buildings

Review

A Bibliometric and Content Review of Carbon Emission Analysis for Building Construction

Yuanhang Wang [1], Zhiwen Jiang [2], Lingzhi Li [2,*], Yujun Qi [2,*], Jianwei Sun [1] and Zhangzhang Jiang [1]

[1] China Construction Third Bureau First Engineering Co., Ltd., Shanghai 201107, China
[2] College of Civil Engineering, Nanjing Tech University, Nanjing 211816, China
* Correspondence: lilingzhi5566@njtech.edu.cn (L.L.); qiyujun@njtech.edu.cn (Y.Q.)

Abstract: To combat climate change and meet energy conservation and emission reduction goals, the building sector must adopt low-carbon technologies and low-carbon management methods. To systematically explore existing research areas and track future research trends of carbon emission in the construction stage (CECS), this study conducts a bibliometric and content analysis of CECS studies. 563 relevant publications published between 2000 and 2022 are examined and analyzed using data from the Web of Science (WoS) core collection database. The findings reveal that studies of CECS have evolved through three stages: preliminary exploratory period, stable development period, and rapid development period. In addition, the literature co-citation network and content analysis classify the 13 found co-citation clusters into four knowledge domains: sources definition, data statistics, assessment methods, and carbon reduction strategies. Finally, a knowledge map of CECS studies is presented, outlining significant aspects of research, existing gaps in knowledge, and directions for future study. This work will make it easier for academics and professionals to pinpoint promising areas of study, fill in knowledge gaps, and broaden the scope of existing research on CECS.

Keywords: carbon emissions; construction; carbon reduction; science mapping; bibliometric analysis; content analysis

Citation: Wang, Y.; Jiang, Z.; Li, L.; Qi, Y.; Sun, J.; Jiang, Z. A Bibliometric and Content Review of Carbon Emission Analysis for Building Construction. *Buildings* **2023**, *13*, 205. https://doi.org/10.3390/buildings13010205

Academic Editors: Tao Wang, Hanliang Fu and Zezhou Wu

Received: 19 December 2022
Revised: 5 January 2023
Accepted: 6 January 2023
Published: 12 January 2023

1. Introduction

With the progressive improvement of people's living conditions and the rapid development of the social economy, greenhouse gas emissions, especially CO_2, have increased tremendously. Given the tight association between carbon emissions and climate change, regulating carbon emissions has become an urgent global concern to minimize global warming. According to the International Energy Agency, the building industry accounts for 40% of world energy consumption and between 30–50% of total human greenhouse gas emissions, which suggests that the construction industry has enormous potential for energy saving and emission reduction [1]. If the building industry wishes to achieve a breakthrough in energy saving and emission reduction, quantitative studies on carbon emissions and emission reduction studies are important. When compared to the operation phase, the building phase consumes more energy and resources per unit of time, resulting in a concentration of carbon emissions [2,3]. Therefore, it is of considerable importance as the basis for quantitative analysis of low-carbon buildings to accurately monitor carbon emissions during this phase and to devise matching emission reduction methods [4].

A large and growing body of literature reviewed the studies on carbon emissions quantification and discussed the factors influencing carbon quantification. For instance, Fenner et al. (2018) [5] reviewed current approaches for carbon footprint assessment and outlined the discrepancies of most life-cycle carbon assessment studies, and Chen et al. (2022) [6] conducted a thorough analysis of research about embedded carbon emissions in prefabricated structures. Much of the literature since the 2000s emphasizes the carbon emissions in the construction stage (CECS). Among them, there are different theories on CECS abatement. For example, Sizirici et al. (2021) [7] compiled the most up-to-date findings on cutting down on carbon emissions during the building process itself, including material manufacturing and construction. More recent attention has focused on the provision of new concepts such as green building and sustainable building. For instance, Lu et al. (2020) [8] summarized the knowledge system, research hotspots, and future development of green building carbon emissions. Obviously, more and more scholars around the world have devoted their efforts to promoting CECS studies from different perspectives, and have obtained remarkable results. There are a number of publications that provide reviews of CECS research, but they tend to focus on either a specific area of CECS research or on a different part of the building's life cycle. For example, several articles are limited to the management of CECS [9], while others focus on embodied carbon emission [6]. Most of the literature is dominated by qualitative studies, which are highly subjective and ambiguous, and lack systematic analysis and rigorous argumentation [10–13]. Herein, it is necessary to systematically review CECS studies through the mixing of quantitative and qualitative methods, clarify the critical research contents of CECS, and explore existing knowledge gaps and future directions.

The bibliometric analysis allows a quantitative study of the hotspot distribution structure, quantitative relationships, and change patterns of CECS research [14]. Content analysis is a qualitative technique used by academics to uncover the findings and aims of a study [15]. Combined with thematic analysis, this study conducts a comprehensive review of CECS research from 2000 to 2022 using bibliometric and content analysis. The overall research status may be better understood by analyzing publication years, countries, institutions, subject categories, journals, highly cited articles, keywords, etc. It is possible that research frontiers and hotspots can be found by an analysis of both citing and cited papers. Using a network diagram, the citation analysis visualization method illustrates the current and future state of research in the field of study. Moreover, a CECS knowledge map is provided, revealing essential research components, knowledge gaps, and future objectives.

2. Methodology

Figure 1 illustrates the research framework for this study. Using bibliometric and content analysis techniques, this research undertakes a quantitative and qualitative analysis of CECS investigations. There are three specific steps to follow.

2.1. Data Collection

The first step is to collect data from high-quality articles on CECS. This study uses the Web of Science (WoS) core collection as its data source. The search algorithm is utilized based on article kinds and parameters to discover more relevant articles. Following that, we review the abstracts of the publications we find and screen the literature.

2.1.1. Literature Retrieval

Following pre-analysis and comparison, the following search schema has been chosen to search the WoS core collection database: TS = (carbon emission* OR CO_2 emission* OR carbon dioxide emission* OR CO(2) emission* OR greenhouse gas* emission* OR GHG* emission* OR carbon footprint OR cf OR on-site emission*) AND TS = (construction site* OR building construction* OR materialization stage*). The terms "TS" and "*" stand for the article's topic and a fuzzy search, respectively. Literature published between 2000 and 2020 (including 2000 and 2020) is retrieved from the WoS core database. The document type is restricted to articles and reviews, and the language is only available in English. A total of 3259 articles are obtained after data deduplication.

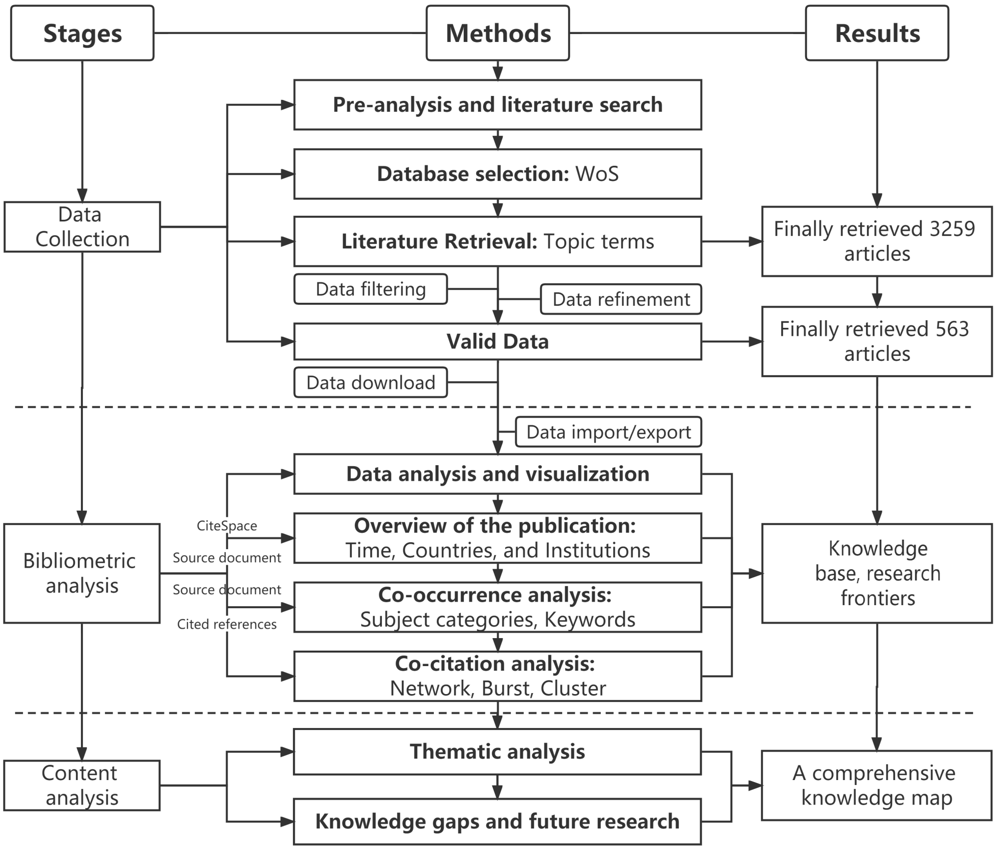

Figure 1. Research framework.

2.1.2. Exclusion Criteria

Examination of the obtained results is necessary to insure that the selected papers fulfill the criteria for subsequent investigation [16,17]. After reading the abstract, unrelated material is removed from the complete study and analysis based on the following criteria:

(1) Each article focuses on carbon emissions in construction processes such as building material manufacture and transportation, on-site construction, and construction waste transportation and disposal.
(2) To better explore cross-cutting articles, the selection process does not limit the research areas to mainstream fields such as engineering, environmental sciences technology, and building construction technology.
(3) Research papers exploring the operational or dismantling phase, or articles that focus on assessing several types of sectors encompassing a specific region at a macro level, are excluded from this review.

563 articles are ultimately chosen for bibliometric and content analysis through additional screening.

2.2. Bibliometric Analysis

Because of the magnitude and scope of CECS investigations, manual bibliometric analyses are almost impossible. Through bibliometric analysis and visual analytics, CiteSpace software can evaluate classic research topics and reveal future trends [18]. Thus, the second step of this research was a bibliometric analysis of the literature's distribution, co-occurrence, and co-citation using Cite Space. Critically, a quantitative analysis of research hotspots and trends in the selected knowledge topics is conducted.

2.3. Content Analysis

The final step will involve creating a knowledge map of CECS studies, which will outline the key components of the research and some knowledge gaps.

3. Results and Interpretation

3.1. Overview of the Publication Year

Figure 2 depicts a general upward trend in researchers' interest in CECS from 2000 to 2022, which can be separated into three distinct stages. Before 2012, the number of publications each year was at most ten, and there were even a few years when no relevant articles were published, indicating that this period was the preliminary exploration stage. From 2012 through 2016, yearly publications remained steady at about 30. From 2017 to 2021, the number of publications increased from 42 to 128 for a total of 380, with only an unexpectedly rapid decline in 2019 during this period. As a result, it is expected that CECS research will expand in the coming years.

