique for estimating commercial building energy consumption from a small number of building features through machine learning modelling of national data from the Commercial Building Energy Consumption Survey (CBECS) [30].

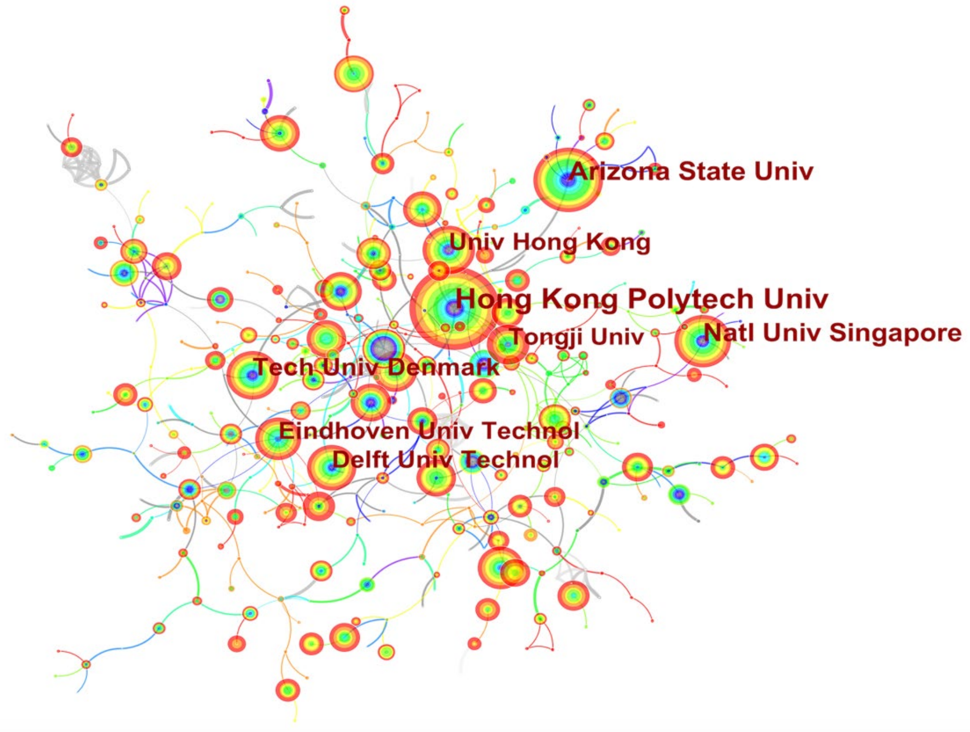

Figure 3. The power co-occurrence map of sustainable building design research institutions from the WoS core collection.

Table 2. Power distribution of sustainable building design research institutions from the WoS core collection sources.

Serial No.	Name of Institution	Year of Debut	Number of Articles
1	Hong Kong Polytech Univ	2002	196
2	Arizona State Univ	2009	118
3	Natl Univ Singapore	2007	104
4	Tech Univ Denmark	2009	88
5	Delft Univ Technol	2001	78
6	Univ Hong Kong	2008	74
7	Eindhoven Univ Technol	2011	74
8	Tongji Univ	2001	71
9	Georgia Inst Technol	2007	70
10	Tsinghua Univ	2013	67
11	City Univ Hong Kong	2000	65
12	Univ Nottingham	2010	63
13	Swinburne Univ Technol	2011	59
14	Univ Cambridge	2007	57
15	De Montfort Univ	2004	56
16	Aalborg Univ	2005	55
17	Concordia Univ	2005	54
18	Politecn Torino	2002	53
19	Univ Melbourne	2011	53
20	MIT	2001	50

3.2.3. Analysis of Global Research Country Distribution

To a certain extent, the publication of national literature reflects the importance and influence of a country on a certain research field, and the mutual exchange between countries can promote large-scale scientific and technological innovation and breakthroughs. The node type was set to Country, the number of publications and intermediary centrality of the research countries were calculated, and the distribution of research country power is plotted in Figure 4; the top 15 research countries were extracted, according to the number of publications, as shown in Table 3. In terms of the number of papers published, the USA was the oldest and had the highest number of papers published, accounting for 18.46% of the total number of papers published; China had the second highest number of papers published, with 1368 papers (including 84 papers from Taiwan), accounting for 18.26% of the total number of papers published. This indicates that the USA and China were the core forces in the field of sustainable building design research, with their contributions far outstripping those of other countries. In terms of centrality, among the top 15 countries, the USA (0.5), South Korea (0.15), the Netherlands (0.14), and England (0.11) had a high intermediary centrality, while China had a low centrality of 0.02, indicating that the USA had a high international influence in this research area. Figure 4 shows that the USA (11 articles), England (7 articles), and South Korea (5 articles) had more links, which indicates a high academic cooperation atmosphere and openness and close ties with many countries; the Netherlands had a small number of articles and fewer links, but its centrality was higher, which indicates that its research results were more important and belonged to the key nodes in the field of sustainable architectural design research. In general, there was close cooperation and exchange in the field of sustainable architectural design research abroad, while China was less connected to other countries and should strengthen intercountry cooperation, which is more conducive to the integration of academic resources and the dissemination of research results in different regions, as well as the diversification and sustainable development of this research field in the future.

Figure 4. WoS core collection source sustainable building design research country mapping.

Table 3. Distribution of the number of national publications in the WoS core collection of sources for sustainable building design studies.

