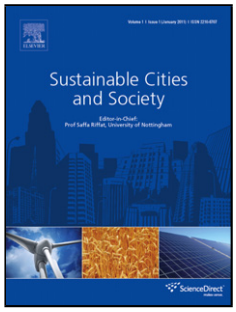

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Authors: Carmen Díaz-López, Manuel Carpio, María Martín-Morales, Montserrat Zamorano

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ANALYSIS OF THE SCIENTIFIC EVOLUTION OF BUILDING SUSTAINABILITY ASSESSMENT METHODS

Carmen Díaz-López[a], Manuel Carpio[b], María Martín-Morales[c], Montserrat Zamorano[a,d*]

[a]Department of Civil Engineering. ETS Ingeniería de Caminos, Canales y Puertos. University of Granada. Campus Fuentenueva s/n, 18071 Granada, Spain .

[b]Department of Construction Engineering and Management, School of Engineering, Pontificia Universidad Católica de Chile, Vicuña Mackenna 4860, Macul, Santiago, Chile.

[c]Department of Building Construction. ETS Ingeniería de Edificación. University of Granada. Severo Ochoa S/N, Granada, Spain.

[d]PROMA, Proyectos de Ingeniería Ambiental, S.L. Gran Vía de Colón, 48 Granada, Spain.

[*]Corresponding author. Dr. M. Zamorano. Department of Civil Engineering. ETS Ingeniería de Caminos, Canales y Puertos. University of Granada. Campus Fuentenueva s/n, 18071 Granada, Spain. Email: zamorano@ugr.es

Highlights

- Science mapping analyses the evolution of the cognitive structure of building sustainability assessment methods.
- The results show that the research field is in constant evolution and has not yet reached a state of maturity.
- The analysis has shown that building sustainability assessment methods and sustainable building are significant themes, especially over the last five years
- It can be seen how the evaluation instruments have evolved towards more complete instruments that include economic and social aspects in the evaluation of building sustainability

Abstract

The research field concerning building sustainability assessment methods is broad, complex and fragmented due to the great diversity of disciplines and approaches involved. This makes it difficult to obtain useful and unbiased information for future studies so a full review of contributions could provide a comprehensive critical perspective. This paper applies the SciMAT software to analyse the evolution of this research field by means of a systematic literature review of bibliographic records for building sustainability assessment methods, and a review based on the bibliometric analysis of 4203 selected records. In addition, hidden themes and their development in this field have been identified from 1975 to 2017 to produce strategic diagrams of the thematic evolution and performance indicators of the research field in different periods. The results obtained show a scientific field in constant evolution, from its initial focus on environmental impacts and energy efficiency to the gradual inclusion of the social and economic aspects of sustainability building. This has served as a basis for the

development of study models, such as LEED and BREEAM. This study makes a valuable contribution because it gives field experts a comprehensive view of the status quo and predicts the dynamic directions of future research.

Keywords

bibliometric analysis; analysis of science mapping; SciMAT; systematic literature review; building sustainability assessment methods; sustainable building

1. Introduction

Since the 1970s, the performance evaluation and environmental assessment of buildings have generated intense research (Cole, 1998) in parallel with the development of the concept of sustainable building and motivated by the growing focus on the main agents involved. However, it was not until the 1990s that the construction sector began to recognise the significant impact of its activities on the environment (Haapio & Viitaniemi, 2008), the economy, public health (Darko, Chan, Ameyaw, He, & Olanipekun, 2017) and well-being in cities (Macías & García Navarro, 2010). In fact, construction is currently one of the main reasons for accelerating climate change (de Klijn-Chevalerias & Javed, 2017).

To address this problem, in the last few decades, numerous building sustainability assessment methods -tools that allow the grading and certification of the sustainability of the building and its surroundings in all phases of its life cycle (Haapio & Viitaniemi, 2008)- have been developed. These methods, based on a series of indicators that measure different environmental aspects (Haapio & Viitaniemi, 2008), are based on a set of criteria that provide quantitative and qualitative performance, economic, social and usability indicators.

In the academic literature, numerous studies, based on different approaches and disciplines (industrial, social, economic, environmental, political, etc.), analyse the most common assessment methods; a large number of bibliographic reviews on sustainable building also exist. For example, Viitaniemi and Haapio (Haapio & Viitaniemi, 2008) performed a bibliographic review of 16 methodologies. Syahrul *et al.* (Kamaruzzaman, Lou, Zainon, Mohamed Zaid, & Wong, 2016) compared 10 methods based on the most commonly used assessments found in the literature and the accessibility of their manuals. Darko *et al.* (Darko & Chan, 2016) used the Scopus database to classify the main agents involved in ecological construction. Aarseth *et al.* (Aarseth, Ahola, Aaltonen, Økland, & Andersen, 2017) performed a systematic literature review and highlighted several sustainability strategies to improve building performance. Timothy *et al.* (Olawumi & Chan, 2018) performed a scientometric review of global research on sustainability and sustainable development. Marcio *et al.* (Thomé, Ceryno, Scavarda, & Remmen, 2016) carried out a review and constructed a research agenda for sustainable architecture based on science mapping, where assessment methods appear as a satellite theme. Although that research reviewed 2,096 bibliographic records, it focused on the concept of sustainable architecture as the main theme. No studies have been found that analysed evaluative tools while considering the different disciplines and approaches on which they are based. In addition, no other previous review has drawn a map of the relationships between studies on assessment methods, the concept of sustainable building and its main satellite themes.