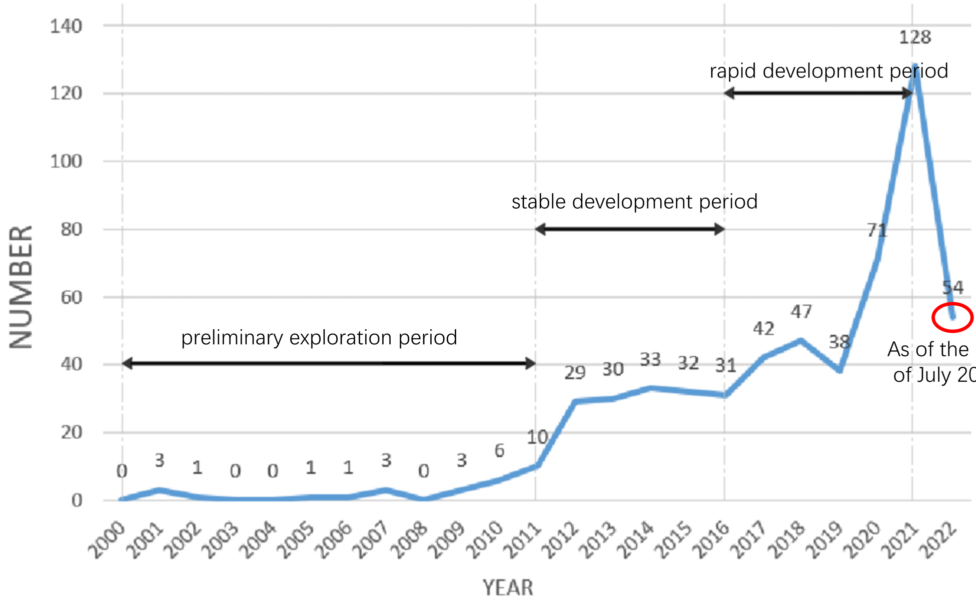

Figure 2. The number of articles on carbon emissions in the construction stage.

3.2. Overview of Publishing Institutions and Publishing Countries

The co-occurrence network of CECS studies by nation and institution is depicted in Figure 3. Publication-wise, the top five nations are China, Australia, the United States, South Korea, and the United Kingdom, with China coming in first with 168 papers (29.8% of the total), demonstrating the prominence of Chinese scholars in this subject but also the lack of international interaction (the centrality of 0.30). Although the UK has just 47 publications (8.35% of the total), its centrality is as high as 0.93, showing that the UK is an essential player in cross-national collaborative research on this subject. The distribution of institutions often correlates to the distribution of nations, as is widely known (regions). Chinese research institutes seem particularly active in CECS research, with Hong Kong Polytechnic University leading the list with 20 papers, followed by Chongqing University (19) and Southeast University (19). RMIT University in Australia is second with 19 papers, while Victoria University is third with 11 publications. In general, CECS research is prioritized by both developed and developing nations. However, the research institutions seem relatively fragmented, indicating that each institution is not doing enough ongoing research in this sector.

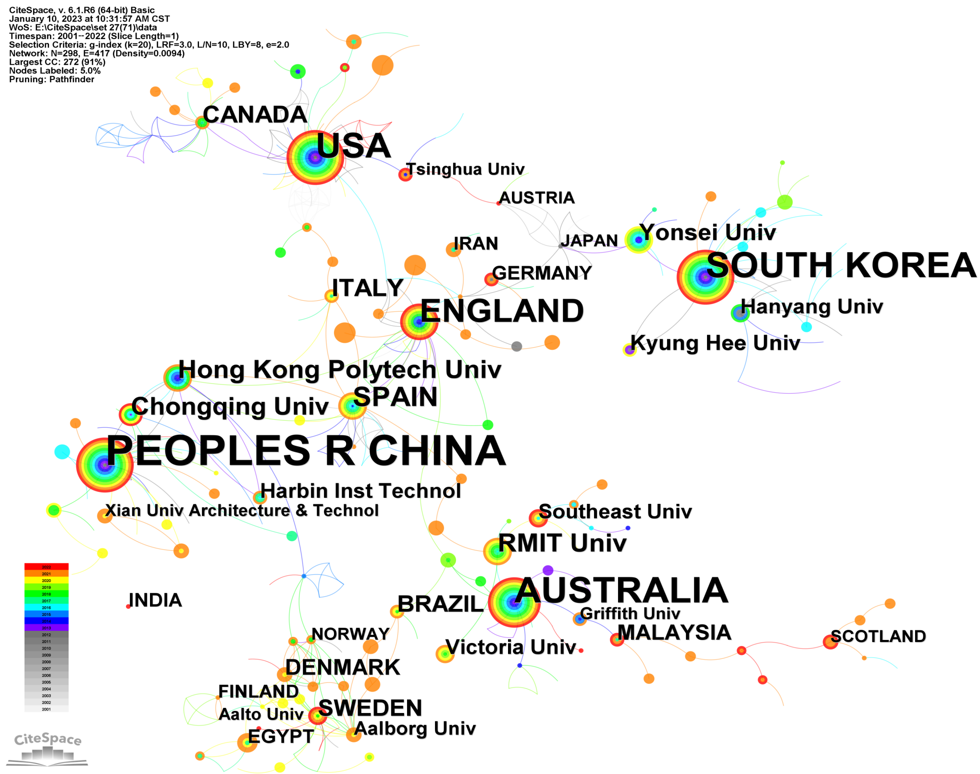

Figure 3. Countries and institutions' co-occurrence network.

3.3. Subject Categories and Published Journals

The WoS categories with the most publications (>150) are environmental sciences (210, 37.3%), construction building technology (196, 34.8%), green sustainable science technology (190, 33.7%), engineering civil (189, 33.6%), and engineering environmental (155, 27.5%). This shows that environment, architecture, sustainability, and engineering are key research themes.

The top journal sources for CECS have listed in Table 1. Among the many journals that have published articles about CECS, the top two journals are Journal of Cleaner Production (75) and Sustainability (62). One of the most important measures of a journal article's significance is how often it is cited by other works [17]. Total citations, average citations per article, and average citations per year are employed to quantify the effect of journals on CECS research [19]. Renewable Sustainable Energy Reviews has the highest average number of citations per article, with 125.12 for the 17 pieces it produced on the topic. It is also ranked first in terms of average citation frequency, with more than twice as many as the second-place paper. Additionally, the misunderstanding brought on by older articles receiving more citations than new articles can be corrected by average citations per year. The most cited journal is Journal of Cleaner Production, which averages 272.5 citations annually.

Table 1. Top research journal sources in 2000–2022.

Rank	Journal Title	No. of Articles	Total Citations	Ave. Citations per Article	Ave. Citations per Year
1	Journal of Cleaner Production	75	2180	29.07	272.5
2	Sustainability	62	510	8.23	46.36
3	Energy and Buildings	55	2660	48.36	204.62
4	Building and Environment	33	1878	56.91	110.47
5	Journal of Building Engineering	17	100	5.88	25
6	Renewable Sustainable Energy Reviews	17	2127	125.12	177.25
7	International Journal of Life Cycle Assessment	14	941	67.21	58.81
8	Sustainable Cities and Society	14	405	28.93	36.82
9	Resources Conservation and Recycling	13	469	36.08	24.68
10	Buildings	11	178	16.18	29.67

Citation data were obtained from the Web of Science core collection database (8 July 2022).

3.4. Keyword Co-Occurrence Analysis

Keywords highlight an article's focus and core content [20]. By displaying the connections and organization of research topics, keyword networks give an overview of knowledge bodies [21]. In this study, a network of keyword co-occurrences is created using keywords from the 563 documents that were gathered. Similar-meaning keywords (like "LCA" and "life cycle assessment") are merged during keyword analysis to hide unnecessary associations. In addition, "carbon emission", "greenhouse gas emission", "carbon footprint", "construction", "building", and other generic terms are excluded since they are already used as search terms. Figure 4 displays the completed network structure, which includes 364 nodes and 679 connections. Each node in the figure represents a keyword, and keywords that appear more than seven times are visible. The top five keywords, "life cycle assessment", "embodied energy", "energy", "impact", and "embodied carbon" appear 249, 102, 82, 80 and 77×, respectively.

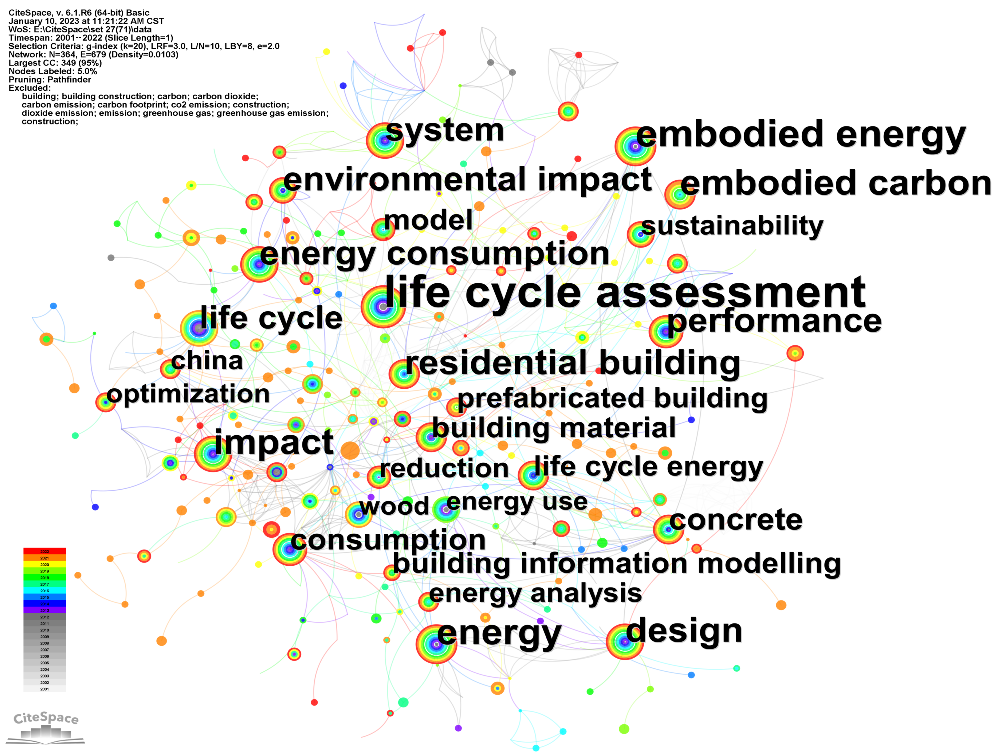

Figure 4. Keywords co-occurrence network.

Figure 5 shows a timeline view of keyword co-occurrence to illustrate the evolutionary trend of keywords. The terms "life cycle assessment", "embodied energy", and "construction sector" rose in popularity between 2000 and 2004, indicating that researchers have started looking at embodied carbon emissions over the course of a building's life cycle [22]. According to the new keywords "environment impact" and "impact" from 2005 to 2008, researchers began to notice the interaction between CECS and the environment [23]. Between 2009–2012, the terms "design", "building material", "concrete", and "wood" emerged, suggesting that green building design and low-carbon materials can also reduce carbon emissions [24]. BIM is being employed for the first time in CECS studies at this stage [25]. From 2013–2016, the rise of the keywords "residential building", "office building", and "green building" showed that CECS studies are being done for different kinds of buildings. During 2017–2022, "prefabricated building" received a lot of attention, and research clearly showed that using prefabricated processes and prefabricated components in buildings is effective in lowering emissions [26], while keywords like "genetic algorithm" and "multi-objective optimization" were frequently cited, indicating that computer-based optimization methods are gaining popularity [27–29].