Serial No.	Country or Area	Year of Debut	Number of Articles	Intermediary Centrality
1	USA	2000	1383	0.5
2	People's R China	2006	1368	0.02
3	England	2005	855	0.11
4	Australia	2007	570	0.01
5	Italy	2008	412	0.02
6	Spain	2008	354	0.04
7	Canada	2006	333	0.02
8	Germany	2004	315	0.06
9	Malaysia	2008	258	0.04
10	The Netherlands	2007	227	0.14
11	Sweden	2009	220	0
12	South Korea	2008	218	0.15
13	India	2009	207	0
14	France	2008	188	0.06
15	Singapore	2007	179	0.03

3.3. Keyword Analysis

3.3.1. Keyword Common Line Analysis

Representing the core viewpoint of the paper, keywords provide a summary of the topic and content of the article, which can intuitively reflect the fields and contents involved in the literature and tap the research hotspots and knowledge structure of a certain research field. The node type was set to Keyword; the frequency and intermediary centrality of the keywords were calculated and plotted to obtain the keyword colinear mapping, as shown in Figure 5; and the 15 most used keywords were selected, as shown in Table 4. The purple-red colour of the outer ring or connecting lines of some nodes indicates the high centrality and strong influence of the keyword. The higher was the frequency and centrality, the more important the node was in the research field [31]. As can be seen from Figure 5, there were 750 keyword nodes in the graph and 1073 connected lines, with a density of 0.0038, indicating a low association and low aggregation between keywords in the field. Table 4 shows that the frequency and centrality of performance, model, building, energy, and construction were high, indicating that these keywords had a strong association with sustainable building design and represented an important focus for this research area. As the demand for 'sustainable' and 'green' buildings continues to grow, high performance, low cost, and environmentally friendly buildings are increasingly being emphasized in various research fields [14]. Researchers are looking to reduce building costs and energy consumption in a variety of ways, including through building information simulations and improvements to building materials [32,33]. The economic and environmental costs of buildings are assessed through various sustainable building design evaluation systems.

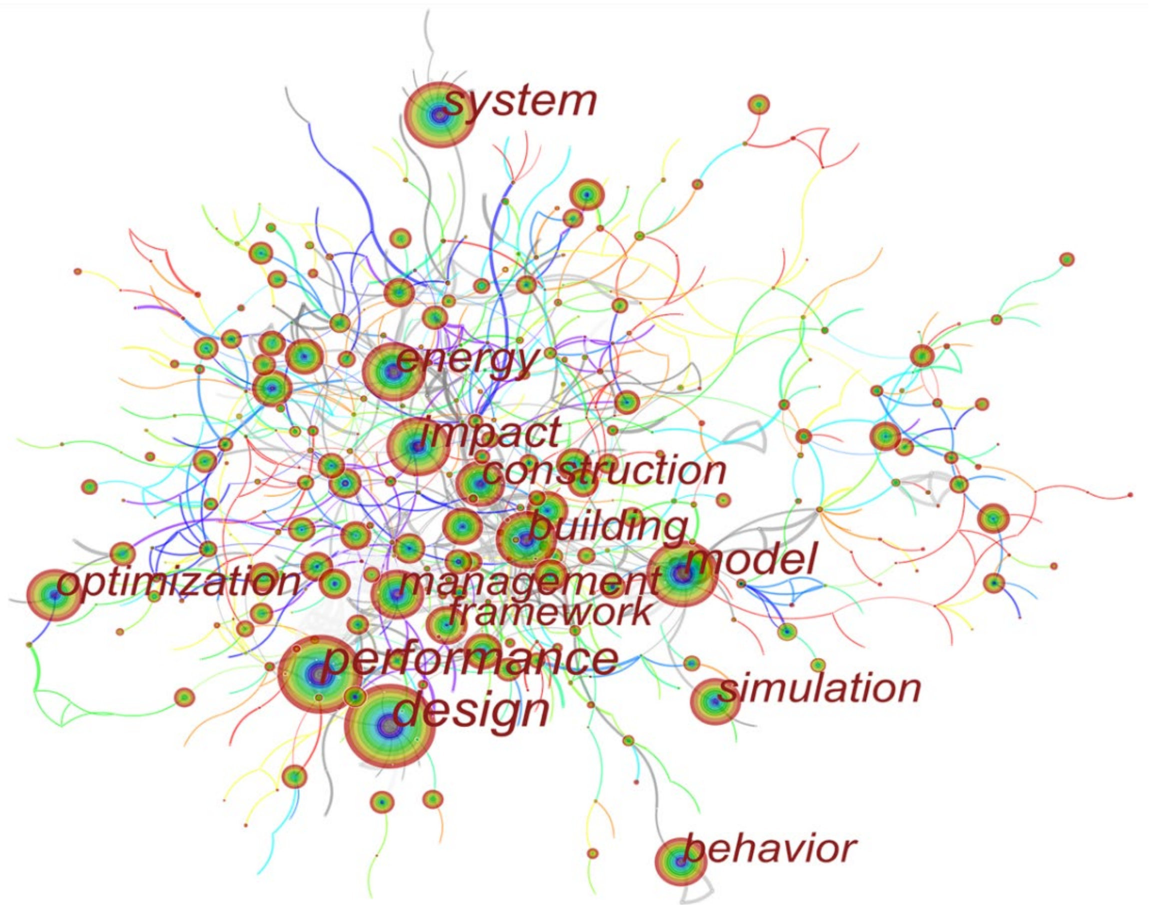

Figure 5. WoS core ensemble source sustainable building design research keyword colinear mapping.

