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Review

A review of research on embodied energy of buildings using bibliometric analysis

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ABSTRACT

The share of embodied energy within the total life cycle of a building is expected to increase and become more significant as low energy and net-zero energy buildings become the norm. In the last two decades, many researchers have studied the embodied energy of buildings and published their findings. However, a comprehensive, quantitative analysis of the literature on the embodied energy of buildings is missing. In this study, in order to provide a better understanding of the field as a whole, a bibliometric approach is applied to create a knowledge map and discover more information about the topic. The primary knowledge structure and the topics for study were discovered by analyzing the keywords and abstract terms of 398 papers published from 1996 to 2015. The results show that *life cycle assessment* is the keyword with the greatest frequency of occurrence and *design* is the keyword that has the highest number of co-occurrence relationships with other keywords in the 398 papers. The major three research areas for the embodied energy of buildings are life cycle assessment (LCA), building design, and greenhouse gas emissions. By using the bibliometric method, this study analyzes previous studies to provide new insights into the embodied energy of buildings.

Contents

1. Introduction

Energy and environmental issues have been considered to be major problems globally. On the basis of the World Oil Outlook 2015 report [1], it is estimated that the global energy demand will increase by 49% from 2013 to 2040. Especially for developing countries, fossil fuels are expected to continue to dominate as

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the source of primary energy demand. The rising production of limited and nonrenewable fossil fuels is accelerating the depletion of fossil fuel resources. How long we can continue to use nonrenewable resources to meet the increasing demand for energy with low prices is a concern. Meanwhile, the huge volume of anthropogenic carbon dioxide (CO_2) emissions has caused irreversible environmental changes, including global warming, precipitation-pattern changes, and sea-level rise, all of which could result in severe damage [2]. Because of increasing CO_2 emissions, it has been observed that the global temperature kept increasing since the mid-20th century. Many studies have supported this point or strengthened the view [3–6]. Zhang et al. [7] showed that anthropogenic greenhouse gas (GHG) emissions have an obvious influence on observed precipitation changes within latitudinal bands. A drying mode is already occurring in the Northern Hemisphere subtropics and tropics. Pollard et al. [8] indicated that Antarctica has the potential to contribute more than 1 m of sea level rise by the end of this century if there is no aggressive reduction of GHG emissions. That rise could be disastrous for many low-altitude metropolises, such as New York, Boston, and Miami. Pollard et al.'s estimate is nearly double the earlier Intergovernmental Panel on Climate Change (IPCC) prediction for the future rise in sea level.

As a primary energy consumer and contributor of CO_2 emissions, the construction industry expects to boom in the coming decade [9]. The construction of buildings also consumes a huge amount of natural resources, and that has resulted in a variety of environmental problems. Needless to say, reducing the energy consumption and environmental impact of buildings is an important and urgent issue and has been studied by many researchers in past decades.

The life cycle energy consumed by buildings includes embodied energy and operational energy [10,11]. Some researchers consider embodied energy, operational energy, and demolition energy to be the life cycle energy of buildings [12–14]. However, embodied energy (10%–20%) and operational energy (80%–90%) account for the largest part of the life cycle energy of buildings, whereas demolition energy has a much smaller impact [13].

With a more detailed consideration, the life cycle energy of buildings includes initial embodied energy, operational energy, recurring embodied energy, and decommissioning energy. Fig. 1 shows the energy consumption of buildings through their life cycle period. Initial embodied energy is the energy consumed in the production process of a product, from the extraction of raw materials and processing of natural resources to the manufacturing and transport of a product to a building site. According to Cole [12], initial embodied energy consists of direct energy and indirect energy, which are used to manufacture, transport and install building components. Direct energy is the energy consumed in the process of construction of buildings, and indirect energy is the energy consumption of extracting raw materials and transporting and manufacturing the building materials and products. Operational energy is the energy consumed during the running period of buildings, such as the heating and cooling loads, lighting loads, plug loads, and other miscellaneous appliance loads. Recurring embodied energy includes the energy required to maintain and refurbish buildings during their running period. Decommissioning energy is the energy consumed during deconstruction/demolition of buildings and recycling/disposal of salvaged/waste materials. Fig. 1 also illustrates the different phases of LCA and the processes included. For example, "cradle to gate" includes extraction of raw materials, transportation, and manufacturing processes.

Because operational energy accounts for more than 80% of the total energy consumption during the life cycle period of a traditional building [15], researchers and designers focus primarily on reducing operational energy. However, with the rapid development of building technology, buildings have become increasingly energy efficient, and even net-zero energy buildings are emerging. Many researchers and designers focus on reducing the operational energy to enhance the energy efficiency of buildings. Reducing operational energy can be achieved in many ways, including optimizing building design by such methods as selecting the orientation, choosing the form or applying passive design, using a high-performance envelope (e.g., doors and windows, roofs, exterior walls, etc.) or choosing more efficient equipment (light, HVAC), or even applying renewable energy technologies. Because buildings are becoming increasingly more energy efficient operationally [16–20], the share of embodied energy is expected to increase and become ever more significant over the next 50 years [21,22].

With an increasing awareness of the embodied energy of buildings, many researchers have reviewed different aspects of embodied energy. Dixit et al. [23] identified 10 parameters that influence the quality of measurements of embodied energy, including system boundaries, the method of analysis, geographic location, the form of energy (primary or secondary), the age of the data, the completeness of the data, the manufacturing technology, the feedstock energy, and temporal representation. Moncaster and Song [24] compared the existing data and methodologies for calculating the embodied energy and carbon emissions of buildings. They found that it is necessary to develop a robust methodology for measuring the entire life of embodied energy and carbon emissions of buildings in order to make the outcomes easily comparable. Mohammed et al. [11] compared the difference between operational and embodied emissions in buildings. Their work acknowledged the increasing proportion of the embodied emissions of a building to the building's total energy consumption and that proportion's significance when considering reduction strategies for GHG emissions.

The papers referenced above provide valuable information to help us better understand the research on the embodied energy of buildings. However, due to the abundance of published papers, the researchers were limited in the comprehensiveness of their review and might have been subjective in selecting related papers. By applying a bibliometric analysis, the development and evolving trends of research on the embodied energy of buildings can be studied more explicitly. Bibliometric studies focus on using quantitative measures to analyze the literature in a specific field and have been used by many researchers to isolate the big picture of knowledge on different aspects of their fields. With advances in technology, the bibliometric method can visualize or map the structure and evolution of large-scale bodies of literature by using a quantitative visualization program [25,26]. The method has received more attention and has become a sought-after means of research in analyzing the knowledge domain or visualizing the knowledge structure networks in order to acquire a big picture perspective. For example, Su and Lee [27] applied the bibliometric method in mapping the knowledge structure by keyword network analysis. He et al. [28] discussed the knowledge structure of managerial areas of building information modeling (BIM) by using a keyword network and term cluster analysis. By using a bibliometric analysis, researchers can find the big picture of a field of study through reviewing large quantities of the relevant literature.

The objectives of this paper are to collect and summarize papers that are related to the study of the embodied energy of buildings, to generate a visualized knowledge structure and research status based on keyword co-occurrence and term co-occurrence, and to identify the emerging trends and future research topics based on the accurate analysis of previous studies.

The remainder of this paper is organized as follows: section 2 discusses the research method, which includes information on data collection scheme design, and on data collection and data analysis; section 3 reviews the results and discusses the analysis; and section 4 discusses the major findings and draws the conclusion.