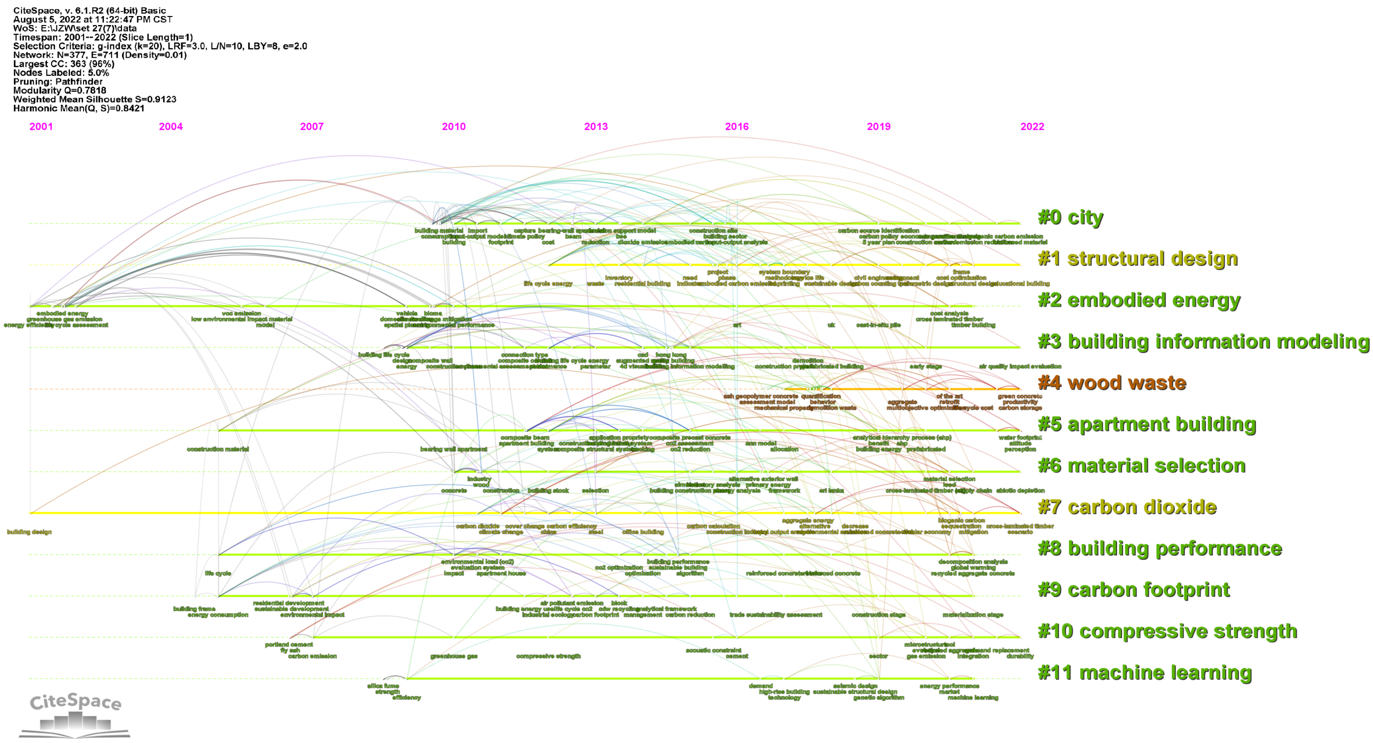

Figure 5. A timeline view of keyword co-occurrence in 2000–2022.

3.5. Documents Co-Citation Analysis and Cluster Analysis

3.5.1. Documents Co-Citation Network

The 563 articles of CECS were cited by 9064 articles, with the average citation frequency of each article was 28.85. One year is selected as a period, and the g-index method (k-value was taken as 20) is chosen to conduct literature co-citation and cluster analysis. Figure 6 shows the co-citations of multiple documents. For instance, Luo et al. (2016) [30], Zhang et al. (2016) [31], and 13 other articles have shared references since 2016, resulting in several closely linked circles. A few links are purple, which corresponds to the years 2000 to 2006, while the majority of links are yellow and orange. This shows that the majority of the document co-citations emerged after 2010 when the quantity of carbon emission articles during construction began to skyrocket. The top three articles that have received the most co-citations are written by Mao et al. (2013) [32], Hong et al. (2015) [33], and Chau et al. (2015) [34], and they have 68, 53, and 47 co-citations, respectively.

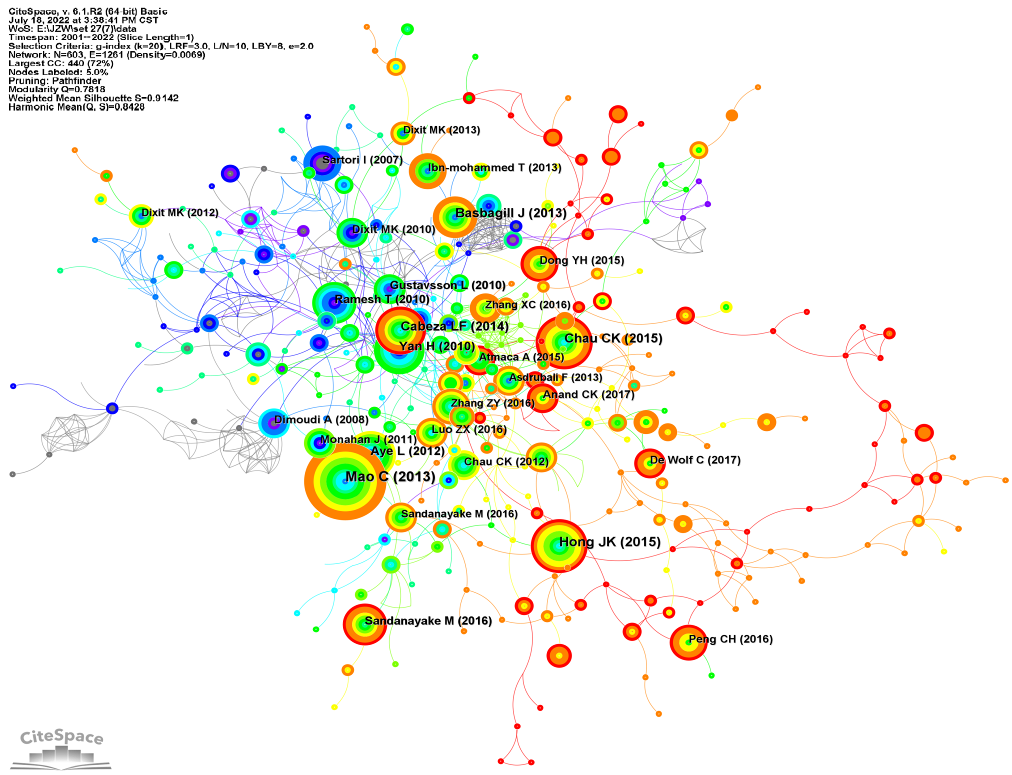

Figure 6. Documents co-citation network.

3.5.2. Citation Bursts

Burst detection is a type of temporal analysis that seeks out high-intensity features over a predetermined time frame [35]. CiteSpace uses burst detection to determine if there has been a noticeable increase in frequency over a given period of time [36]. As illustrated in Table 2, citation bursts have been detected in 25 articles. The strongest burst is related to Sartori et al. (2007) [37] (burst strength = 13.21, 2012–2015), which shows that buildings carefully designed with "green materials" but without special energy measures are less efficient than equivalent solar houses by the analysis of 60 cases. Another burst is related to Dimoudi et al. (2008) [38] (burst strength = 10.52, 2010–2016), which investigates the role of different construction materials, and suggests promoting construction methods that can save quantities of material.

Table 2. Top 25 references with the strongest citation bursts in 2001–2022.

Strength of Burst	Start of Burst	End of Burst	2001–2022	Pub. Year	References
13.21	2012	2015		2007	Sartori et al. (2007)
10.53	2010	2016		2008	Dimoudi et al. (2008)
10.05	2013	2018		2009	Yan et al. (2009)
8.95	2013	2018		2010	Ramesh et al. (2010)
8.02	2016	2020		2015	Hong et al. (2015)
8	2011	2015		2007	Nassen et al. (2007)
7.32	2010	2014		2006	Junnila et al. (2006)
6.89	2012	2015		2010	Dixit et al. (2010)

Table 2. *Cont*.

Strength of Burst	Start of Burst	End of Burst	2001–2022	Pub. Year	References
6.43	2010	2015		2007	Asif et al. (2007)
6.39	2011	2014		2005	Li et al. (2005)
6.28	2012	2018		2009	Gustavsson et al. (2009)
6.24	2012	2017		2007	Ortiz et al. (2007)
6.11	2014	2017		2009	Bribian et al. (2009)
6.04	2012	2014		2005	Gonzalez et al. (2005)
5.98	2013	2016		2009	Goggins et al. (2009)
5.89	2020	2022		2018	Pomponi et al. (2018)
5.83	2019	2020		2017	Li et al. (2017)
5.8	2012	2016		2007	Huberman et al. (2007)
5.8	2012	2016		2009	Gustavsson et al. (2009)
5.66	2020	2022		2016	Peng et al. (2016)
5.66	2020	2022		2020	Rock et al. (2020)
5.56	2015	2018		2012	Wu et al. (2012)
5.43	2017	2020		2015	Chou et al. (2015)
5.38	2012	2016		2008	Blengini et al. (2008)
5.36	2020	2022		2017	De Wolf et al. (2017)

Citation data were obtained from the Web of Science core collection database (8 July 2022).

3.5.3. Cluster Analysis

CiteSpace literature co-citation cluster analysis is an algorithmic approach to uncovering common themes in closely related literature, which is more efficient than manual summarization when dealing with large volumes of literature and can reduce the burden on researchers [39]. The cluster analysis of the co-citation network yielded 65 clusters, and Figure 7 lists the 13 largest co-citation clusters in terms of size. Each cluster stands for a current research project in the area of carbon emissions. In order to determine cluster labels, the log-likelihood rate is used (LLR) [40]. The Modularity value of 0.8863 provides in the upper left information column of the CiteSpace plot is greater than 0.3, indicating that the structure of the clusters delineates is significant, and the Silhouette value of 0.9116 is higher than 0.7, meaning that the clustering results are convincing.

Each cluster's intellectual foundation can be thought of as a collection of tightly related references, and the publications that refer to the clusters are regarded as the research frontiers [41]. By combining citation-linked and text-based techniques, the central documents (the representative cited papers and the active citing papers) allow us to understand the dynamic connection between the intellectual foundation and the prospective research front of a cluster [36].

Based on the original research content, four knowledge domains are created from 13 clusters (Numbered KD1-KD4).

(1) KD1 "carbon emissions sources" = cluster #1 "embodied carbon emissions" + cluster #9 "web-cyclone" + cluster #10 "residential sustainability"

This knowledge domain KD1 focuses on carbon source coverage, composed of four aspects: system boundary, Greenhouse gases (GHG) type, project type, and quantification space. As of now, there is no consensus on the sources of CECS. Researchers are mainly concerned with whether activities (such as energy consumption, material production, manufacturing and transportation, equipment and labor use, etc.) should be included within the system boundary.