Table 4. WoS core ensemble sources sustainable building design research high-frequency keywords and centrality.

Serial No.	Keywords	Frequency	Year of Debut	Intermediary Centrality
1	design	1149	2000	0.06
2	performance	989	2000	0.21
3	system	605	2003	0.04
4	model	559	2001	0.18
5	impact	479	2007	0.04
6	energy	427	2001	0.13
7	building	394	2004	0.25
8	optimization	366	2003	0.01
9	construction	335	2001	0.19
10	simulation	331	2002	0.01
11	management	320	2000	0.1
12	behaviour	307	2005	0.01
13	framework	274	2002	0.03
14	life cycle assessment	250	2012	0.01
15	consumption	227	2004	0.09

3.3.2. Keyword Clustering Analysis

Keyword clustering allows for the combination of words with the same characteristics in a literature sample to be classified to further examine the knowledge structure of different research hotspots. The LLR algorithm was used to perform keyword clustering on the mapping data, and the Show the Largest K Clusters in Clusters was set to 10 to obtain the top 10 clusters in this research area; see Figure 6 (partial only). As can be seen from Figure 6, the module value modularity Q = 0.8144 > 0.3 indicated that the cluster structure of this cluster was significant, and the mean profile value mean S = 0.9281 > 0.5 indicated that the cluster was reasonable [34]. The clustering labels are numbered #0–#9, in the order of #0 (system), #1 (fly ash), #2 (smart city), #3 (material selection), #4 (LEED), #5 (BIM), #6 (LCA), #7 (life cycle assessment), #8 (heating), and #9 (rap) for a total of 10 clusters. All of them had a silhouette degree greater than 0.7, indicating a good degree of keyword closeness between clusters. In order to make the content more obvious, the clustering results and the high-frequency keywords in the clusters were integrated and grouped into the following four major categories.

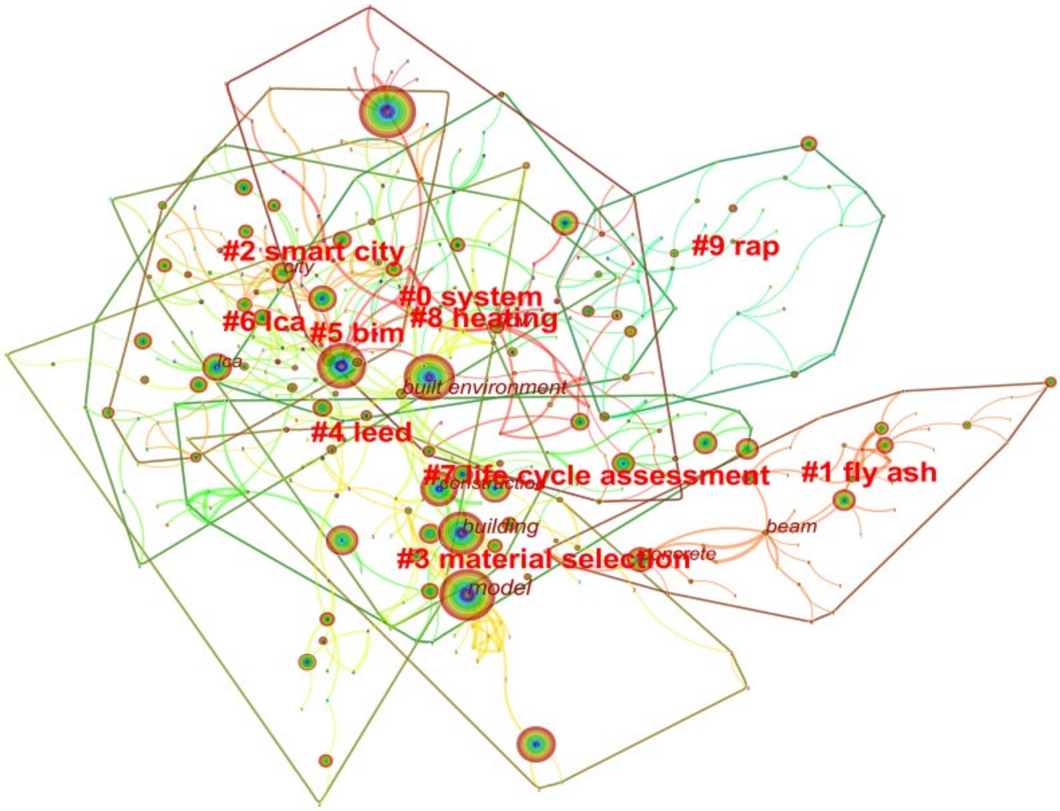

Figure 6. WoS core ensemble source sustainable building design research keyword clustering mapping.

(1) Environment and energy (Cluster #0, Cluster #2). The high-frequency keywords in this cluster included sustainability, energy, heat, carbon, policy, land use, and so on. This cluster reflected that the European Union (EU) proposed a climate-neutral green deal for Europe by 2050 in response to the impact of environmental pollution on climate and energy consumption, which is reflected in the commitment of EU member states to meet the directive's near-zero energy building (nZEB) standard in buildings [35]. Individual countries have put policies in place to minimise energy demand and greenhouse gas emissions over the lifetime of the building. Energy issues include building uses (cooling, heating, lighting, etc.) [36,37] and the production of building material components (steel, bricks, and glass). Environmental issues include carbon emissions, greenhouse gases, and so on. By addressing these issues, the complete life cycle of the building is made low carbon, zero energy, and resource efficient to achieve sustainable development.