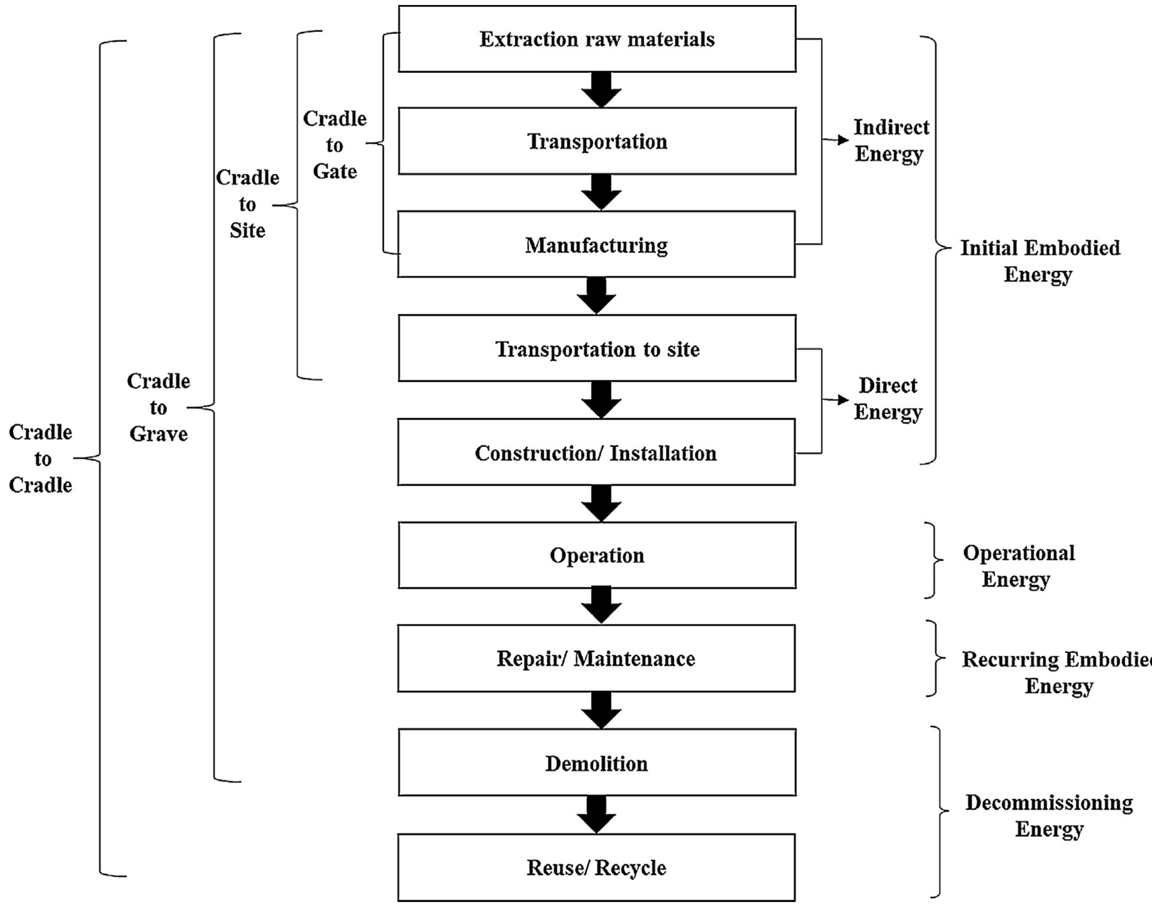

Fig. 1. Energy consumption of buildings through their life cycle period.

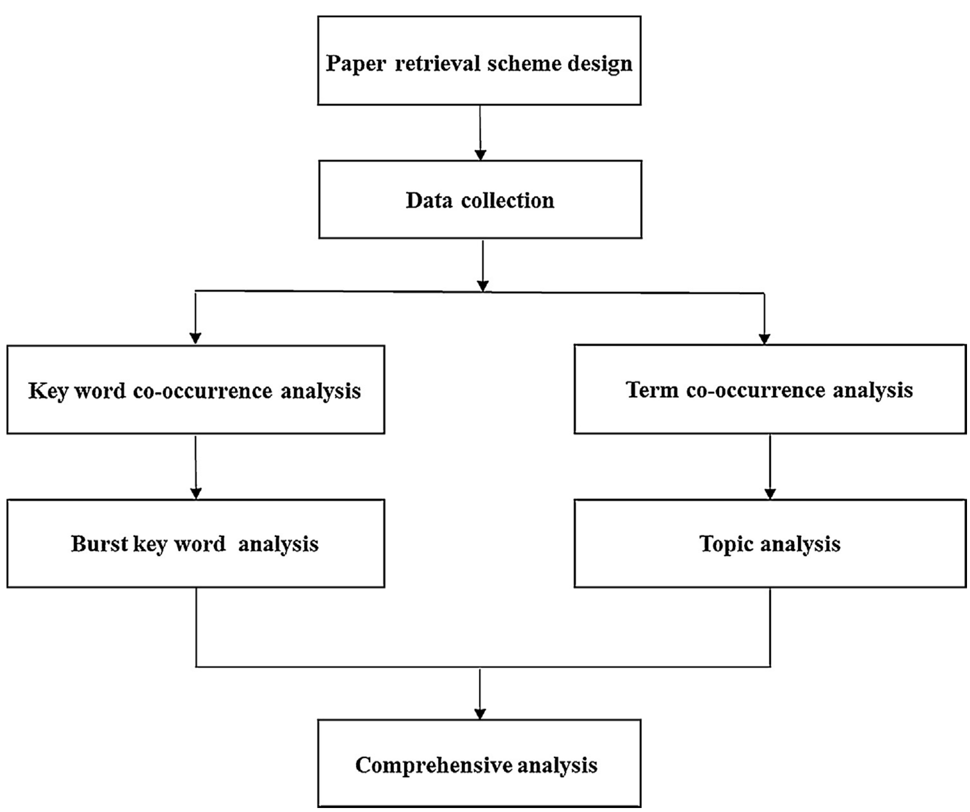

Fig. 2. Research process.

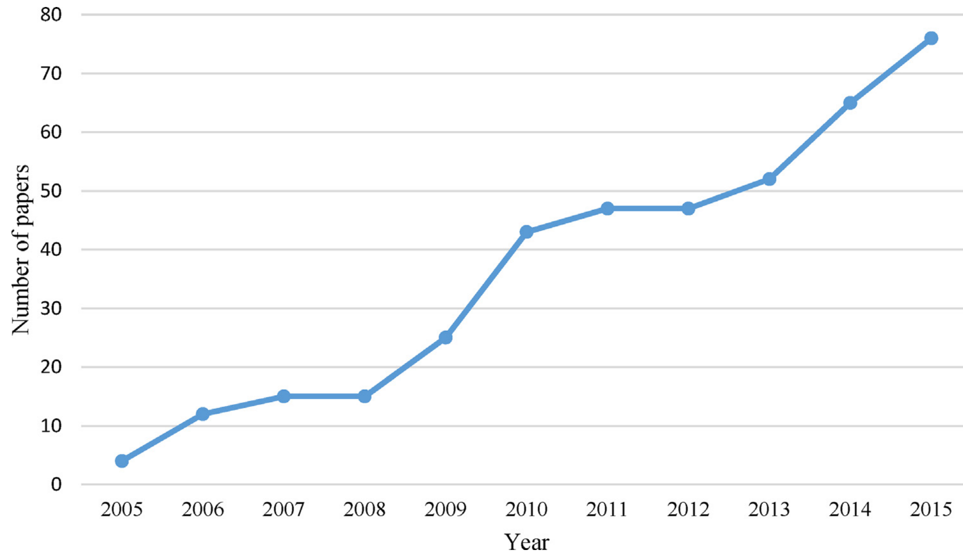

Fig. 3. Distribution of selected papers for the period 2005–2015.