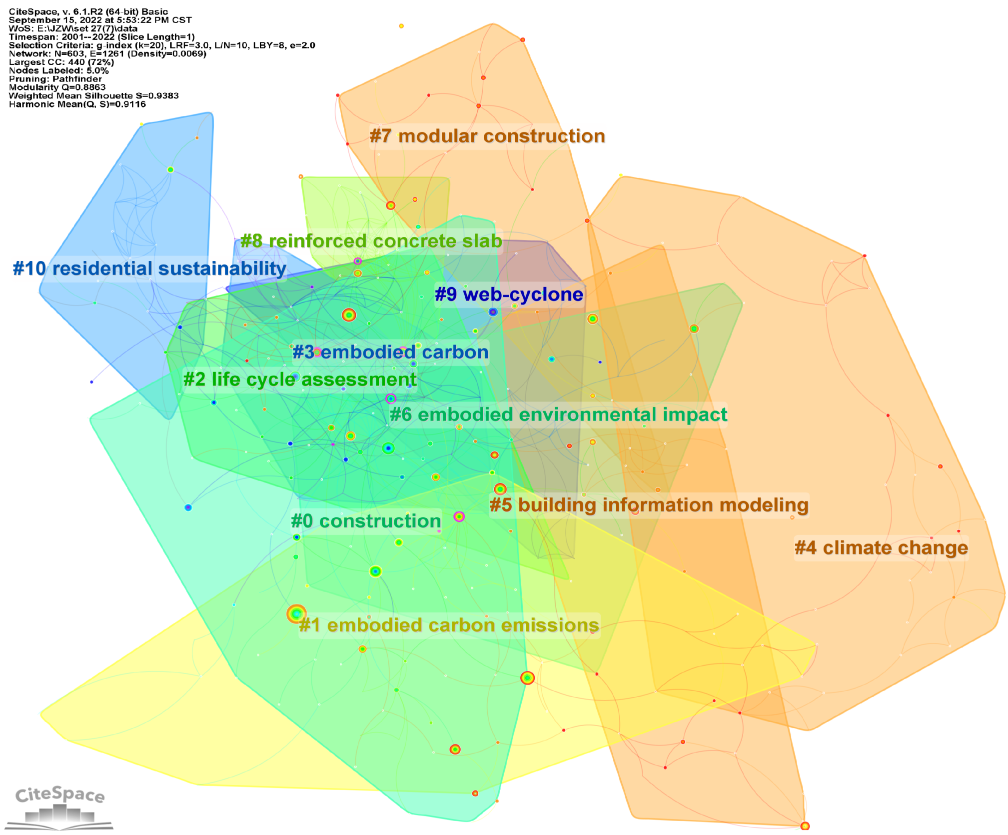

Figure 7. Cluster view of literature co-citation network.

The most cited article proposed a "cradle-to-site" assessment approach that included raw material harvest, building material production and transportation, on-site construction, and construction waste management [42]. In other highly cited articles, a few researchers considered only the CECS of major construction materials (e.g., concrete, cement, brick, steel, wood, glass, and plastic) and heavy machinery and excluded activities that had little effect on the results or for which data were lacking [43,44]. The study of Nuri Cihat et al. (2014) [45] extended the carbon source tracking pathway for building materials transportation and proposed a scope-based carbon footprint analysis to track the GHG emissions throughout the supply chain. Peng (2015) [46] and Seo et al. (2016) [47] divided the carbon emissions from construction waste disposal into three stages: transportation, disposal, and landfill for detailed calculations.

In terms of active citing publications, Zhang et al. (2021) [48] extended the system boundaries of the "cradle-to-site" assessment model by considering auxiliary construction materials. In addition, Hong et al. (2015) [33] divided the CECS into direct carbon emissions and indirect carbon emissions. A number of researchers argue that the calculation should not consider the materials that make up the building itself [49,50]. But Su et al. (2016) [51] pointed out that the ideal system boundary using the inventory analysis processing method should include the production and transportation of raw materials. Several researchers have focused on the carbon emissions of modular components during the factory manufacturing stage, because prefabricated buildings offload some of the labor of cast-in-place construction to factories [52,53].

(2) KD2 "CECS assessment framework" = cluster #2 "life cycle assessment (LCA)" + cluster #3 "embodied carbon" + cluster #8 "reinforced concrete slab" + cluster #13 "data representativeness" + cluster #14 "life cycle CO_2"

In this knowledge domain, researchers have developed various methods for calculating CECS. In the most cited article, Chau et al. (2015) [34] used a process-based method to assess the embedded carbon emissions. There are typically two formulas for calculating carbon emissions. One is to multiply the activity data by the emission factor corresponding to the activity, and the other is to multiply the energy consumed by the activity by the carbon emission factor of the corresponding energy. As for the active citing articles, Zhang et al. (2021) [48] used the input-output method to calculate the embedded carbon emissions of auxiliary building materials that lacked process-level carbon emission factors. In general, there are three main calculation methods for calculating CECS, process-based method(PBM) [54,55], input-output method(IOM) [56–58], and hybrid method(HM) [59,60]. Current interpretation and quantification processes have been widely and experimentally explored in qualitative terms, notably in the combination of PBM and IOM [61,62].

(3) KD3 “BIM-integrated evaluation framework” = cluster #5 “building information modeling” + cluster #6 “embodied environment impact”

BIM has a fine-grained ontology model and a database containing rich semantic information that provides practical material information, such as material quantities and composition [63]. As a result, time-consuming and error-prone human operations can be avoided by having BIM generate an exact bill of quantities automatically [64].

For highly cited articles, Peng used BIM to provide basic material amount information and hence calculate CECS. At the same time, Li et al. (2021) [65] employed BIM-related software to carry out digital information simulations to obtain the consumptions such as building materials, machinery shifts, and labor. Various intelligent methods are utilized to enhance data collecting and processing during carbon emission assessments. The visualization impact of a BIM model is superior. Wong et al. (2013) [66] used virtual prototyping and mixed reality technologies to “try before you build” or “construct the building many times” before the project started, and exported schedule information and 3D models via Autodesk NavisWorks to the simulation, where they were converted into 4D models. An assessment of carbon emissions based on BIM can also use schedule management and cost management details to visualize the time and space of carbon emissions and calculate their intensity [67].

Integration of BIM and LCA to estimate CECS is a hot topic. A connection between the compiled LCA database and the BIM model was automatically set up using the Dynamo development plugin [68]. The overall implied impact of different construction scenarios on a building can be calculated by multiplying the building components’ environmental impact quantities (possibly volume, weight, and cost) in BIM by the respective environmental impact factors in the LCA database. Construction carbon assessments can be streamlined through BIM by capturing graphical information about the building’s constituent elements and materials [69]. Construction and demolition waste can be predicted and disposed of using information technology based on BIM and scientific logistics networks [70]. Liu et al. (2015) [71] looked at BIM in reducing construction waste, including construction waste minimization, design waste minimization, and on-site and demolition waste management.

(4) KD4 “carbon reduction” = cluster #0 “construction” + cluster #4 “climate change” + cluster #7 “modular construction”

For the most cited article, Mao et al. (2013) [32] found that there are three key ways to cut GHG emissions. The first is to reduce the number of steel pre-built elements by optimizing the design of the reinforced connections of the elements. The second is to develop a reasonable and cost-effective ratio of concrete to brick on the exterior walls. The third is to pick a factory that is close to the project or a material distribution hub. Hong et al. (2015) [33] also made three recommendations. To increase compatibility, create a uniform conversion formula for carbon emission inventory and traditional bills of quantities. Second, emphasize local raw materials, prefabricated components, secondary processed construction goods, and low-impact construction procedures. Third, highlight realistic construction management solutions for equipment use, people activities, and transportation. Prefabricated steel construction material reuse was shown to be promising [72].

The active citing articles [34] summarized four major categories of shortcomings of LCA in carbon emission studies, including boundary scope, methodological framework, database inventory, and practice. According to Andersen et al. (2021) [73], wood has good carbon sequestration capacity, and it should be used more in buildings to reduce implicit GHG emissions. Cross-laminated timber is a low-carbon alternative to steel/concrete [74]. Javed et al. (2020) [75] proved that compressed lime-bentonite clay bricks made from locally available materials provide better energy efficiency, sustainability, and eco-friendliness. Furthermore, Yoon et al. (2018) [76] proposed a sustainable design approach that sets objective functions for cost, embodied energy, and CO_2 emissions, and performs extensive optimization analysis.

4. Discussion

Despite numerous CECS research, the available results have not been subjected to a quantitative and thorough study. Therefore, based on the foregoing bibliometric review and in-depth content analysis, a comprehensive knowledge map of CECS is proposed (Figure 8). The next section discusses the study's essential components, present research gaps, and future studies.

4.1. Critical Research Parts of CECS

The four major study components of CECS, including scope definition, data collection, assessment methods, and carbon reduction strategies, are all represented in the framework, as shown in Figure 8. The current status of their research is described below:

4.1.1. Sources Definition

The definition of carbon sources is the first step in CECS studies, which serves as the basis for quantification and assessment. Sources of CECS are related to the system boundaries studied, greenhouse gases considered, projects involved in the construction phase, and the quantified construction space.

System boundaries are designed to delineate the boundaries between CECS-related activities and the outside world while determining the amount and type of activities [11]. The system boundaries of CECS studies differ in two ways. First, it is unclear how far upstream and downstream the study extends during the construction phase [77,78]. Another point is whether the study considers the whole building [32,54,79] or only a divisional work [80,81], a subdivision [82–84] or even a component [80,85]. There are six kinds of greenhouse gases stipulated in the Kyoto Protocol, and GHG that affect global warming are mainly CO_2, CH4, and N2O [86]. Among them, CO_2 produces 55 % of the greenhouse effect, and there is an increasing trend year by year. Previous researchs only consider CO_2 [2] or major greenhouse gases, and some also conduct environmental assessments of greenhouse gases and non-greenhouse gases [84,87]. CECS studies are often based on actual projects, which are unique due to factors such as different structural types [88–90], different building functions, and different construction methods [91,92]. CECS quantified space is a general term for all spatial sites where carbon emissions are generated by the construction of buildings or components. The embodied carbon emissions have been scrutinized in recent years [93–95].

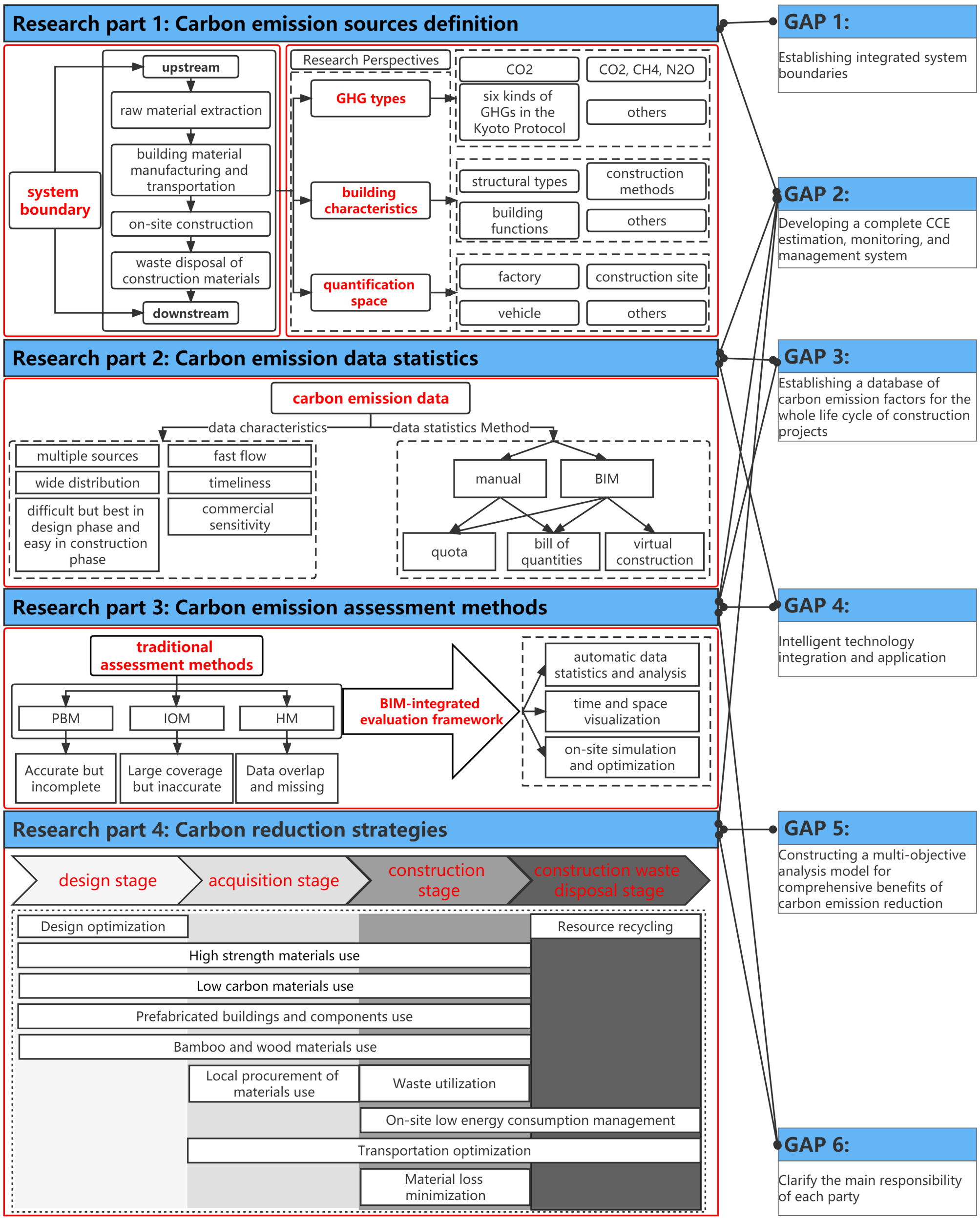

Figure 8. Knowledge map for construction phase carbon emissions research.