(2) Natural materials and building material performance (Cluster #1, Cluster #9). The high-frequency keywords in this cluster included concrete, strength, compressive strength, microstructure, fibre, density, and so on. Natural materials are abundant, easy to handle, flexible, and inexpensive and have better toughness and compression resistance as construction materials compared with man-made fibres [38,39]. The incorporation of natural plant fibres into building composites reduces energy consumption, lowers the cost of building

materials, and improves the performance and load-bearing capacity of building materials, making them more durable and sustainable [40,41]. Its environmental friendliness, sustainability, and economy promote the sustainable development of buildings.

(3) Cooling and heating and building energy consumption (Cluster #4, Cluster #8). The high-frequency keywords in this cluster included climate change, LEED, HVAC, infrastructure, impact, and so on. The clusters were based on the influence of geographic location and climatic environment on temperature, and part of research on sustainable building design focused on heating and cooling energy consumption in harsh and hot areas, which are under greater pressure to save energy due to the long-term need for heating or cooling. Researchers have proposed a range of sustainable development strategies, such as regulating urban temperatures by changing the urban form such as building land cover, building height, and green space ratio [42,43] and using on-site power generation and energy storage systems to reduce energy costs and consumption [36,44].

(4) Building information modelling and life cycle assessment (Cluster #5, Cluster #3, Cluster #6, Cluster #7). The high-frequency keywords in this cluster included model, simulation, BIM, LCA, methodology, framework, and construction. This combination of clusters corresponded to the research methods used by most researchers in the field of sustainable building design. Building information simulation (BIS) is a series of inputs on building shape, orientation, size, time of use, cost, material composition and its properties (thermal conductivity, thermal resistance, etc.), and so on. The simulation run provides the energy demand for building operation as well as other detailed information [45]. In addition, the energy demand of a building comes from the various stages of material production, construction, maintenance, replacement, and demolition, as well as heating, cooling, ventilation, lighting, equipment, and electrical appliances [46] throughout the building's life cycle. Therefore, for sustainable building design studies, building information/energy modelling and life cycle assessment are often used in combination.

3.3.3. Keyword Timeline Analysis

The keyword timeline shows the time span and the evolution of each cluster's hotspot and also presents the association between the clusters. With the node type set to Keyword and the layout set to Timeline View, the top 10 clusters were extracted and plotted, as shown in Figure 7 (partial only). Where the keywords of the same cluster lie on a horizontal line, the longer was the time span, the earlier the cluster existed in this study, and the longer it lasted. Based on the mapping, the following conclusions can be drawn: (1) As a whole, the sustainable building design research clusters were closely linked, and there was more cross study. (2) The Cluster #0 system, Cluster #3 material selection, Cluster #6 LCA, and Cluster #7 life cycle assessment were early and persistent; among them, the model and simulation in Cluster #3 and the system in Cluster #0 appeared early and were associated with the emergence of the new class clusters. (3) Cluster #5 BIM was an important foundation for sustainable building research. (3) The BIM in cluster #5, thermal comfort in cluster #0, and CO_2 emission in cluster #6 emerged relatively late, appeared relatively frequently, and were linked to the previous and subsequent keywords in the same cluster and other clusters, playing a bridging role in the overall research, which was an extension and innovation of the basic research in the new environment and new needs.