2. Research method

The major focus of this study is to investigate the concept of the embodied energy of buildings. Koskela [29] defined embodied energy as the energy consumed in production of the materials used to create a building. Crowther [30] defined embodied energy as "the total energy required in the creation of a building, including the direct energy used in the construction and assembly process and indirect energy required to manufacture the materials and component of buildings" (p. 2). Considering Crowther's definition, the next step is to design a process for reviewing and analyzing publications, from the last two decades, on the topic of the embodied energy of buildings. This includes designing the proper search scheme, collecting data from searched keywords and abstracts of publications on the Web of Science Core Collection, applying keyword co-occurrence and abstract term co-occurrence analyses, and determining the burst key words and topics for the embodied energy of buildings. The final stage is to construct networks of keywords, topics, and the knowledge structure for the embodied energy of buildings. Fig. 2 illustrates the framework of the research.

2.1. Paper retrieval scheme design

The paper retrieval source for the analysis is the Web of Science Core Collection, which is maintained by Clarivate Analytics. The Web of Science is a multiple-database platform that includes Science Citation Index Expanded (SCI-Expanded), Social Science Citation Index (SSCI), and Arts & Humanities Citation Index (A&HCI). It contains more than 12,000 high-impact international journals and is regularly used by researchers around the world [31]. By searching data in the Web of Science, users can specify a topic and its time span of publication, and can then gather reliable data through keywords or term co-occurrence analysis.

This study searched the Web of Science for the two topics of "embodied energy" and "building or construction." The searching syntax used the Boolean operators "AND" to link the two fields and "OR" to combine the building and construction fields in searching the topics. In addition, the term "building" was followed by an asterisk, "building*," to search for and retrieve the words "building" and "buildings." The "near/0" operator was used as a filter to ensure that only cases with no words between "embodied" and "energy" were retrieved during the search. The types of documents searched were articles and reviews; the time span was set at 1996–2015; the citation indexes selected were SCI-Expanded, SSCI, A&HCI, and Emerging SCI (ESCI); and English was selected as the language of the articles and reviews. Table 1 shows the search parameters for document retrieval.

Table 1
Search data parameters for document retrieval.

Parameter	Settings
Title	(Building* OR Construction*) AND (Embodied near/0 energy)
Type	Article or Review
Time span	1996–2015
Citation Index	SCI-EXPANDED, SSCI, A&HCI, ESCI
Language	English

2.2. Data collection

By using the proposed paper retrieval scheme, 398 papers were identified after duplications and irrelevant papers had been excluded. The papers, including their abstract, title, author, source, and cited-reference information, were exported as Plain Text files to comprise the initial data for further analysis.

A review of the initial data shows rapidly increasing interest in the topic of embodied energy of buildings. As shown in Fig. 3, the publication count soared during the time span 2005–2015. The search results show that only four papers related to the topic were published in 2005, but the number increased to 76 in 2015.

When considering the source of selected papers, most of the papers were published in journals in the fields of building construction and building energy. Fig. 4 shows the distribution of the sources of selected papers. The papers selected from two journals, "Energy and Buildings" and "Building and Environment," account for 28% of the total retrieved papers. The next step was to use a bibliometric technique to analyze the data, map the structure, and identify the main subjects discussed in papers related to the embodied energy of buildings.

2.3. Data analysis

In this study, CiteSpace and Gephi were selected as the bibliometric analysis tools to map and visualize the networks and identify the structure and subjects of the study field. CiteSpace was used as a data-mining tool to generate the networks. Gephi was applied to further analyze the characteristics of the networks. CiteSpace is

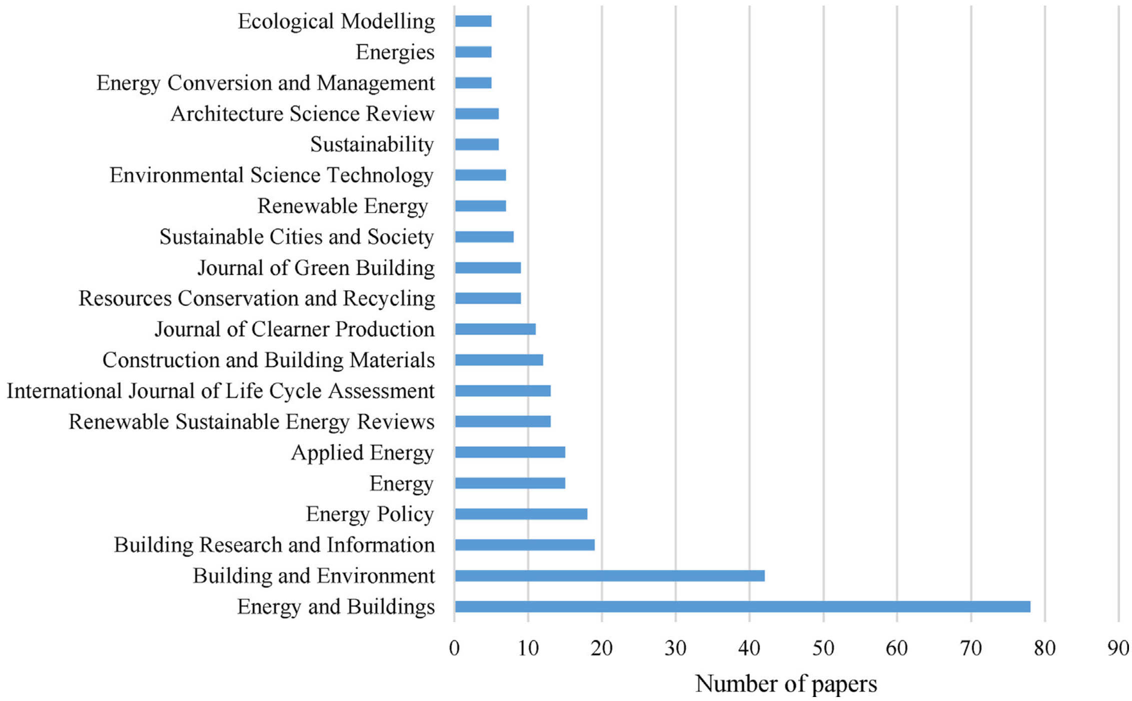

Fig. 4. Distribution of the sources of the retrieved papers.

a software package for visualizing and analyzing knowledge networks in scientific literature. It is designed as a tool for progressive knowledge domain visualization [32]. CiteSpace provides various functions for facilitating the understanding and interpretation of network patterns, including identifying the major topic areas, finding citation hotspots, decomposing a network into clusters, and automatically labeling clusters with terms from selected literature. Gephi is a software tool for graph and network analysis [33]. In this study, CiteSpace graph files were generated and imported into Gephi for further data analysis.

Keywords from the literature are the basic units of a specific field of study, and can provide a view of the knowledge structure and research trends. By using keyword co-occurrence analysis, a network can be mapped. Each node in the network represents a keyword, and the link between the nodes represents the co-occurrence of the keywords. The co-occurrence count is normalized to determine the strength of each link. The Salton's cosine coefficient is used to normalize the co-occurrence count of each link and to generate a value from 0 (no co-occurrence) to 1 (highest measurement) [32]. Furthermore, CiteSpace incorporates Kleinberg's algorithm to achieve the burst detection function, which can identify emergent research interests of a specialty [32].