4.1.2. Data Statistics

High-quality CECS data is the foundation of all carbon emission reduction efforts. Data quality is the key to building a policy system that promotes effective carbon emission reduction targets. CECS data have the following characteristics:

(1) Multiple sources. Under the common design-bid-construction model, primary building materials are selected by the general contractor or owner, labor subcontracts select auxiliary materials, and finishing materials are often selected by the owner, suggesting that statistical information on materials needs to be coordinated by multiple sources.

(2) Wide distribution. The delivery of materials, the transfer of construction trash, the use of on-site construction machinery and equipment, as well as the on-site office, are all sources of carbon emissions at the job site.

(3) Fast flow. The carbon source data is not only at the edges of the construction site, but also in the supply chain and, in the case of assembled buildings, in prefabrication

plants. In addition, construction materials, machinery, and equipment constantly flow during construction, and the carbon source rushes with them.

(4) Difficult but best in the design phase and easy in the construction phase. Detailed and accurate data (such as construction log, bill of quantities, etc.) can be collected during construction but not during the most meaningful design phase for carbon reduction [96], which means that the traditional carbon assessment cannot provide timely feedback and guidance on how to improve carbon emissions in construction effectively.

(5) Timeliness. The artificial statistical data has timeliness, as a batch of materials procurement costs is different at different times, and the fuel price of construction equipment consumption also fluctuates, which is easy to cause errors based on production analysis.

(6) Commercial sensitivity. The collection of CECS data requires the relevant parties to be responsible for the authenticity, accuracy, and completeness of their respective carbon emission data. Project participants may refuse to share information due to concerns about technology leaks to competitors, potential violations becoming known to the supervising party, etc. Therefore, the communication and integration of information among and within stakeholders must be carefully handled.

4.1.3. Assessment Methods

Traditional LCA evaluation approaches, such as PBM, IOM, and HM, still have several limitations for calculating [46].

The basic concept of PBM for calculating carbon emissions is "Emission = Quantity × Coefficient" [97]. There are two ways to obtain the material, fuel, and electricity consumption: bill of quantities and building information model [98]. PBM permits an accurate and detailed study of a specific product but ignores indirect contributions from higher upstream processes, which can result in a large underestimation of total impacts [45]. Additionally, a complete library of carbon emission factors and detailed information on the construction process are both required for the process-based method. Carbon emission factors of the same building material may vary depending on the manufacturer, production process, raw material supply chain, etc. The use of industry averages is not conducive to the promotion of green building materials.

Theoretically, IOM systematically examines not only the direct environmental impact of the analyzed product or service but also all the indirect consequences involved in the supply chain [99]. Unlike the process-based approach, it does not have problems with truncation bias [54,56]. As a result, the average published estimate of the IO model is higher than that of the process-based model. IOM requires statistics on the cost of materials, transport costs, the monetary value of machinery, etc., from bills of quantities and construction quotas, as well as access to parameters such as emission intensity. However, IOM inherits uncertainty, data aggregation, homogeneity assumption, age of data, and capital equipment [100].

As seen from the above analysis, HM combining PBM and IOM's advantages would be a feasible option. However, this approach suffers from two drawbacks. Firstly, there are truncation errors when combining process-based and input-output data, resulting in the omission or double-counting of specific data [101]. Secondly, the hybrid strategy is well-known for its data and time needs [77,102].

A BIM-integrated evaluation framework has outstanding advantages in automatic data statistics and analysis, time and space visualization, on-site simulation, and optimization, but it is rarely used in practical engineering.

4.1.4. Carbon Reduction Strategies

The construction sector is beginning to show interest in incorporating carbon assessment thinking into building design and construction. As a result, a greater knowledge of the CECS reduction potentials of various solutions is highly relevant and necessary [103].

Concrete is the world's most frequently used building material, producing 14 billion m^3 per year and accounting for 6–10% of global anthropogenic CO_2 emissions. Reducing cement consumption is the most effective way to reduce the carbon footprint of concrete, so cement replacement has also received a great deal of scholarly attention [104]. Develop sustainable concrete alternatives to conventional concrete, such as fly ash as an alternative to ordinary Portland cement [105,106]. Some scholars have used parametric design methods to reduce emissions by enhancing the utilization of concrete and steel [107–111]. Other studies indicated that sourcing local materials can reduce emissions from off-site transportation [24,112]. Construction waste recycling not only extends the life of construction materials but also reduces carbon emissions during the transportation and disposal of construction waste [113–115].

As renewable resources and carbon-sequestering materials, wood and bamboo are widely used. According to Sandanayake et al. (2018) [116], timber use reduces embodied and transport greenhouse gas emissions during construction. Chen et al. (2021) [117] also suggested improved logistics, manufacturing optimization, and local sourcing as ways to cut carbon emissions. The glued timber and sawn timber value chains have a more positive sustainability impact than cast-in-place concrete and precast reinforced concrete [118]. Since China consumes over 50% of its timber from abroad, carbon emissions from the imported timber supply chain are of concern [119]. The short growth cycle, hardness, and water resistance of bamboo make it the ideal material for saving timber and replacing wood. Xu et al. (2022) [120] calculated the carbon emissions and storage of bamboo and verified the vital role of bamboo promotion in carbon reduction.

On construction sites, carbon reduction strategies can be divided into two categories: on the one hand, more effective planning, management, and utilization of mechanical equipment can cut down fuel and power consumption and improve site management to reduce waste of materials and energy [121,122]. Alternatively, we should promote new construction technologies, such as prefabricated assembly buildings [32,52,67,123], 3D concrete printing technology [124,125], and Post-Tensioned in situ construction methods [126], to reduce waste on site and increase productivity.

4.2. *Knowledge Gaps and Future Research*

This analysis reveals topics that still require further research by evaluating CECS-related literature from 2000 to 2022. According to Figure 8, six knowledge gaps as well as their future directions are explored.

4.2.1. Establishing Integrated System Boundaries

The first knowledge gap is related to the lack of comprehensive system boundaries. The subjective nature of system boundary definitions is one of the reasons for incomplete, inaccurate, and unrepresentative study data [11]. Since there is currently no agreement in the literature on what constitutes a standard system boundary model and what should be contained in a CECS study, future research should focus on developing a comprehensive system boundary definition model [127]. This future endeavor has two purposes. To begin, it must include a lucid and exhaustive summary of recent research on boundary definitions. Researchers will be able to determine whether this boundary definition is feasible and the limitations of tracking CECS using this model. In this case, existing computational methods can be optimized or appropriate computational methods can be developed. Additionally, it will provide an approach to quantify buildings' embodied carbon emissions. A model of the system boundary could be developed to facilitate the conversion of carbon emission data at different scope levels (building materials, components, divisional works, the whole building, etc.).

4.2.2. Develop a Complete CECS Estimation, Monitoring, and Management System

The second knowledge gap is that data statistics are time-consuming and costly, while data reliability and comprehensiveness are difficult to guarantee. Managing CECS shouldn't end with evaluating carbon emissions after implementing a project. Additionally, project parties need to manage carbon emissions and optimize project plans before and during implementation [78,128]. In addition, the CECS accounting system should guide the accounting parties to complete pre-project carbon emission projections and CECS monitoring. BIM-based assessment methods can predict CECS at the planning and design stage, while GIS, BIM, and IoT technologies can be used to monitor, visualize, communicate, and analyze carbon emissions from construction activities in real-time, and to display the spatial distribution and dynamic changes of CECS using an intuitive interface [53,67]. The evaluation methods and auditing standards for domestic low-carbon buildings should be established as soon as possible to provide guidelines for design agencies, construction units, real estate developers, etc. Promote the formation of novel low-carbon design strategies and technology systems, and at the same time urge the emission reduction actions of various construction-related industries to achieve carbon reduction goals [129].

4.2.3. Establishing a Database of Carbon Emission Factors for the Whole Life Cycle of Construction Projects

The third knowledge gap is the imperfection of carbon emission factor libraries. While the quantitative system is being established, to ensure the reliability of the data sources and the results of the calculation in the application of the system, it is also suggested that the state should start from the macro policy and step up the research, collation and statistics on the energy consumption data, transportation channels and raw material inputs of all domestic industries, to build and continuously improve the database of carbon emission factors in China.

4.2.4. Intelligent Technology Integration and Application

The fourth knowledge gap is caused by a lack of comprehensive control over CECS, which leads to ambiguity. Nahangi et al. (2021) [96] confirmed the high model requirements for BIM-based assessments and highlighted the challenges and resulting uncertainties of accurately and completely quantifying material and energy use on site. Therefore, it is necessary to control CECS more comprehensively. The use of more intelligent technologies for monitoring and managing CECS sustainability is recommended in future studies [130]. In the future, greater attention should be focused on developing more accurate, comprehensive, and systematic tools for the automatic collection, analysis, and visualization of emission data.

4.2.5. Constructing a Multi-Objective Analysis Model for Comprehensive Benefits of Carbon Emission Reduction

The fifth knowledge gap concerns the direct or indirect impacts of low-carbon construction on all its stakeholders in practical application, and there are no analytical models that consider the environmental, economic, social, and other benefits of low-carbon construction [4]. The construction of a multi-objective analysis model for the comprehensive benefits of carbon reduction in future studies will allow the selection of factors to be considered according to the researcher's needs and the optimal reduction strategy to be derived from the analysis model.

4.2.6. Clarify the Main Responsibility of Each Party

The sixth knowledge gap is the need for more clarity on the responsibilities of all parties in implementing low-carbon construction. Most low-carbon construction cases are used as demonstration projects, but few are applied in daily buildings [131]. Low carbon pathways in buildings are implemented by four parties: government, owner, designer, and constructor. The lack of chain management responsibility and top management commitment may be fundamental barriers to low-carbon construction [34].

5. Conclusions and Implications

Construction of building projects emits a large number of greenhouse gases into the environment within a short time frame and in a concentrated manner. Therefore, it is of great significance to accurately measure carbon emissions at this stage and to formulate corresponding emission reduction measures, which is a key link to realizing energy saving and emission reduction in the construction industry and is the basis for quantitative analysis of low-carbon construction. The goal of this bibliometric and content evaluation is to identify the current state and future trends in carbon emissions research in construction. Through targeted search and screening, 563 articles from 2000 to 2022 were collected from the WoS core database.