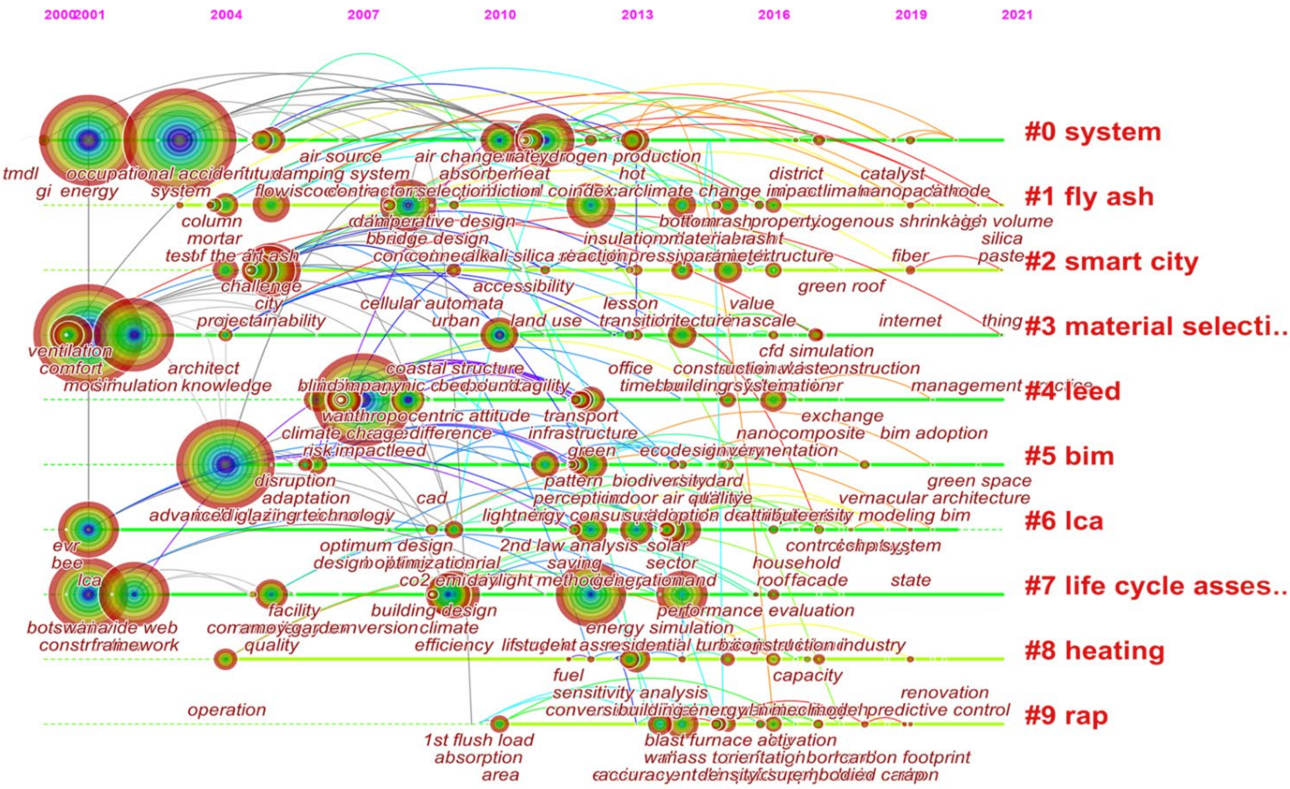

Figure 7. WoS core ensemble source sustainable building design research keyword timeline mapping.

3.3.4. Keyword Emergence Analysis

Keyword bursts are key terms that grow suddenly in a short period of time, used to observe the trend and change in keyword word frequency in a specific cycle and to identify influential topics in a field by burst intensity and duration. Burstness was set to the top 15, resulting in a total of 56 burst terms, which were sorted according to keyword burst intensity, as shown in Figure 8 (partial only); 8 burst terms according to their first duration are shown in Table 5, where Begin refers to the first year of the burst term, End represents the end year, red represents the burst time period, and blue represents the time slice in years. For the field of sustainable architectural design research, this paper analysed two dimensions of emergent intensity and emergent time:

Table 5. Eight keywords from WoS core collection source sustainable building design research in the order of emergence time.

Serial No.	Keywords	Year of Debut	Intermediary Centrality
1	nanoparticle	2019	4.18
2	rating system	2019	3.48
3	sand	2019	3.48
4	safety	2019	3.37
5	transition	2019	3.34
6	benefit	2019	3.24
7	fibre	2019	3.19
8	deposition	2019	3.17

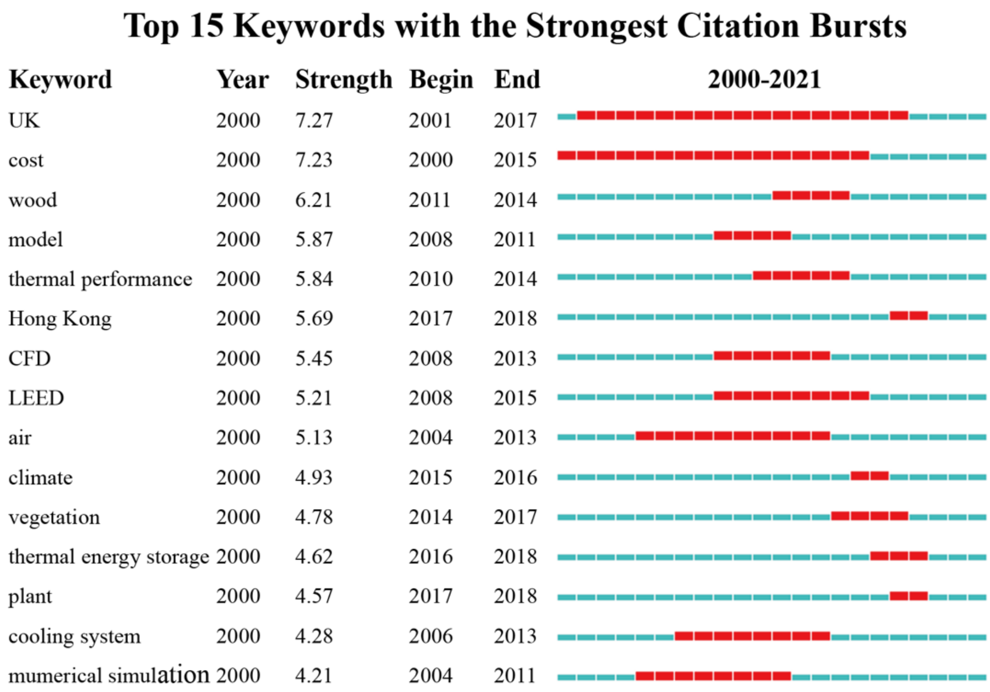

Figure 8. Top 15 keywords by emergent strength from the WoS core collection source sustainable building design study.