Keyword co-occurrence analysis can provide information about the field of study, but it is not adequate for comprehensively analyzing the structure or major areas of study. The keywords in the literature may not present the topic precisely; so abstract term cluster analysis was also conducted. Cluster analysis can be applied to group similar objects together and determine clusters that represent related study areas [26,34]. Citespace provides a cluster analysis function that can be used to group the terms from keywords; titles; and abstracts and automatically label the clusters from noun phrases from each cluster; ranked by different algorithms. The algorithms include term frequency – inverse document frequency (tf*idf) weighting; log-likelihood ratio (LLR) tests; and mutual information. The LLR method has the best term-ranking results compared with the other two methods [35]. In this study; terms from the abstracts were selected for the cluster analysis because they provide much more information about the study topics than do terms from titles or keywords.

Table 2
Characteristics of the networks.

Characteristics	Value
Nodes	342
Links	1136
Modularity	0.65
Average Degree	6.60

3. Results and discussion

3.1. Keyword co-occurrence analysis

The selected 398 papers were analyzed on the basis of the keyword co-occurrence analysis function in CiteSpace. At the beginning, three keywords: *embodied energy*, *construction*, and *building* were excluded from the analysis because these words were used as the main search keywords for papers. In addition, a few similar words, such as *residential building*, *commercial building*, and *house* were excluded because their presence can influence the accuracy of other keyword co-occurrence networks. Several words may describe the same concept and should be standardized [27,28]. For example, *life cycle assessment*, *LCA*, and *life cycle* were standardized as *life cycle assessment*.

On the basis of the selected papers, a keyword co-occurrence network was generated by identifying keywords and performing a keyword co-occurrence matrix with CiteSpace. Fig. 5 illustrates the keyword co-occurrence network. The size of the node represents the frequency of use of a specific keyword – the more a keyword occurred, the larger the size of its node. The different colors of the links represent the time of the node connections. The blue links denote the oldest connections, whereas the red links represent the newest connections. Table 2 shows the overall characteristics of the network. By selecting the top 50 keywords with the highest occurrence each year, a network with 342 nodes and 1136 links

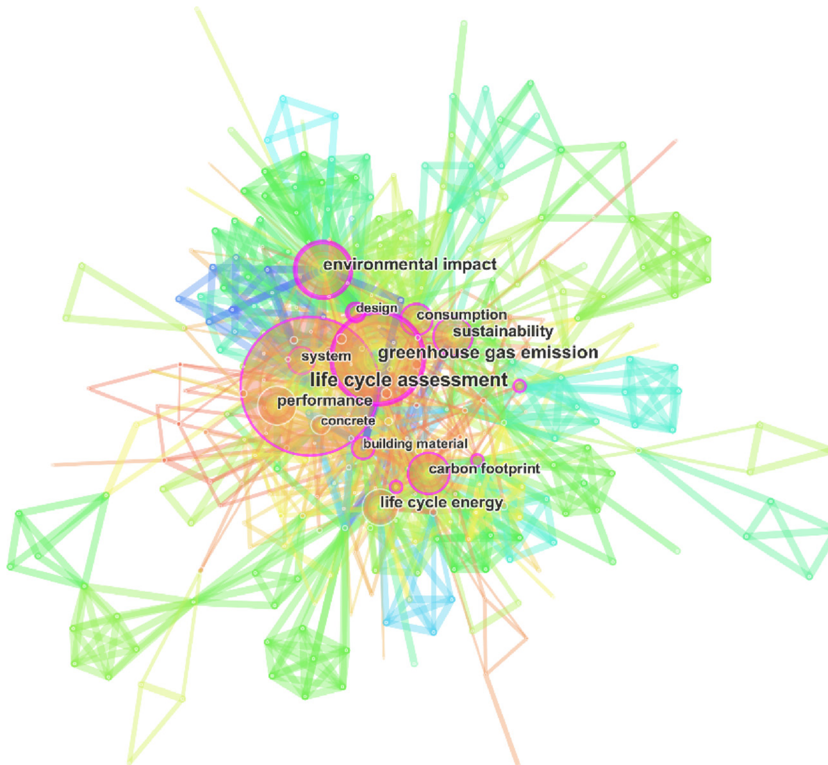

Fig. 5. Keyword co-occurrence network and top keywords that occurred more than 20 times.

Table 3
Top frequently occurring keywords.

Keywords	Frequency
Life cycle assessment	150
Greenhouse gas emission	102
Environmental impact	67
Sustainability	51
Performance	49
Life cycle energy	48
Carbon footprint	46
Consumption	42
System	36
Building materials	29
Design	29
Concrete	25
Model	20

Table 4
Top degree of co-occurrence keywords.

Keywords	Degree
Design	68
Environmental impact	63
Greenhouse gas emission	46
Carbon footprint	37
Consumption	37
Building material	34
Sustainability	33
Life cycle assessment	32
Life cycle inventory	32

was developed. The modularity score indicates the extent to which a network can be divided into independent modules [36]. The modularity score ranges from 0 to 1, and a high modularity may imply a well-structured network [35]. The modularity of a generated network is 0.65, which is relatively high and means that several modules exist in the well-structured networks. The more a node links to others nodes, the more important the role it plays [32] and the higher its degree will be. Determining the degree of nodes is useful for identifying which nodes play a pivotal role in the network. The average degree of the nodes in the network is 6.6, which means on average, each keyword has a co-occurrence relation with 6.6 other keywords.

CiteSpace can label the keyword that represents each node. Fig. 5 also shows the network labeled with the top most frequently occurring keywords. Table 3 illustrates the keywords that occurred more than 20 times within the selected literature. *Sustainability* and *environmental impact* occurred more than 50 times in response to an environmental crisis such as resource depletion, global warming, and ecological destruction. The terms *life cycle assessment* and *life cycle energy* are highly occurring keywords that represent the fundamental concept and method of thinking with regard to the embodied energy of buildings. Other keywords, such as *greenhouse gas emission* and *carbon footprint*, indicate emissions issues related to the environmental impact of the embodied energy of buildings. Another group of keywords, such as *building materials*, *design*, *concrete* and *model* are keywords that relate to the methods of reducing the embodied energy of buildings. Table 4 shows the 10 keywords with the highest co-occurrence with other keywords. The keyword *design* has the highest degree of co-occurrence among all the keywords with a co-occurrence with 68 other keywords, and hence a degree of 68. The degree of co-occurrence for *environmental impact* is 63 and that for *greenhouse gas emission* is 46. It is obvious that those keywords are important in the network and are highly prevalent in the topic of embodied energy of buildings.