In terms of time, research on carbon emissions in the construction stage has passed through three phases: the initial exploration period (2000–2011), the steady development period (2012–2016), and the rapid growth period (2017–2022). Regarding the spatial distribution of institutions, most studies originated in China, Australia, the United States, South Korea, and the United Kingdom. In addition, the institutions conducting carbon emission research are relatively dispersed. The statistics of the Web of Science categories show that environment, architecture, sustainability, and engineering are the main research themes. In terms of keywords, "life cycle assessment", "embodied energy", "energy", "impact", and "embodied carbon" appeared most frequently. A keyword timeline view is used to understand each hotspot's duration and past research hotspots.

According to the literature co-citation network, 13 clusters are identified. This study divides them into four knowledge domains: sources definition, data statistics, assessment methods, and carbon reduction strategies. Based on the above bibliometric and content analysis, a knowledge map is proposed. The key research components on carbon emissions at the construction stage are discussed in detail, including sources definition, data statistics, assessment methods, and carbon reduction strategies. In addition, the key research components in system boundary definition, data statistics, carbon emission factor library establishment, and data uncertainty. Immediately after that, knowledge gaps in system boundary definition, data statistics, carbon emission factor database establishment, data uncertainty, emission reduction strategy development, and emission reduction responsibility analysis are also identified. Finally, a future research agenda is proposed. (1) establishing integrated system boundaries, (2) developing a complete carbon emission estimation, monitoring, and management system, (3) establishing a database of carbon emission factors for the whole life cycle of construction projects, (4) intelligent technology integration and application, (5) constructing a multi-objective analysis model for the comprehensive benefits of carbon emission reduction, and (6) clarifying the main responsibility of each party.

Author Contributions: Conceptualization, L.L. and Y.Q.; methodology, L.L. and Y.Q.; software, Z.J. (Zhiwen Jiang); validation, Y.W., J.S. and Z.J. (Zhangzhang Jiang); formal analysis, Y.W.; investigation, Y.W. and Z.J. (Zhiwen Jiang); resources, Y.W. and Z.J. (Zhiwen Jiang); data curation, Z.J. (Zhiwen Jiang); writing—original draft preparation, Y.W.; writing—review and editing, Y.W., L.L., Y.Q. and Z.J. (Zhiwen Jiang); visualization, Z.J. (Zhiwen Jiang), J.S. and Z.J. (Zhangzhang Jiang); supervision, L.L. and Y.Q.; project administration, L.L. and Y.Q.; funding acquisition, L.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (Grant number: NSFC-71901120).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets generated and analyzed for this study can be requested from the correspondence authors at lilingzhi5566@njtech.edu.cn (Li, L.).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Skillington, K.; Crawford, R.H.; Warren-Myers, G.; Davidson, K. A review of existing policy for reducing embodied energy and greenhouse gas emissions of buildings. *Energy Policy* **2022**, *168*, 112920. [CrossRef]
2. Kim, J.; Koo, C.; Kim, C.J.; Hong, T.; Park, H.S. Integrated CO_2, cost, and schedule management system for building construction projects using the earned value management theory. *J. Clean. Prod.* **2015**, *103*, 275–285. [CrossRef]

3. Li, L.; Chen, K. Quantitative assessment of carbon dioxide emissions in construction projects: A case study in Shenzhen. *J. Clean. Prod.* **2017**, *141*, 394–408. [CrossRef]
4. Akbarnezhad, A.; Xiao, J. Estimation and Minimization of Embodied Carbon of Buildings: A Review. *Buildings* **2017**, *7*, 5. [CrossRef]
5. Fenner, A.E.; Kibert, C.J.; Woo, J.; Morque, S.; Razkenari, M.; Hakim, H.; Lu, X. The carbon footprint of buildings: A review of methodologies and applications. *Renew. Sustain. Energy Rev.* **2018**, *94*, 1142–1152. [CrossRef]
6. Chen, Y.; Zhou, Y.; Feng, W.; Fang, Y.; Feng, A. Factors That Influence the Quantification of the Embodied Carbon Emission of Prefabricated Buildings: A Systematic Review, Meta-Analysis and the Way Forward. *Buildings* **2022**, *12*, 1265. [CrossRef]
7. Sizirici, B.; Fseha, Y.; Cho, C.S.; Yildiz, I.; Byon, Y.J. A Review of Carbon Footprint Reduction in Construction Industry, from Design to Operation. *Materials* **2021**, *14*, 6094. [CrossRef]
8. Lu, W.; Tam, V.W.Y.; Chen, H.; Du, L. A holistic review of research on carbon emissions of green building construction industry. *Eng. Constr. Archit. Manag.* **2020**, *27*, 1065–1092. [CrossRef]
9. Joseph, V.R.; Mustaffa, N.K. Carbon emissions management in construction operations: A systematic review. *Eng. Constr. Archit. Manag.* **2021** . [CrossRef]
10. Wang, B.Z.; Zhu, Z.H.; Yang, E.; Chen, Z.; Wang, X.H. Assessment and management of air emissions and environmental impacts from the construction industry. *J. Environ. Plan. Manag.* **2018**, *61*, 2421–2444. [CrossRef]
11. Dixit, M.K.; Culp, C.H.; Fernández-Solís, J.L. System boundary for embodied energy in buildings: A conceptual model for definition. *Renew. Sustain. Energy Rev.* **2013**, *21*, 153–164. [CrossRef]
12. Wu, P.; Xia, B.; Pienaar, J.; Zhao, X. The past, present and future of carbon labelling for construction materials—A review. *Build. Environ.* **2014**, *77*, 160–168. [CrossRef]
13. Kang, G.; Kim, T.; Kim, Y.W.; Cho, H.; Kang, K.I. Statistical analysis of embodied carbon emission for building construction. *Energy Build.* **2015**, *105*, 326–333. [CrossRef]
14. Li, W.; Zhao, Y. Bibliometric analysis of global environmental assessment research in a 20-year period. *Environ. Impact Assess. Rev.* **2015**, *50*, 158–166. . [CrossRef]
15. Bhatt, Y.; Ghuman, K.; Dhir, A. Sustainable manufacturing. Bibliometrics and content analysis. *J. Clean. Prod.* **2020**, *260*, 120988. [CrossRef]
16. Jussila, J.; Nagy, E.; Lähtinen, K.; Hurmekoski, E.; Häyrinen, L.; Mark-Herbert, C.; Roos, A.; Toivonen, R.; Toppinen, A. Wooden multi-storey construction market development—Systematic literature review within a global scope with insights on the Nordic region. *Silva Fenn.* **2022**, *56*, 10609. [CrossRef]
17. He, C.; Hou, Y.; Ding, L.; Li, P. Visualized literature review on sustainable building renovation. *J. Build. Eng.* **2021**, *44*, 102622. [CrossRef]
18. Li, Y.; Li, M.; Sang, P. A bibliometric review of studies on construction and demolition waste management by using CiteSpace. *Energy Build.* **2022**, *258*, 111822. [CrossRef]
19. Liu, H.; Yu, Z.; Chen, C.; Hong, R.; Jin, K.; Yang, C. Visualization and bibliometric analysis of research trends on human fatigue assessment. *J. Med. Syst.* **2018**, *42*, 1–12. [CrossRef]
20. Zhao, X.; Ke, Y.; Zuo, J.; Xiong, W.; Wu, P. Evaluation of sustainable transport research in 2000–2019. *J. Clean. Prod.* **2020**, *256*, 120404. [CrossRef]
21. Li, L.; Liao, S.; Yuan, J.; Wang, E.; She, J. Analyzing Healthcare Facility Resilience: Scientometric Review and Knowledge Map. *Front. Public Health* **2021**, *9*, 764069. [CrossRef] [PubMed]
22. Shipworth, D. A stochastic framework for embodied greenhouse gas emissions modelling of construction materials. *Build. Res. Inf.* **2002**, *30*, 16–24. [CrossRef]
23. González, M.J.; García Navarro, J. Assessment of the decrease of CO_2 emissions in the construction field through the selection of materials: Practical case study of three houses of low environmental impact. *Build. Environ.* **2006**, *41*, 902–909. [CrossRef]
24. Ng, S.T.; Wong, J.M.W.; Skitmore, S.; Veronika, A. Carbon dioxide reduction in the building life cycle: A critical review. *Proc. Inst. Civ. Eng.–Eng. Sustain.* **2012**, *165*, 281–292. [CrossRef]
25. Stadel, A.; Eboli, J.; Ryberg, A.; Mitchell, J.; Spatari, S. Intelligent Sustainable Design: Integration of Carbon Accounting and Building Information Modeling. *J. Prof. Issues Eng. Educ. Pract.* **2011**, *137*, 51–54. [CrossRef]
26. Teng, Y.; Li, K.; Pan, W.; Ng, T. Reducing building life cycle carbon emissions through prefabrication: Evidence from and gaps in empirical studies. *Build. Environ.* **2018**, *132*, 125–136. [CrossRef]
27. Sandanayake, M.; Gunasekara, C.; Law, D.; Zhang, G.; Setunge, S.; Wanijuru, D. Sustainable criterion selection framework for green building materials—An optimisation based study of fly-ash Geopolymer concrete. *Sustain. Mater. Technol.* **2020**, *25*, e00178. [CrossRef]
28. Gan, V.J.L.; Wong, C.L.; Tse, K.T.; Cheng, J.C.P.; Lo, I.M.C.; Chan, C.M. Parametric modelling and evolutionary optimization for cost-optimal and low-carbon design of high-rise reinforced concrete buildings. *Adv. Eng. Inform.* **2019**, *42*, 100962. [CrossRef]
29. Xu, J.; Deng, Y.; Shi, Y.; Huang, Y. A bi-level optimization approach for sustainable development and carbon emissions reduction towards construction materials industry: A case study from China. *Sustain. Cities Soc.* **2020**, *53*, 101828. [CrossRef]
30. Luo, Z.; Yang, L.; Liu, J. Embodied carbon emissions of office building: A case study of China's 78 office buildings. *Build. Environ.* **2016**, *95*, 365–371. [CrossRef]