(1) From the perspective of emergence intensity, 'wood' had a high emergence intensity in a short period of time, with the emergence time in 2011, decreasing in 2014. Some countries (e.g., the Nordic countries) have introduced policies for buildings based on the environmental and energy problems caused by heating and cooling. There is a growing interest in low-energy buildings and a greater focus on the environmental impact of building material production. As a sustainable and renewable building material, more and more scholars are focusing on the use of wood in construction, including framing, interior decoration, site construction, and maintenance, and as an energy material; and many case studies and research studies have demonstrated that the use of wood can significantly reduce greenhouse gas emissions and energy consumption [47,48]. The use of wood can reduce CO_2 emissions through the carbon sink effect of forests and the carbon storage of wood as a substitute for carbon-intensive materials [49]. Moreover, as an alternative material, it can reduce fossil fuel consumption.

(2) In terms of time to emergence, 'UK' and 'cost' had the longest emergence time, from 2001 to 2007 and 2000 to 2015, respectively. The reason for the longer emergence of 'UK' is closely related to the importance and policies of the country. The world's first green building rating system (BREEAM) was developed in 1990, and a sustainable building strategy titled 'improving quality of life' was developed in 2000. Further legislation and policies (e.g., Landfill Tax, 2008) have been introduced to promote sustainable construction. As a central concern of the construction industry, 'cost' is closely linked to the economy. The challenges of sustainable design in the construction industry in terms of energy consumption and cost efficiency have led to tools or systems such as LEED, BIM, and Blockchain (BC) to estimate building costs, reduce risks in engineering applications through smart digital technologies, eliminate unnecessary time and material waste, and reduce costs. Other keywords, such as 'plant' and 'climate', were shorter in duration, but the idea of sustainability was always present. The emergent words 'nanoparticle', 'rating system', and 'fibre' appeared later and were more central, persistent since 2019. Because of the continuity of the emergent terms, they may become cutting-edge research topics in the field of sustainable building design research if research is continued in depth.

3.4. Analysis of Co-Cited Literature

3.4.1. Clustering Analysis of the Main Cited Literature

Co-citation clustering can reflect the knowledge base of a field, which is the prerequisite and support for the evolution of knowledge in the research field. The node type was set to Reference, and the co-citation map was obtained by clustering, as shown in Figure 9. (1, #5). This literature mainly focused on the integration of the life cycle of buildings and the circular economy, carrying out research from a sustainable perspective; the content focused on energy conservation and reuse throughout the life cycle of buildings from construction to demolition [50–52]. The aim is to achieve resource and energy conservation, alleviate the environmental load, and achieve sustainable development between the economy, environment, and society while ensuring economic benefits [53]. The second was research (#4) that addressed green buildings and green evaluation systems (GB). This part of the literature focused on the methodological analysis and application. The main contents included the definition and scope of green buildings, benefits and costs, and methods to achieve green buildings [54]. It also included the application and comparison of different green evaluation systems, and five of the more common evaluation systems are summarized in this paper, as shown in Tables 6 and 7 [55,56]. Third, computer-aided tools, such as building information simulation (BIM) and building energy simulation (BEM) (#2, #3, #17), were addressed. This part of the literature focused on research, application, and optimization of building simulation tools, usually combined with building life cycle assessment; the aim is to minimize the waste of human and material resources caused by changes and errors in all aspects of building design and construction, which can better control construction costs and reduce the waste of resources [57,58].

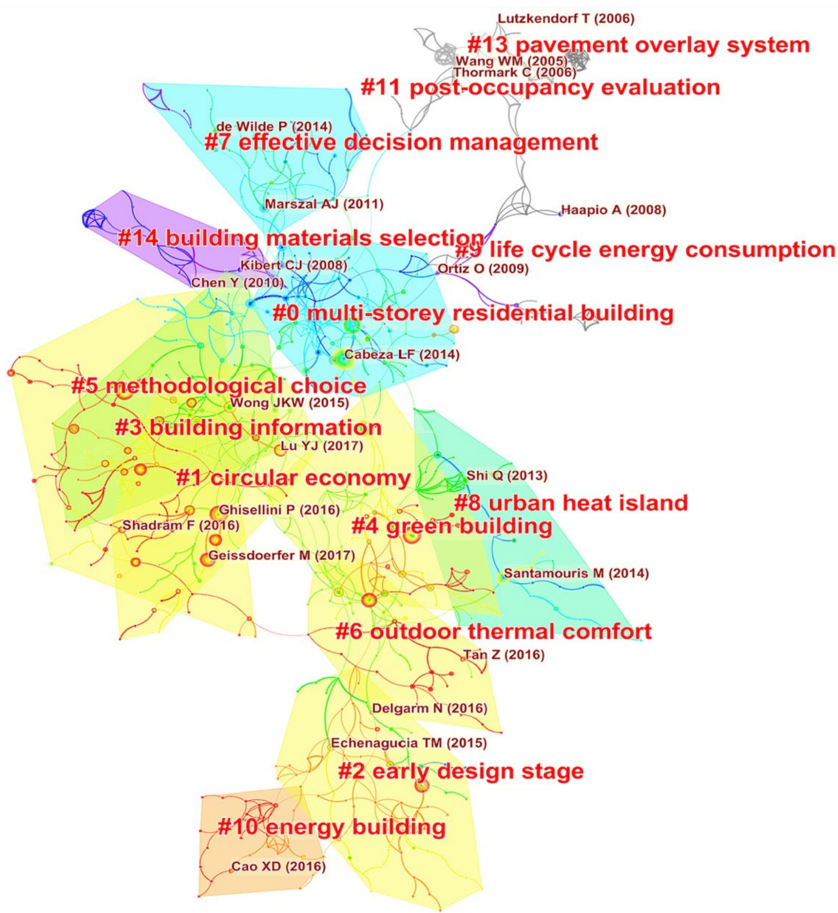

Figure 9. Co-citation clustering map of the research literature on sustainable building design from the WoS core collection sources.