CiteSpace also provides a time-zone visualization, which shows when the keywords occurred for the first time, presented in chronological order, and illustrates the co-occurrence relationships between pairs of keywords. Fig. 6 highlights the time-zone visualization for the study. The lines connecting keywords are co-occurrence links for each pair of keywords. The colors of lines represent the year of the first co-occurrence; the blue links denote the oldest connections whereas the red links represent the newest

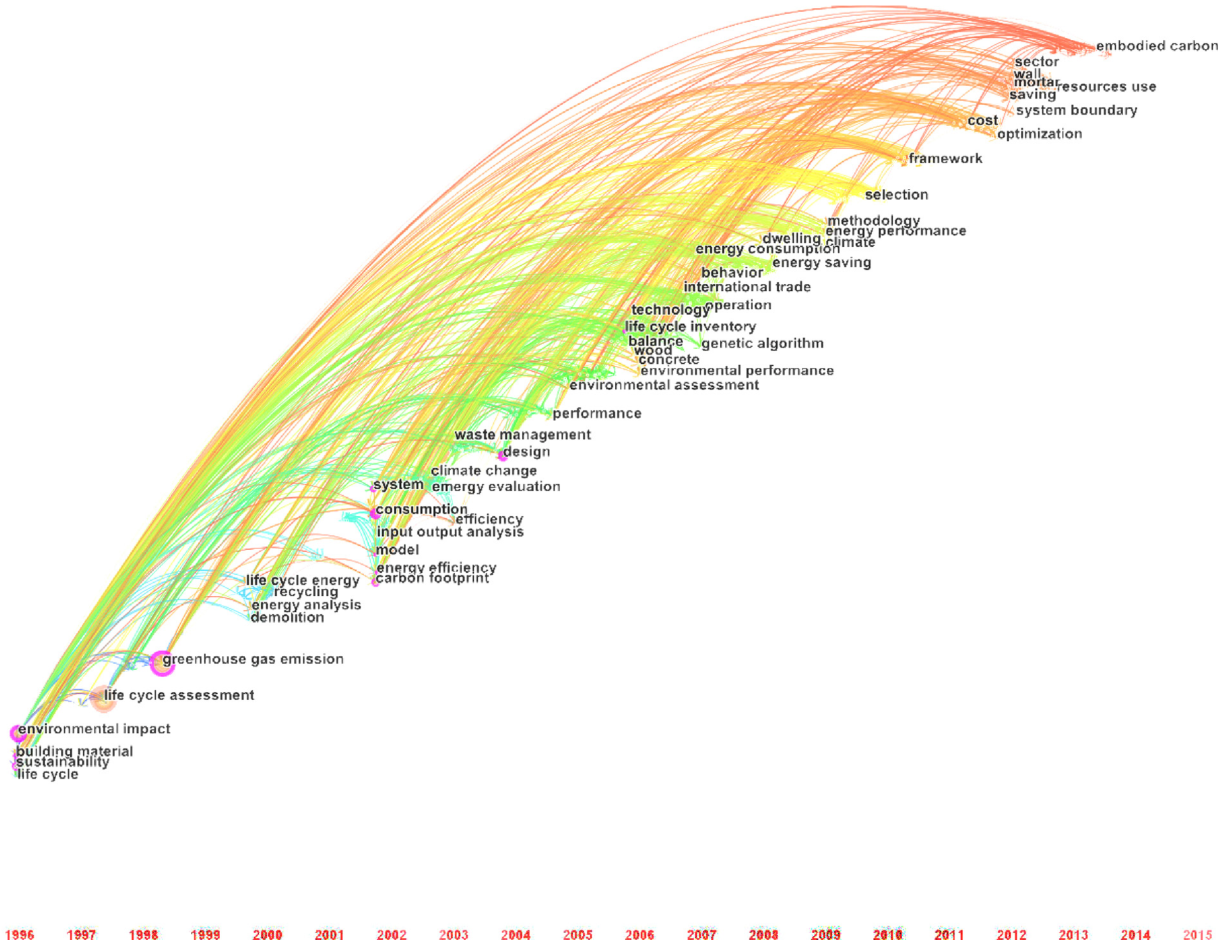

Fig. 6. Time-zone visualization.

connections. The early emerging interest on keywords such as *life cycle assessment* and *environmental impact* is declining, as is shown by fewer red lines being connected to these keywords. This finding is partially due to inconsistent research on the embodied energy of buildings, and many researchers have noted that the lack of a high-quality database and a detailed, standardized method for calculating the embodied energy of buildings has greatly hampered the expansion of research in this area [24,10].

A time-zone visualization can provide a chronological view of keyword occurrence and co-occurrence relations. However, such a visualization 't provide sufficient information related to emerging research interests. CiteSpace incorporates Kleinberg's algorithm to achieve the burst-detection function, which can identify emerging research topics within a specific area [32].

Table 5
Keyword burst detection results from 1996.

Keywords	Begin	End
Environmental impact	1996	2001
Life cycle assessment	1996	2008
Sustainable construction	2004	2008
Concrete	2007	2008
Building envelop	2008	2009
Energy policy	2009	2010
Consumption	2009	2010
Technology	2012	2013
Industry	2012	2013
Optimization	2013	2015

3.2. Burst detection

Keywords burst detection is associated with identifying keywords that have a high frequency of occurrence within a specific time period. The detected keywords attract more interest by researchers during a given period of time. In this study, the time period is set at one year. Table 5 shows a relevant keyword burst detection result, beginning from a first literature retrieval year of 1996. The keywords environmental impact, life cycle assessment, and sustainable construction were bursting from 1996 to 2001, 1996–2008, and 2004–2008, respectively. The keywords concrete, building envelop, energy policy, and consumption were detected as bursting from 2007 to 2008, 2008–2009, and 2009–2010, respectively. Table 5 shows that technology and industry aroused interest from 2012 to 2013. The keyword optimization burst from 2013 to 2015. Interest in the embodied energy of buildings shifted from earlier discussions of concepts and methods, to specific areas of reduction of the embodied energy, and finally to a broad system perspective of optimization of the design, materials use or even the methodology employed in reducing the embodied energy of buildings.

The keyword co-occurrence network analysis provides several aspects of information related to the embodied energy of buildings. analysis offers a much greater emphasis on the nodes and their linked relations. To further determine the major areas of research within the embodied energy of buildings, an abstract term co-occurrence analysis was performed.

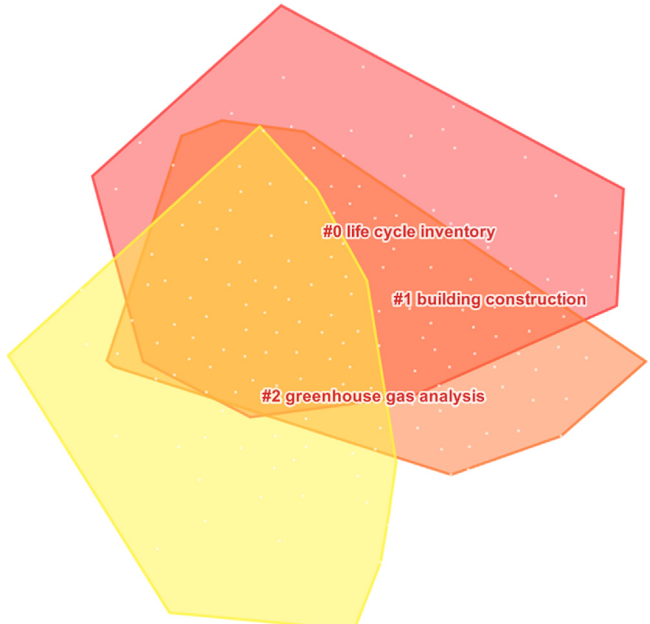

Fig. 7. Cluster analysis of the embodied energy of buildings.

3.3. Term co-occurrence network analysis

In CiteSpace, the word "term" refers to noun phrases that can be extracted from the titles, abstracts, and keywords of documents. When one is considering the major study areas or structure of a field of research, terms contain more precise information than keywords do. Moreover, to some extent, isolated keyword co-occurrences can lead to misinterpretation if they are taken out of context [37]. Once the term co-occurrence network is generated, a further step is to determine the major study areas of the research field by applying clustering function of CiteSpace.