31. Zhang, Z.; Wang, B. Research on the life-cycle CO_2 emission of China's construction sector. *Energy Build.* **2016**, *112*, 244–255. [CrossRef]
32. Mao, C.; Shen, Q.; Shen, L.; Tang, L. Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: Two case studies of residential projects. *Energy Build.* **2013**, *66*, 165–176. [CrossRef]
33. Hong, J.; Shen, G.Q.; Feng, Y.; Lau, W.S.t.; Mao, C. Greenhouse gas emissions during the construction phase of a building: A case study in China. *J. Clean. Prod.* **2015**, *103*, 249–259. [CrossRef]
34. Chau, C.K.; Leung, T.M.; Ng, W.Y. A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings. *Appl. Energy* **2015**, *143*, 395–413. [CrossRef]
35. Hou, J.; Yang, X.; Chen, C. Emerging trends and new developments in information science: A document co-citation analysis (2009–2016). *Scientometrics* **2018**, *115*, 869–892. [CrossRef]
36. Zheng, C.; Yuan, J.; Zhu, L.; Zhang, Y.; Shao, Q. From digital to sustainable: A scientometric review of smart city literature between 1990 and 2019. *J. Clean. Prod.* **2020**, *258*, 120689. [CrossRef]
37. Sartori, I.; Hestnes, A. Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy Build.* **2007**, *39*, 249–257. [CrossRef]
38. Dimoudi, A.; Tompa, C. Energy and environmental indicators related to construction of office buildings. *Resour. Conserv. Recycl.* **2008**, *53*, 86–95. [CrossRef]
39. Chen, C.; Hu, Z.; Liu, S.; Tseng, H. Emerging trends in regenerative medicine: A scientometric analysis in CiteSpace. *Expert Opin. Biol. Ther.* **2012**, *12*, 593–608. [CrossRef]
40. Zhong, B.T.; Wu, H.T.; Li, H.; Sepasgozar, S.; Luo, H.B.; He, L. A scientometric analysis and critical review of construction related ontology research. *Autom. Constr.* **2019**, *101*, 17–31. [CrossRef]
41. Chen, C. Expert Review. Science Mapping: A Systematic Review of the Literature. *J. Data Inf. Sci.* **2017**, *2*, 1–40. [CrossRef]
42. Ya Hong, D.; Ng, S.T. A life cycle assessment model for evaluating the environmental impacts of building construction in Hong Kong. *Build. Environ.* **2015**, *89*, 183–191. [CrossRef]
43. Wu, H.J.; Yuan, Z.W.; Zhang, L.; Bi, J. Life cycle energy consumption and CO_2 emission of an office building in China. *Int. J. Life Cycle Assess.* **2011**, *17*, 105–118. [CrossRef]
44. Baek, C.; Park, S.H.; Suzuki, M.; Lee, S.H. Life cycle carbon dioxide assessment tool for buildings in the schematic design phase. *Energy Build.* **2013**, *61*, 275–287. [CrossRef]
45. Nuri Cihat, O.; Murat, K.; Omer, T. Scope-based carbon footprint analysis of U.S. residential and commercial buildings: An input–output hybrid life cycle assessment approach. *Build. Environ.* **2014**, *72*, 53–62. [CrossRef]
46. Peng, C. Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling. *J. Clean. Prod.* **2016**, *112*, 453–465. [CrossRef]
47. Seo, M.S.; Kim, T.; Hong, G.; Kim, H. On-Site Measurements of CO_2 Emissions during the Construction Phase of a Building Complex. *Energies* **2016**, *9*, 599. [CrossRef]
48. Zhang, X.; Zhang, X. Comparison and sensitivity analysis of embodied carbon emissions and costs associated with rural house construction in China to identify sustainable structural forms. *J. Clean. Prod.* **2021**, *293*, 126190. [CrossRef]
49. Boqiang, L.; Hongxun, L. CO_2 mitigation potential in China's building construction industry: A comparison of energy performance. *Build. Environ.* **2015**, *94*, 239–251. [CrossRef]
50. Yao, F.; Liu, G.; Ji, Y.; Tong, W.; Du, X.; Li, K.; Shrestha, A.; Martek, I. Evaluating the Environmental Impact of Construction within the Industrialized Building Process: A Monetization and Building Information Modelling Approach. *Int. J. Env. Res. Public Health* **2020**, *17*, 8396. [CrossRef]
51. Su, X.; Zhang, X. A detailed analysis of the embodied energy and carbon emissions of steel-construction residential buildings in China. *Energy Build.* **2016**, *119*, 323–330. [CrossRef]
52. Kong, A.; Kang, H.; He, S.; Li, N.; Wang, W. Study on the Carbon Emissions in the Whole Construction Process of Prefabricated Floor Slab. *Appl. Sci.* **2020**, *10*, 2326. [CrossRef]
53. Liu, G.; Chen, R.; Xu, P.; Fu, Y.; Mao, C.; Hong, J. Real-time carbon emission monitoring in prefabricated construction. *Autom. Constr.* **2020**, *110*, 102945. [CrossRef]
54. Yan, H.; Shen, Q.; Fan, L.C.H.; Wang, Y.; Zhang, L. Greenhouse gas emissions in building construction: A case study of One Peking in Hong Kong. *Build. Environ.* **2010**, *45*, 949–955. [CrossRef]
55. Liu, G.; Gu, T.; Xu, P.; Hong, J.; Shrestha, A.; Martek, I. A production line-based carbon emission assessment model for prefabricated components in China. *J. Clean. Prod.* **2019**, *209*, 30–39. [CrossRef]
56. Mohamed Abdul Ghani, N.M.A.; Egilmez, G.; Kucukvar, M.; Bhutta, M.K.S. From green buildings to green supply chains. *Manag. Environ. Qual. Int. J.* **2017**, *28*, 532–548. [CrossRef]
57. Chen, J.; Shen, L.; Song, X.; Shi, Q.; Li, S. An empirical study on the CO_2 emissions in the Chinese construction industry. *J. Clean. Prod.* **2017**, *168*, 645–654. [CrossRef]
58. Teh, S.H.; Wiedmann, T.; Castel, A.; de Burgh, J. Hybrid life cycle assessment of greenhouse gas emissions from cement, concrete and geopolymer concrete in Australia. *J. Clean. Prod.* **2017**, *152*, 312–320. [CrossRef]
59. Säynäjoki, A.; Heinonen, J.; Junnonen, J.M.; Junnila, S. Input–output and process LCAs in the building sector: Are the results compatible with each other? *Carbon Manag.* **2017**, *8*, 155–166. [CrossRef]

60. Zhang, X.; Wang, F. Analysis of embodied carbon in the building life cycle considering the temporal perspectives of emissions: A case study in China. *Energy Build.* **2017**, *155*, 404–413. [CrossRef]
61. Ogungbile, A.J.; Shen, G.Q.; Wuni, I.Y.; Xue, J.; Hong, J. A Hybrid Framework for Direct CO_2 Emissions Quantification in China's Construction Sector. *Int. J. Env. Res. Public Health* **2021**, *18*, 11965. [CrossRef] [PubMed]
62. Li, H.; Luo, Z.; Xu, X.; Cang, Y.; Yang, L. Assessing the embodied carbon reduction potential of straw bale rural houses by hybrid life cycle assessment: A four-case study. *J. Clean. Prod.* **2021**, *303*, 127002. [CrossRef]
63. Zhou, Y.W.; Hu, Z.Z.; Lin, J.R.; Zhang, J.P. A review on 3D spatial data analytics for building information models. *Arch. Comput. Methods Eng.* **2020**, *27*, 1449–1463. [CrossRef]
64. Teng, Y.; Xu, J.; Pan, W.; Zhang, Y. A systematic review of the integration of building information modeling into life cycle assessment. *Build. Environ.* **2022**, *221*, 109260. [CrossRef]
65. Li, X.J.; Lai, J.y.; Ma, C.y.; Wang, C. Using BIM to research carbon footprint during the materialization phase of prefabricated concrete buildings: A China study. *J. Clean. Prod.* **2021**, *279*, 123454. [CrossRef]
66. Wong, J.K.W.; Li, H.; Wang, H.; Huang, T.; Luo, E.; Li, V. Toward low-carbon construction processes: The visualisation of predicted emission via virtual prototyping technology. *Autom. Constr.* **2013**, *33*, 72–78. [CrossRef]
67. Ding, Z.; Liu, S.; Luo, L.; Liao, L. A building information modeling-based carbon emission measurement system for prefabricated residential buildings during the materialization phase. *J. Clean. Prod.* **2020**, *264*, 121728. [CrossRef]
68. Martin, R.; Alexander, H.; Guillaume, H.; Alexander, P. LCA and BIM: Visualization of environmental potentials in building construction at early design stages. *Build. Environ.* **2018**, *140*, 153–161. [CrossRef]
69. Soust-Verdaguer, B.; Llatas, C.; García-Martínez, A. Critical review of bim-based LCA method to buildings. *Energy Build.* **2017**, *136*, 110–120. [CrossRef]
70. Shi, Y.; Xu, J. BIM-based information system for econo-enviro-friendly end-of-life disposal of construction and demolition waste. *Autom. Constr.* **2021**, *125*, 103611. [CrossRef]
71. Liu, Z.; Osmani, M.; Demian, P.; Baldwin, A. A BIM-aided construction waste minimisation framework. *Autom. Constr.* **2015**, *59*, 1–23. [CrossRef]
72. Aye, L.; Ngo, T.; Crawford, R.H.; Gammampila, R.; Mendis, P. Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. *Energy Build.* **2012**, *47*, 159–168. [CrossRef]
73. Andersen, C.E.; Rasmussen, F.N.; Habert, G.; Birgisdóttir, H. Embodied GHG Emissions of Wooden Buildings—Challenges of Biogenic Carbon Accounting in Current LCA Methods. *Front. Built Environ.* **2021**, *7*, 729096. [CrossRef]
74. Younis, A.; Dodoo, A. Cross-laminated timber for building construction: A life-cycle-assessment overview. *J. Build. Eng.* **2022**, *52*, 104482. [CrossRef]
75. Javed, U.; Khushnood, R.A.; Memon, S.A.; Jalal, F.E.; Zafar, M.S. Sustainable incorporation of lime-bentonite clay composite for production of ecofriendly bricks. *J. Clean. Prod.* **2020**, *263*, 121469. [CrossRef]
76. Yoon, Y.C.; Kim, K.H.; Lee, S.H.; Yeo, D. Sustainable design for reinforced concrete columns through embodied energy and CO_2 emission optimization. *Energy Build.* **2018**, *174*, 44–53. [CrossRef]
77. Omar, W.M.S.W.; Doh, J.H.; Panuwatwanich, K.; Miller, D. Assessment of the embodied carbon in precast concrete wall panels using a hybrid life cycle assessment approach in Malaysia. *Sustain. Cities Soc.* **2014**, *10*, 101–111. [CrossRef]
78. Sandanayake, M.; Zhang, G.; Setunge, S.; Luo, W.; Li, C.Q. Estimation and comparison of environmental emissions and impacts at foundation and structure construction stages of a building—A case study. *J. Clean. Prod.* **2017**, *151*, 319–329. [CrossRef]
79. Wang, S.; Sinha, R. Life Cycle Assessment of Different Prefabricated Rates for Building Construction. *Buildings* **2021**, *11*, 552. [CrossRef]
80. Wang, H.; Zhang, H.; Hou, K.; Yao, G. Carbon emissions factor evaluation for assembled building during prefabricated component transportation phase. *Energy Explor. Exploit.* **2020**, *39*, 385–408. [CrossRef]
81. Zhang, X.; Zhang, X. Sustainable design of reinforced concrete structural members using embodied carbon emission and cost optimization. *J. Build. Eng.* **2021**, *44*, 102940. [CrossRef]
82. Lyu, F.; Shao, H.; Zhang, W. Comparative analysis about carbon emission of precast pile and cast-in-situ pile. *Energy Rep.* **2022**, *8*, 514–525. [CrossRef]
83. Liu, T.Y.; Ho, S.J.; Tserng, H.P.; Tzou, H.K. Using a Unique Retaining Method for Building Foundation Excavation: A Case Study on Sustainable Construction Methods and Circular Economy. *Buildings* **2022**, *12*, 298. [CrossRef]
84. Li, X.J.; Zheng, Y.d. Using LCA to research carbon footprint for precast concrete piles during the building construction stage: A China study. *J. Clean. Prod.* **2020**, *245*, 118754. [CrossRef]
85. Xu, K.; Kang, H.; Wang, W.; Jiang, P.; Li, N. Carbon Emission Estimation of Assembled Composite Concrete Beams during Construction. *Energies* **2021**, *14*, 1810. [CrossRef]
86. O'Neill, B.C.; Oppenheimer, M. Dangerous climate impacts and the Kyoto Protocol. *Science* **2002**, *296*, 1971–1972. [CrossRef]
87. Xinying, C.; Xiaodong, L.; Yimin, Z.; Zhihui, Z. A comparative study of environmental performance between prefabricated and traditional residential buildings in China. *J. Clean. Prod.* **2015**, *109*, 131–143. [CrossRef]
88. Lin, C.L.; Chiang, W.H.; Weng, Y.S.; Wu, H.P. Assessing the anthropogenic carbon emission of wooden construction: An LCA study. *Build. Res. Inf.* **2022**, 1–20. [CrossRef]
89. Chau, C.K.; Hui, W.K.; Ng, W.Y.; Powell, G. Assessment of CO_2 emissions reduction in high-rise concrete office buildings using different material use options. *Resour. Conserv. Recycl.* **2012**, *61*, 22–34. [CrossRef]