Table 6. Comparison of evaluation systems.

	BREEAM	LEED	CASBEE	Green Star NZ	HQE
Name	**Building Research Establishment Environmental Assessment Method**	**Leadership in Energy and Environmental Design**	**Comprehensive Assessment System for Building Environmental Efficiency**	**Green Star NZ**	**High Environmental Quality**
First version	1990	1998	2002	2007	1994
Country	UK	USA	Japan	NZ	France
Scope of application	Europe and beyond	South America, Europe, Asia, etc.	Already launched abroad	Countries such as Australia, New Zealand, and South Africa	Europe and beyond
Building's life cycle assessment	Design, build, operation, and refurbishment	Design, build, operation, and refurbishment	Design, build, operation, and refurbishment	Design, build, and refurbishment	Design, build, operation, and refurbishment
Rating approach	Preweighted categories	Additive credits	BEE ranking chart	Preweighted categories except for innovation	-
Evaluation content	Overall performance of the building	Evaluation of overall building performance with an emphasis on environmental aspects	Measuring the ratio between the quality and performance of the built environment and the load on the built environment	Assessing the environmental performance of projects through nine environmental impact categories	Based on 14 target areas, divided into four themes: environmental construction, environmental management, comfort, and health
Evaluation type	Design, procurement, construction, management, operation	Combination of design review, construction review, design review, and construction review	Design, construction or renovation, operation	Joint design and construction review	Combination of design review, construction review, and design review and construction review

Table 7. WoS core collection sources of sustainable building design research with top 10 total citations.

Serial No.	Title of the Article	Number of Citations	Type of Literature	Clustering	Journals
1	Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review	54	Article	#0	Renewable & Sustainable Energy Reviews
2	Green building research—current status and future agenda: A review	39	Article	#4	Renewable & Sustainable Energy Reviews
3	A review on simulation-based optimization methods applied to building performance analysis	36	Article	#17	Applied Energy

Table 7. *Cont.*

Serial No.	Title of the Article	Number of Citations	Type of Literature	Clustering	Journals
4	A critical comparison of green building rating systems	35	Article	#4	Building and Environment
5	Recent developments, future challenges and new research directions in LCA of buildings: A critical review	34	Article	#5	Journal of Civil Engineering and Management
6	A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems	30	Article	#1	Journal of Cleaner Production
7	Enhancing environmental sustainability over building life cycles through green BIM: A review	30	Article	#3	Automation in Construction
8	Urban building energy modelling—A review of a nascent field	29	Review	#2	Building and Environment
9	Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts	29	Article	#0	Building and Environment
10	Life cycle energy analysis of buildings: An overview	28	Review	#0	Energy and Buildings

3.4.2. Interdisciplinary Knowledge Flow Analysis

The biplot overlay can reflect the dynamic progress at the disciplinary level in the field of sustainable building design research, including citation trajectories, knowledge flows, and the distribution of papers in other information areas [59]. We selected JCR Journal Maps in Overlay Maps; entered the biplot overlay interface, Overlay-add Overlay to add data literature sources; generated a journal biplot overlay; and selected Z scores to adjust the clustering graphical interface to standardize and simplify it. As shown in Figure 10, the biplot overlay consists of a left-hand side and a right-hand side, with the cited literature on the left-hand side representing the main subject areas of sustainable building design research and the cited literature on the right-hand side representing the main cited subjects in that research area. Therefore, the left side can be seen as the application area of sustainable building design, and the right side can be seen as an important knowledge base for sustainable building design.

As can be seen from Figure 10, there were eight citation trajectories that were more evident in the field of sustainable building design research: (1) from mathematics, systems, and mathematical to economics, economic, and political; (2) from mathematics, systems, and mathematical to environmental, toxicology, and nutrition; (3) from mathematics, systems, and mathematical to systems, computing, and computer; (4) from mathematics, systems, and mathematical to chemistry, materials, and physics; (5) from mathematics, systems, and mathematical to mathematical, mathematics, and mechanics; (6) from veterinary, animal, and science to economics, economic, and political; (7) from veterinary, animal, and science to environmental, toxicology, and nutrition; and (8) from veterinary, animal, and science to chemistry, materials, and physics. More than four disciplines in one citation track (e.g., (2)) included mathematics, systems, environmental, toxicology, nutrition, and so on, indicating a multidisciplinary trend in sustainability research. The LEED standards issued by the U.S. Green Building Council and the office and administrative building design manuals issued by the German Council for Sustainable Building (DGNB) reflect this multidisciplinary character.