One of the most important functions of CiteSpace is clustering and automatically labeling the clusters. A cluster analysis was performed by using the CiteSpace clustering function for identifying research themes within the topic of embodied energy of buildings. CiteSpace has adapted spectral clustering, which provides clearly defined information for a subsequent automatic labeling function [35]. In this study, the cluster labels were selected from noun phrases that appeared in article abstracts. CiteSpace ranked noun phrase labels with three different algorithms; namely, term frequency-inverse document frequency (tf*idf) [38], log-likelihood ratio (LLR) tests [39], and mutual information (MI) [35]. A study by Chen [40] showed that LLR tests usually provide the best results when one is considering uniqueness and coverage. Therefore, this study selected LLR tests as the automatic labeling algorithm for labeling different clusters. The cluster size is the number of terms included in each cluster. The cluster analysis assigned the terms that share the same meaning to associated clusters and classified each word with different latent semantics due to various contexts, which means that some of the terms belong to several clusters and the clusters can be overlapped [28,34]. Fig. 7 shows the three most prominent clusters that were labeled as major research areas on the basis of different terms retrieved from the selected papers. The labels of the three major areas are life cycle inventory, building construction, and greenhouse gas analysis. It should be noted that the label of each cluster could be misleading and it is necessary to consider other terms from a cluster to further understand the meaning and scope of that cluster. Table 6 shows the characteristics of the three prominent clusters. CiteSpace assigns the cluster ID zero to the largest cluster and the ID one to the second largest, and so on.

Table 6
Characteristics of clusters.

Cluster ID	Size	Silhouette	Representative terms
0	39	0.549	Life cycle inventory; Calculation method; Life cycle assessment
1	38	0.7	Building construction; Building design; Building material
2	34	0.613	Greenhouse gas analysis; Life cycle energy

The silhouette coefficient is used to estimate how well units are grouped within their cluster [41]. The silhouette coefficient (s) is defined as follows:

$$s(i) = \frac{\mathrm{b}(i) - \mathrm{a}(i)}{\max\left\{\mathrm{a}(i), \mathrm{b}(i)\right\}}, \tag{1}$$

where i denotes each element in the dataset, a(i) is the average dissimilarity of element i linked with all other elements within its cluster, and b(i) represents the minimum average dissimilarity of element i with other elements within neighboring clusters. A smaller value of a(i) means that i is a better match within its cluster, whereas a larger value of b(i) means that i is not a good match with its neighboring clusters. The silhouette coefficient value of a cluster ranges from −1 to 1. The value of 1 represents a perfectly compact cluster, separated from other clusters. An average silhouette coefficient greater than 0.5 indicates reasonable clustering of data [42]. The silhouette coefficients of all three major clusters exceed 0.5, which shows reasonable clustering results.

Fig. 7 shows that the three main research areas overlap with one another, and the silhouette values in Table 6 indicate that those primary research areas have a reasonable clustering of data. Therefore, the three identified main research themes for the embodied energy of buildings are not completely independent and are correlated. For example, the calculations of embodied energy and embodied emissions of buildings are strongly related to the life cycle inventory and the method of calculation, and the building design and materials selection affect the embodied energy and embodied emissions of buildings. In other words, the three identified main research areas of embodied energy of buildings are not independent of each other. In this study the overall review of the literature on the embodied

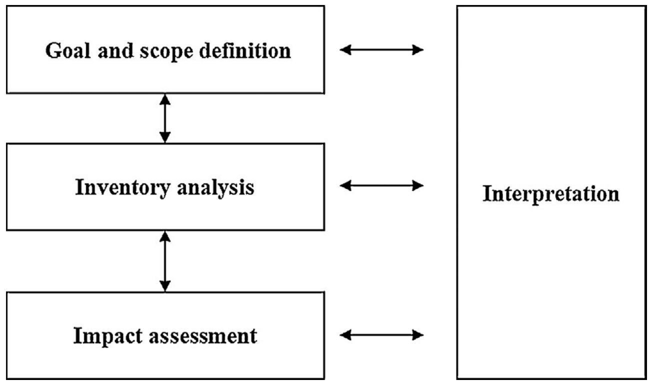

Fig. 8. Life cycle assessment framework.

energy of buildings was performed on the basis of the three identified cluster areas. The papers that were related to each cluster and their relationships to other clusters are discussed below.

3.3.1. Life cycle Inventory/Assessment

Cluster #0 refers to the life cycle inventory phase of life cycle assessment and to the calculation methods. The inventory analysis involves data input and output and is primarily responsible for the life cycle assessment results. There are three major methodologies when one is considering the life cycle inventory phase as well as the life cycle assessment model: the process-based method, the economic input-output (I-O) analysis-based method, and the hybrid method. The process-based method uses process flow to consider different activities associated with a product. For each activity, all materials and energy used in the process are calculated. The environmental impacts and emissions can be calculated and will account for production of the materials and consumption of the energy. The ISO environmental management standards are based on the process-based method. The [43] ISO 14040:2006: Environmental management – Life cycle assessment – Principles and framework standard describes the principles and framework for life cycle assessment. That framework is illustrated in Fig. 8.

The economic I-O analysis-based method considers not only the direct environmental impact of a product or a service but also all indirect impacts involved in the supply chain [44]. Leontief first developed I-O analysis in 1941 as a method to measure the flow of goods and services through the economy, and Herendeen and Bullard later modified it into an energy analysis method. Their method estimates the material and energy resources needed, and the environmental emissions resulting from activities in an economy using economic and environmental data to determine the effect of changing the output of a single sector.

Both the process-based and I-O analysis-based methods have limitations. Using the process-based method is straightforward; however, it is impossible to achieve a complete system. Furthermore, the quality of the data acquired from the manufacturers depends on their production process, which is continually evolving. Using I-O analysis requires a proper understanding of the method, along with high-quality data and a comprehensive input/output sector table to maintain the accuracy of the results. Moncaster and Song [24] also noted that the I-O analysis is too broad to be applied in designing a building with lower embodied energy because the method is limited in its comparison of impacts from individual products. In an attempt to overcome the problems of the process-based and I-O analysis-based methods, both methods have been combined to form the hybrid method. Treloar et al. [45] developed an I-O based hybrid analysis. However, Treloar et al. indicated that less than three-quarters of the total embodied energy of the residential building sector can be validated, due to the complexity of the embodied energy path in an I-O matrix.

Different kinds of data can be applied to calculate the embodied energy and environmental impact of buildings. Commercial LCA software such as Athena Impact Estimator for Buildings or GaBi, both of which adopt the process-based life cycle inventory method and offer their own databases for building embodied energy and environmental impact assessments. Some associations, such as *ecoinvent*, also provide databases for thousands of products.

Hammond and Jones [46] formulated a study to construct an open-access, reliable inventory of carbon and energy (ICE) database for construction materials in the UK. The majority of its input data were derived from secondary data sources, including peer-reviewed journal papers, technical reports, and monographs. Five criteria were applied for the selection of a data source. The first criterion is that the source must be in compliance with approved methodologies or standards, such as ISO 14040/44 (the international standard on environmental life cycle assessment), and the second requirement is that it must have "cradle-to-gate" system boundaries. The third restriction applies to the region of the data – a much stronger preference was given to data from the UK. The age of the data is the fourth consideration. The last criterion is that the data must be obtained from a study that has considered life cycle carbon emissions.

A source of data for individual products of buildings is the Environmental Product Declaration (EPD) provided by some manufactures and industry associations. EPDs provide detailed information about a product's environmental impacts, and are certified by a third party.

The life cycle inventory and its method of calculation form the foundation for research on the embodied energy of buildings. Adapting different methods and data sources in calculating embodied energy and embodied emissions of buildings can lead to different results. Dixit et al. [23] identified the parameters for embodied energy measurement through the analysis of literature and proposed the development of an embodied-energy measurement protocol to standardize the process of measuring the embodied energy of buildings.

3.3.2. Building design

Cluster #1 represents the aspects of building design and building materials. Many researchers focus on how to optimize the design of buildings or how to use green materials to reduce the embodied energy and embodied emissions of buildings.