90. Najjar, M.K.; Figueiredo, K.; Evangelista, A.C.J.; Hammad, A.W.A.; Tam, V.W.Y.; Haddad, A. Life cycle assessment methodology integrated with BIM as a decision-making tool at early-stages of building design. *Int. J. Constr. Manag.* **2019**, *22*, 541–555. [CrossRef]
91. Ya Hong, D.; Lara, J.; Peggy, C.; Poon, C.S. Comparing carbon emissions of precast and cast-in-situ construction methods—A case study of high-rise private building. *Constr. Build. Mater.* **2015**, *99*, 39–53. [CrossRef]
92. Han, Q.; Chang, J.; Liu, G.; Zhang, H. The Carbon Emission Assessment of a Building with Different Prefabrication Rates in the Construction Stage. *Int. J. Environ. Res. Public Health* **2022**, *19*, 2366. [CrossRef] [PubMed]
93. Liu, K.; Leng, J. Quantitative research on embodied carbon emissions in the design stage: A case study from an educational building in China. *J. Asian Archit. Build. Eng.* **2022**, *21*, 1182–1192. [CrossRef]
94. Sudarsan, J.S.; Vaishampayan, S.; Parija, P. Making a case for sustainable building materials to promote carbon neutrality in Indian scenario. *Clean Technol. Environ. Policy* **2022**, *24*, 1609–1617. [CrossRef]
95. Son, S.; Park, K.; Fitriani, H.; Kim, S. Embodied CO_2 Reduction Effects of Composite Precast Concrete Frame for Heavily Loaded Long-Span Logistics Buildings. *Sustainability* **2021**, *13*, 1060. [CrossRef]
96. Nahangi, M.; Guven, G.; Olanrewaju, B.; Saxe, S. Embodied greenhouse gas assessment of a bridge: A comparison of preconstruction Building Information Model and construction records. *J. Clean. Prod.* **2021**, *295*, 126388. [CrossRef]
97. Zhang, X.; Wang, F. Stochastic analysis of embodied emissions of building construction: A comparative case study in China. *Energy Build.* **2017**, *151*, 574–584. [CrossRef]
98. Gustavsson, L.; Sathre, R. Variability in energy and carbon dioxide balances of wood and concrete building materials. *Build. Environ.* **2006**, *41*, 940–951. [CrossRef]
99. Rodrigo, M.N.N.; Perera, S.; Senaratne, S.; Jin, X. Review of Supply Chain Based Embodied Carbon Estimating Method: A Case Study Based Analysis. *Sustainability* **2021**, *13*, 9171. [CrossRef]
100. Zhang, X.; Wang, F. Assessment of embodied carbon emissions for building construction in China: Comparative case studies using alternative methods. *Energy Build.* **2016**, *130*, 330–340. [CrossRef]
101. Wan Omar, W.M.S. A hybrid life cycle assessment of embodied energy and carbon emissions from conventional and industrialised building systems in Malaysia. *Energy Build.* **2018**, *167*, 253–268. [CrossRef]
102. Bilec, M.M.; Ries, R.J.; Matthews, H.S. Life-Cycle Assessment Modeling of Construction Processes for Buildings. *J. Infrastruct. Syst.* **2010**, *16*, 199–205. [CrossRef]
103. Malmqvist, T.; Nehasilova, M.; Moncaster, A.; Birgisdottir, H.; Nygaard Rasmussen, F.; Houlihan Wiberg, A.; Potting, J. Design and construction strategies for reducing embodied impacts from buildings—Case study analysis. *Energy Build.* **2018**, *166*, 35–47. [CrossRef]
104. Aboshia, A.M.A.; Rahmat, R.A.; Zain, M.F.M.; Ismail, A. Enhancing mortar strengths by ternary geopolymer binder of metakaolin, slag, and palm ash. *Int. J. Build. Pathol. Adapt.* **2017**, *35*, 438–455. [CrossRef]
105. Sandanayake, M.; Gunasekara, C.; Law, D.; Zhang, G.; Setunge, S. Greenhouse gas emissions of different fly ash based geopolymer concretes in building construction. *J. Clean. Prod.* **2018**, *204*, 399–408. [CrossRef]
106. Amran, M.; Fediuk, R.; Murali, G.; Avudaiappan, S.; Ozbakkaloglu, T.; Vatin, N.; Karelina, M.; Klyuev, S.; Gholampour, A. Fly Ash-Based Eco-Efficient Concretes: A Comprehensive Review of the Short-Term Properties. *Materials* **2021**, *14*, 4264. [CrossRef]
107. Jayasinghe, A.; Orr, J.; Ibell, T.; Boshoff, W.P. Minimising embodied carbon in reinforced concrete flat slabs through parametric design. *J. Build. Eng.* **2022**, *50*, 104136. [CrossRef]
108. Jayasinghe, A.; Orr, J.; Ibell, T.; Boshoff, W.P. Minimising embodied carbon in reinforced concrete beams. *Eng. Struct.* **2021**, *242*, 112590. [CrossRef]
109. Ismail, M.A.; Mueller, C.T. Minimizing embodied energy of reinforced concrete floor systems in developing countries through shape optimization. *Eng. Struct.* **2021**, *246*, 112955. [CrossRef]
110. Choi, S.W.; Oh, B.K.; Park, H.S. Design technology based on resizing method for reduction of costs and carbon dioxide emissions of high-rise buildings. *Energy Build.* **2017**, *138*, 612–620. [CrossRef]
111. Yeo, D.; Potra, F.A. Sustainable Design of Reinforced Concrete Structures through CO_2 Emission Optimization. *J. Struct. Eng.* **2015**, *141*, B4014002. [CrossRef]
112. Atmaca, A.; Atmaca, N. Life cycle energy (LCEA) and carbon dioxide emissions (LCCO2A) assessment of two residential buildings in Gaziantep, Turkey. *Energy Build.* **2015**, *102*, 417–431. [CrossRef]
113. Marey, H.; Kozma, G.; Szabó, G. Effects of Using Green Concrete Materials on the CO_2 Emissions of the Residential Building Sector in Egypt. *Sustainability* **2022**, *14*, 3592. [CrossRef]
114. Bheel, N.; Khoso, S.; Baloch, M.H.; Benjeddou, O.; Alwetaishi, M. Use of waste recycling coal bottom ash and sugarcane bagasse ash as cement and sand replacement material to produce sustainable concrete. *Env. Sci. Pollut. Res. Int.* **2022**, *29*, 52399–52411. [CrossRef] [PubMed]
115. Robayo-Salazar, R.A.; Valencia-Saavedra, W.; Ramirez-Benavides, S.; Mejia de Gutierrez, R.; Orobio, A. Eco-House Prototype Constructed with Alkali-Activated Blocks: Material Production, Characterization, Design, Construction, and Environmental Impact. *Materials* **2021**, *14*, 1275. [CrossRef] [PubMed]
116. Sandanayake, M.; Lokuge, W.; Zhang, G.; Setunge, S.; Thushar, Q. Greenhouse gas emissions during timber and concrete building construction—A scenario based comparative case study. *Sustain. Cities Soc.* **2018**, *38*, 91–97. [CrossRef]

117. Chen, C.X.; Pierobon, F.; Jones, S.; Maples, I.; Gong, Y.; Ganguly, I. Comparative Life Cycle Assessment of Mass Timber and Concrete Residential Buildings: A Case Study in China. *Sustainability* **2021**, *14*, 144. [CrossRef]
118. Žemaitis, P.; Linkevičius, E.; Aleinikovas, M.; Tuomasjukka, D. Sustainability impact assessment of glue laminated timber and concrete-based building materials production chains—A Lithuanian case study. *J. Clean. Prod.* **2021**, *321*, 129005. [CrossRef]
119. Sun, M.; Peng, H.; Wang, S. Cost-Sharing Mechanisms for A Wood Forest Product Supply Chain under Carbon Cap-and-Trade. *Sustainability* **2018**, *10*, 4345. [CrossRef]
120. Xu, X.; Xu, P.; Zhu, J.; Li, H.; Xiong, Z. Bamboo construction materials: Carbon storage and potential to reduce associated CO_2 emissions. *Sci. Total Environ.* **2022**, *814*, 152697. [CrossRef]
121. Kim, B.; Lee, H.; Park, H.; Kim, H. Greenhouse Gas Emissions from Onsite Equipment Usage in Road Construction. *J. Constr. Eng. Manag.* **2012**, *138*, 982–990. [CrossRef]
122. Li, H.X.; Zhang, L.; Mah, D.; Yu, H. An integrated simulation and optimization approach for reducing CO_2 emissions from on-site construction process in cold regions. *Energy Build.* **2017**, *138*, 666–675. [CrossRef]
123. Pervez, H.; Ali, Y.; Petrillo, A. A quantitative assessment of greenhouse gas (GHG) emissions from conventional and modular construction: A case of developing country. *J. Clean. Prod.* **2021**, *294*, 126210. [CrossRef]
124. Batikha, M.; Jotangia, R.; Baaj, M.Y.; Mousleh, I. 3D concrete printing for sustainable and economical construction: A comparative study. *Autom. Constr.* **2022**, *134*, 104087. [CrossRef]
125. Jipa, A.; Dillenburger, B. 3D Printed Formwork for Concrete: State-of-the-Art, Opportunities, Challenges, and Applications. *3D Print. Addit. Manuf.* **2022**, *9*, 84–107. [CrossRef] [PubMed]
126. Miller, D.; Doh, J.H.; Mulvey, M. Concrete slab comparison and embodied energy optimisation for alternate design and construction techniques. *Constr. Build. Mater.* **2015**, *80*, 329–338. [CrossRef]
127. Anand, C.K.; Amor, B. Recent developments, future challenges and new research directions in LCA of buildings: A critical review. *Renew. Sustain. Energy Rev.* **2017**, *67*, 408–416. [CrossRef]
128. Abanda, F.H.; Tah, J.H.M.; Cheung, F.K.T. Mathematical modelling of embodied energy, greenhouse gases, waste, time–cost parameters of building projects: A review. *Build. Environ.* **2013**, *59*, 23–37. [CrossRef]
129. Chen, G.Q.; Chen, H.; Chen, Z.M.; Zhang, B.; Shao, L.; Guo, S.; Zhou, S.Y.; Jiang, M.M. Low-carbon building assessment and multi-scale input–output analysis. *Commun. Nonlinear Sci. Numer. Simul.* **2011**, *16*, 583–595. [CrossRef]
130. Wong, J.K.W.; Zhou, J. Enhancing environmental sustainability over building life cycles through green BIM: A review. *Autom. Constr.* **2015**, *57*, 156–165. [CrossRef]
131. Cabeza, L.F.; Rincón, L.; Vilariño, V.; Pérez, G.; Castell, A. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renew. Sustain. Energy Rev.* **2014**, *29*, 394–416. [CrossRef]