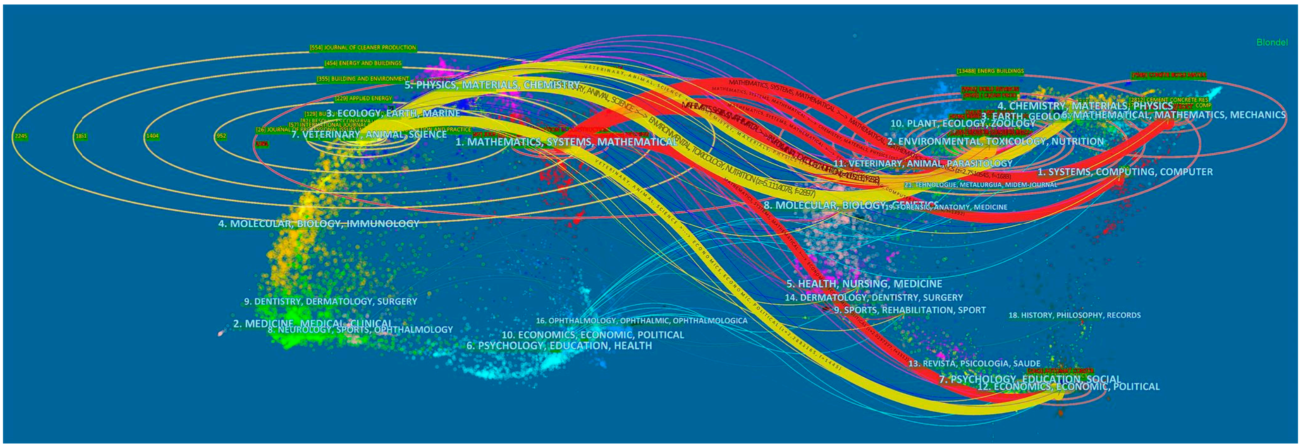

Figure 10. Double graph overlay knowledge map of the WoS core collection source sustainable building design research journals (cited journals on the left, cited journals on the right).

The cited literature was concentrated in mathematics, systems, animals, science, and medicine; and the cited literature was concentrated in economics, politics, computing, environmental studies, chemistry, physics, and materials. As the cited journals provided the knowledge base of the citing journals, their disciplinary centres gradually shifted from economics, politics, computing, environmental science, chemistry, physics, materials, and so on to mathematics, systems, animals, science, medicine, and so on. As can be seen on the left-hand side of Figure 5, emerging disciplines also included psychology, education, health, and so on.

4. Conclusions

This paper used bibliometrics as the research method and the CiteSpace visualization software as the application tool to sort and analyse the research hotspots and development history of sustainable architectural design research by analysing the resulting knowledge map, and we drew the following conclusions.

(1) Analysis of the cooperation in this research field through the distribution of research institutions and countries. During the period of 2000–2021, a total of 626 institutions and 179 countries conducted research on sustainable building design, and the overall trend was rapidly increasing in terms of the number of publications. In terms of centrality, among the top 15 countries, the USA, South Korea, the Netherlands, and England had a higher centrality, while China had a lower centrality, indicating that the USA had a higher international influence in this research field. In terms of international exchange, foreign countries had close cooperation and exchange in the field of sustainable architectural design research, while China had less contact with other countries and needs to strengthen the cooperation and exchange between countries.

(2) The research hotspots and evolution of the field could be seen through keyword colinearity, clustering, and timeline analysis. According to the clustering, sustainable building design was divided into four knowledge structures: environment and energy, natural materials and building material performance, cooling and heating and building energy consumption, and building information modelling and life cycle assessment. The research hotspots included performance, systems, modelling, and energy in addition to the original keywords architecture and design. This means that the focus of this research was on environmental and energy sustainability, the economic and environmental costs of buildings, the use of evaluation systems and computer-aided tools for information modelling, and so on. BIM, thermal comfort, and CO_2 emission were relatively recent,

appeared relatively frequently, and were associated with the same cluster and the other clusters. The keywords of the same cluster and other clusters were related to each other and played a bridging role in the overall research, which was an extension and innovation of the basic research into the new environment and new needs.

(3) The keyword emergence analysis was used to explore the causes and development of a certain issue in sustainable architectural design and to explore the frontier hotspots. In terms of the intensity of emergence, 'wood' emerged with a high intensity in a short period of time, in 2011, and gradually decreased in 2014. Some countries (e.g., the Nordic countries) have proposed policies for buildings based on the environmental and energy problems caused by heating and cooling, and this led to a boom in research. In terms of time to emergence, 'UK' and 'cost' had the longest emergence times, with the longer emergence time of 'UK' as a country being strongly related to the level of national attention and policy. The reasons for the longer period of time for 'UK' as a country are strongly related to the importance of national policies. As the core concern of the construction industry, 'cost' is closely related to the economy. The combination of keyword emergence analysis and keyword timeline analysis showed that nanoparticles, grading systems, fibres, and other keywords may become frontier hotspots.

(4) The knowledge base of this research area was analysed through the co-cited literature. After summarizing and categorizing, it was concluded that the knowledge base mainly included three aspects: first, life cycle and circular economy; second, research on green building and green evaluation systems; and third, research on computer-aided tools, such as building information simulation and building energy simulation.

(5) The flow of knowledge between disciplines in this research area was analysed by means of a biplot overlay. First, this research area had five disciplines in one citation track, such as mathematics, systems, environmental science, toxicology, and nutrition (2), which indicated that sustainable building design was a multidisciplinary concept. Analysis against the biplot overlay revealed a shift in the disciplinary centre of the field of study from economics, politics, computing, environmental science, chemistry, physics, and materials to mathematics, systems, animals, science, and medicine, with the emerging disciplines also including psychology, education, and health.

(6) This research can help sustainable architectural design researchers to quickly capture relevant research institutions, research authors, and specific research directions and fields. Sustainable design is not only applied in architecture. In Figure 10, we can see that sustainable design exists between multiple disciplines, and intersection occurs between mathematics, computer science, physics, and materials science and other disciplines; and the research results can provide reference for these disciplines in the field of sustainability research.

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