Several researchers have conducted LCA studies of different building materials to identify the embodied energy, carbon emission, and environmental impacts of building materials and to analyze the possibilities for reducing the embodied energy of buildings [46–49]. These studies can also be used as data sources when calculating the embodied energy and embodied emissions of different building materials. Some researchers have studied the embodied energy or embodied carbon emissions of buildings by comparing different materials usage. Griffin et al. [50] used an ICE database to measure the embodied energy of different structural systems of a parking garage. The researchers proposed that designers adopt a steel product with a high recycled content in order to reduce the embodied energy of parking garage structures. Robertson et al. [51] studied the embodied energy of a mid-rise office building using laminated timber or reinforced concrete, based on a cradle-to-gate LCA. The results indicated that the laminated timber design consumed 8200 MJ/m^2, compared with 4600 MJ/m^2 for concrete. Robertson et al. concluded that the use of heavy timber as a structural material for mid-rise office buildings increases embodied energy of the building compared with the use of reinforced concrete. Mpakati-Gama et al. [52] compared the embodied energy and GHG emissions of houses built with kiln-burnt bricks (KBBs), soilcement blocks (SCBs), and stabilized solid cement blocks (SSBs) by applying a process-based cradle-to-site LCA. The result showed that KBBs consume 530.64 MJ/m^2 and release 61.32 kg CO_2-e/m^2, more than three times the energy consumption of SCBs and SSBs. The researchers proposed a switch from KBBs to other energy-efficient and emission-efficient materials.

These studies illustrate that applying advanced technology and eco-innovation in production plants, and substituting natural resources with recycled material during production, can significantly reduce the environmental impacts of building materials. For example, in cement production, achieving a more eco-efficient clinker manufacturing process can significantly reduce the energy and environmental impact of production. In addition, substitution of cement with fly ash or other pozzolanic materials in concrete production reduces its carbon footprint.

Several studies on building design and materials selection have focused on developing a comprehensive method for reducing the embodied energy and embodied emissions of buildings through design and materials selection. Basbagill et al. [53] discussed the feasibility of reducing the embodied energy environmental impact during the early stage of building design. The researchers developed a list of building components, with alternative material options for each component, based on a UNIFORMAT work breakdown structure. They then considered different combinations of materials options and used several software such as D-Profiler, the Athena Institute's EcoCalculator, and Excel, to calculate the embodied energy of different scenarios. Finally, they constructed a BIM-enabled decision method to help designers identify the combination that best reduces the embodied environmental impacts of the building. Shrivastava and Chini [54] considered adding the initial embodied energy of building materials to the building information model to help designers determine the environmental impact of their design. By establishing and comparing the initial embodied energy of concrete, steel, and wood structural systems, the researchers illustrated that the BIM can be used as a decision-making tool for designers when they consider the embodied energy of alternative materials or systems.

Recently, producers of construction materials have also realized the importance that customers place on the amount of embodied energy and embodied emissions of their products. Therefore, more and more manufacturers provide EPDs for their materials, and those EPDs contain the material's initial embodied energy and embodied emissions. Many green building rating systems provide additional points for product use, in conjunction with EPDs, to encourage manufacturers to reduce the environmental impacts of their products and make their EPDs available. Designers, on the other hand, consider environmental impacts of materials as a selection criterion when they have access to such data. For example, the U.S. National Ready Mixed Concrete Association (NRMCA) developed a program to generate EPDs for ready-mixed concrete produced in different regions of the U.S., in order to market their product to owners and designers who are seeking LEED certifications.

Building design and materials selection are important study areas relating to the embodied energy of buildings. Academia and industry have both focused on how to minimize the embodied energy and embodied emissions of buildings during the design phase. This includes establishing a database for information on the embodied energy of different construction materials, case studies that compare embodied energy and embodied emissions from alternative materials and systems, and the use of advanced modeling techniques to optimize the environmental impacts of buildings.

3.3.3. Greenhouse gas analysis

Cluster #2 is related to another important issue of the embodied energy of buildings – GHG analysis or embodied emissions. Embodied emissions are strongly related to embodied energy. Usually energy consumption results in emissions, but there is no direct relationship between embodied energy and embodied emissions, due to the chemical processes of the materials themselves. For example, when calculating CO_2 emissions from cement production, three main sources of emissions should be considered – direct emissions from the calcination for clinker production, direct emissions from fossil fuel combustion during production, and indirect emissions from electricity consumption.

As was discussed in section 3.3.2, building design also affects embodied emissions. González and Navarro [55] argued that building materials with high embodied energy could generate more carbon dioxide emissions than materials with low embodied energy. They demonstrated that conclusion by assessing the relatively lower carbon dioxide emissions of three houses made with low environmental impact materials. Thus, a correct selection of materials should be studied to reduce embodied energy and emissions [55]. Hammond and Jones [47] applied an ICE database with respect to a residential house in the UK; the database enables a breakdown of embodied energy and carbon by building materials. The average embodied energy was determined to be 5340 MJ/m^2 and the average embodied carbon was 110 kg/m^2. The results show that concrete and bricks made the greatest contributions to embodied energy and embodied carbon emissions. Those materials contributed more than 30% of total embodied energy and more than 50% of its total embodied carbon emissions. The higher percentage of embodied carbon emissions is due to the fact that cement production releases CO_2 both directly and indirectly: the heating of limestone releases CO_2 directly, and the burning of fossil fuels to heat the kiln indirectly results in CO_2 emissions. Dimoudi and Tompa [56] applied a process-based LCA method to quantify the embodied energy and its equivalents of CO_2 and sulfur dioxide (SO_2) for construction materials used in two office buildings. The two buildings were of different sizes and different envelope materials but both had a typical design used for office buildings in Greece. The quantities of materials used for both buildings were estimated on the basis of their design drawings, and environmental impact data of materials were collected from international literature [57]. The results showed that concrete and reinforcing steel materials used for the structure of the buildings accounted for the largest portion of embodied energy of both buildings. The CO_2 equivalent emissions of the concrete and reinforcing steel represented 73.3% and 75.3% of the total embodied emissions of the two buildings. When comparing embodied emissions of different elements of the buildings (foundations, columns, beams, shear walls, and slabs), slabs had the highest portion due to their high volume.

Many researchers have found that concrete is the main contributor to the initial embodied emissions of buildings, because of its high volume and large environmental impacts during production. Approximately one ton of concrete is produced for every human being in the world each year [58], and its production consumes huge amounts of cement, water, and aggregate. Cement accounts for the largest part of embodied energy and carbon dioxide emissions from concrete production [59]. The cement production industry is estimated to account for 5–7% of the CO_2 generated by human activities [60]. Yan et al. [44] studied GHG emissions from a 30-story, reinforced concrete commercial building in Hong Kong. The system boundary was cradle-to-site and the process-based LCA method was used to calculate GHG emissions of the building materials. The results showed that 82–87% of the embodied GHG emissions were due to production of the building materials, 6–8% of the GHG emissions were due to transportation of the materials to the site, and 6–9% were due to energy consumption by construction equipment. The embodied GHG emissions of concrete and reinforcing steel accounted for 94–95% of the embodied emissions of all the building materials used. Sukontasukkul [61] used the process-based LCA method to calculate the CO_2 emissions in the production of ready-

Table 7
Materials and resources credits in the LEED v4 rating system, awarded as incentives to reduce the environmental life cycle impacts of buildings.

Materials & Resources credits		No. of Points	Intent
Building Life-cycle Impact Reduction	Building and materials reuse	2–6	Materials reuse
	Renovation of abandoned building		Design optimization
			Design optimization
	Whole building LCA		Design optimization
Building Product Disclosure and Optimization	EPD	1–2	Design optimization
	Raw materials	1–2	Raw materials reduction
	Materials ingredients	1–2	Raw materials reduction

Table 8
Resource credits in the Green Globes to reduce environmental life cycle impacts of buildings.

Materials & Resource credits		No. of Points	Intent
Building Life-cycle Impact Reduction	Building Assemblies	33	Design optimization
	Interior Fit-Out	16	Design optimization
	Reuse of existing structures	22	Materials reuse
Resource Conservation	Raw materials	3	Raw materials reduction
	Multi-Functional Assemblies	1	Raw materials reduction

mixed concrete. The calculation was based on recommendations from the World Business Council for Sustainable Development. The CO_2 emissions of raw materials for concrete and ready-mixed plant operations were determined by using cement and aggregate manufacturers' data and the literature survey. Furthermore, Sukontasukkul calculated CO_2 emissions for a specific mix proportion of two mixer types for a medium to large amount of concrete (namely, portable-mixer and ready-mixed concrete), in order to examine the environmental impacts of concrete production. The results show that the ready-mixed concrete method has fewer emissions than the portable mixer method does. Zhang et al. [62] focused on calculating the embodied emissions of Portland cement and concrete used in building construction in Hong Kong and investigated the effects of regional characteristics on the emissions results, using the process-based LCA method. The researchers used a cradle-to-gate system boundary and selected the emission factors for different categories on the basis of first-hand data provided by several reliable databases, including Intergovernmental Panel on Climate Change (IPCC) Guidelines, Cement Sustainability Initiative (CSI), World Resource Institute (WRI), and a Chinese LCI database developed by Sichuan University. The Chinese LCI database consists of 600 LCI datasets for key materials and chemicals, energy carriers, transportation, and waste management. To develop a region-based inventory, Zhang et al. [62] studied the manufacturing processes of cement and concrete in local and nearby areas. Several questionnaires were designed and distributed to local manufacturers to collect the needed information for life cycle assessment of cement and concrete production. The GHG emissions of cement and concrete production were calculated on the basis of the collected data and IPCC guidelines. The results show that embodied carbon for cement production is 1.005 kg CO_2-e/kg cement and 424.28 kg CO_2-e/m^3 concrete within the cradle-to-gate system boundary.

The calculations in GHG analysis are integrated with embodied energy measurement. Therefore, the variation, incompleteness, and difficulties of measuring embodied energy affect the measurement of embodied emissions. Furthermore, there is currently insufficient incentive for designers to consider the embodied emissions of building materials as criteria when they select and use those materials. Writing legislation, creating incentives, and raising the public interest are needed to motivate owners and designers to consider a building design with minimum embodied emissions [63]. As sustainable construction has become an important consideration in the field of building construction, many building-rating systems have been developed in different countries to identify high-performance green buildings. Designers are following these standards in their designs, with the aim of achieving a specific level of green building. The incentives for green-building assessment systems, in terms of reducing embodied energy, are discussed as follows.

3.4. Incentives to design buildings with low embodied energy

In the U.S., the U.S. Green Building Council (USGBC) first published a rating system, Leadership in Energy and Environmental Design (LEED), in 2000. The newest version, LEED v4, allocates 110 points in the major categories of location and transportation, sustainable site, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, and innovation. Table 7 shows the points that LEED v4 allocates, in the materials and resources category, to reward the selection of materials with lower environmental life cycle impacts in the design of buildings. Three points are allocated when the life cycle assessment of the project's structure and enclosure demonstrates a minimum of 10% reduction, compared with a baseline building, in at least three environmental impact categories, one of which must be global warming potential. One point is awarded for using materials with EPDs, and another point is gained for using products with lower environmental impacts than the industry average.

The Green Building Initiative (GBI) acquired the U.S. rights to the Canadian Green Globes building assessment, guidance, and certification program and adopted the Green Globes as an alternative to the LEED rating system in the U.S. in 2004. The evaluation categories include project management, site, energy, water, resources, emissions, and indoor environment, with a total of 1000 points. Table 8 shows the points that relate to the resource category of Green Globes to encourage building designs that use materials with lower environmental life cycle impacts. The Green Globes awards points for choosing materials based on LCA results. This can be accomplished by using the Athena Impact Estimator for Buildings LCA software tool for a minimum of two building assemblies in the design phase.

Neither the LEED nor the Green Globe provides a benchmark for the embodied energy of buildings, and put the burden of identifying the baseline buildings on the designer's shoulders. Designers should reduce the embodied energy and emissions of the buildings they design, within the budget and without compromising safety and quality. Yet, no specific target for embodied energy and emissions has been provided by the building rating systems for designers to meet. In addition, the references that provide guidelines on how to minimize environmental impacts of a building through design and materials selection are limited [46,63]. It is urgent that benchmarks be developed for embodied energy and emissions for different types of buildings, in order to provide guidelines for designers to use during the design phase. In addition, the government should offer more incentives in the form of tax incentives, density bonuses, expedited permits, and the like, encouraging owners to require building designs that minimize environmental impacts.

4. Conclusion

This study applied bibliometric analysis in order to increase the understanding of research on the embodied energy of buildings. The study analyzed 398 papers published during the last two decades on the embodied energy of buildings, and the results provided information on the structure and subjects of this field. Keyword occurrence and co-occurrence analyses showed that *life cycle assessment* is the most frequently occurring keyword and *design* is the keyword that has the greatest co-occurrence relations with other keywords in the papers that were searched. A keyword and abstract term co-occurrence network analysis revealed that *design* and *materials selection* play a significant role in the amount of embodied energy and emissions of buildings. Changes in building design and selection of building materials will be essential to minimize the environmental impacts of buildings and reduce overall energy use and GHG emissions.

Three major research topics were identified by term co-occurrence analysis: life cycle inventory/assessment, building design, and GHG analysis. The literature review showed that measurement accuracy for embodied energy and embodied emissions of buildings depends on the LCA method and the source of the data used. Most of the literature focused on the initial embodied energy and emissions, especially the cradle-to-gate phase, due to its major contributions to the total embodied energy and emissions. For example, many studies focused on the embodied energy and emissions of commonly used construction materials, such as concrete and steel. Few studies attempted to measure the embodied energy and emissions associated with the construction, maintenance, and demolition phases of buildings. This might be due to the minor share of total energy and emissions belonging to those phases, as well as to the complexity and difficulty of collecting the needed data. However, with the ongoing increase in the off-site fabrication of building systems, the greater use of reused/recycled materials/systems, and the construction of more energy-efficient buildings, measuring the life cycle embodied energy and emissions of buildings becomes more important.

The burst detection analysis and relevant literature reviews revealed that the emerging research interests and directions for future research on the embodied energy of buildings are technology, industry, and optimization. This includes incorporating advanced information technology, such as BIM, with the embodied energy of buildings to develop a comprehensive method for optimizing building designs vis-à −vis their embodied energy. Another necessary area of research is the establishment of benchmarks for the embodied energy of different buildings, for designers to consider during the design phase. In addition, reliable EPDs for construction materials must be developed to create a comprehensive, reliable, and dynamic database for research and practices relating to the embodied energy of buildings.

The study's findings included the important keywords, citation hotspots, shifting patterns of interest, trending interests, and major research topics in specific research fields that can be used to comprehensively understand the research on the embodied energy of buildings and familiar with the relevant study topics for further study of minimizing embodied energy, embodied emissions, and environmental impacts of buildings.

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