The sustainability of a building and its assessment is a broad, complex and fragmented research field. The great diversity of disciplines and approaches involved make it

impossible to obtain a single starting point that can be used to access this theme. In addition, not having a broad vision of the research area or the evolution of the themes in this field makes it difficult to obtain useful and unbiased information for future research. Therefore, comprehensive reviews that facilitate integrating these contributions and offer a critical perspective are needed.

To solve this problem, bibliometric analysis provides objective criteria for evaluating the work carried out by researchers (Noyons, Moed, & Luwel, 1999) and a macroscopic overview of large amounts of academic literature (van Nunen, Li, Reniers, & Ponnet, 2018). The concept of bibliometry or bibliometric analysis was presented by Alan Pritchard in 1969, although bibliographic study in a particular field dates back to the 19th century (Osareh, 1996). This methodology has grown exponentially since the arrival of the internet, which has facilitated communication between researchers around the world and has allowed faster access to contributions in a given area (Roig-Tierno, Gonzalez-Cruz, & Llopis-Martinez, 2017).

There are two main methods in bibliometric research: performance analysis and science mapping. While performance analysis aims to evaluate the impact of citations in the scientific production of different scientific agents, science mapping seeks to show the conceptual, social and intellectual scientific research structure and its evolution and dynamic aspects. These methods provide a spatial representation of how the disciplines, fields, specialties and documents or individual authors relate to one another (Small, 1999) by examining the bibliographic material from an objective and quantitative perspective (Albort-Morant & Ribeiro-Soriano, 2016). Many research fields use bibliometric methods to explore the impact of their field, of a group of researchers or of a particular document in order to show the structural and dynamic aspects of scientific research (Henderson, Shurville, & Fernstrom, 2009).

The current objective of this study was thus to perform a bibliographic analysis of building sustainability assessment methods and sustainable building using a science mapping approach. To meet this goal, the following specific objectives were established: (i) to perform a qualitative analysis based on a systematic review, (ii) to perform a quantitative review using bibliometric analysis, (iii) to analyse the results obtained from previous reviews.

This study will contribute to the existing body of knowledge by highlighting the trends and patterns in the research field of building sustainability and assessment, establishing its research themes, mapping researcher networks and recommending areas for future studies.

2. Material and methods

To achieve the objectives of this study, the double integrated analysis shown in figure 1 was performed. It consists of (i) a systematic literature review of the bibliographic records on building sustainability assessment methods and sustainable building and (ii) a review based on the bibliometric analysis of selected records. Each of these procedures is described in the following section.

2.1. Systematic literature review

To generate the systematic literature review (SLR), a protocol is followed that defines the search strings and strategy, exclusion criteria, and methods for extracting data to synthesise the results. Therefore, the relevant body of literature was screened with clearly defined and understandable search options and with specific selection criteria (Ruhlandt, 2018). A large number of authors have implemented SLRs in their research, considering different stages with the aim of developing a replicable, scientific and transparent research process (Bhimani, Mention, & Barlatier, 2018; Gupta et al., 2018; Polater, 2018; Ruhlandt, 2018; Savaget, Geissdoerfer, Kharrazi, & Evans, 2019; Theisen

et al., 2018). The objective of this approach is to avoid any possibility of bias or prejudice that may arise from applying pre-set criteria. In this paper, an SLR based on the guidelines contained in Thomé *et al*. (Thomé, Scavarda, & Scavarda, 2016) was carried out in the following stages (Figure 1):

(i) Planning and formulation of the problem. The first step in the SLR is planning and formulating the problem and setting the scope of the review. Establishing well-founded research questions is critically important for the next stages [59] and researchers must therefore determine the inclusion and exclusion criteria for the final selection of relevant documents. The co-authors discuss the conceptualisation of the research field, propose research questions and define expected results.

(ii) Selection of the database(s). The second step is to define the most suitable bibliographic databases for the document search.

(iii) Selection of keywords. One of the most challenging aspects of bibliometric studies is the delimitation of keywords. The number of keywords should be large enough not to restrict the number of studies and specific enough to include only studies related to the subject. The search string is applied to obtain a first set of pre-selected records.

(iv) Final selection of the literature. This stage is essential to ensure that a considerable and manageable number of relevant documents are selected. The relevant documents are those that contain the necessary data to address the research questions in our SLR. In this stage, the relevant documents will be selected based on the PRISMA flowchart guidelines.

(v) Identification of the time horizon. Once the relevant documents are selected and the number of records per year is established, the time horizon is selected, as are the different periods. These are established according to various criteria, such as number of records, relevant items and turning points in the research field.

2.2. Bibliometric analysis

In recent years, innovative methods have been used to show the change and continuity of research over time (Cocosila, Serenko, & Turel, 2011). In this study, the bibliometric analysis was performed using SciMAT (Science Mapping Analysis Software Tool) software, a freeware science mapping tool that allows researchers to analyse the social, intellectual and conceptual evolution in a scientific field (Cobo, López-Herrera, Herrera-Viedma, & Herrera, 2011; Oakleaf, 2009). SciMAT has been applied successfully in many areas, such as computer science, psychology, marketing and/or management, among others (Alcaide–Muñoz, Rodríguez–Bolívar, Cobo, & Herrera–Viedma, 2017; Castillo-Vergara, Alvarez-Marin, & Placencio-Hidalgo, 2018; Cobo, Martínez, Gutiérrez-Salcedo, Fujita, & Herrera-Viedma, 2015b; Gomez-Jauregui, Gomez-Jauregui, Manchado, & Otero, 2014; López-Robles, Otegi-Olaso, Porto Gómez, & Cobo, 2019; Moral-Muñoz, Cobo, Peis, Arroyo-Morales, & Herrera-Viedma, 2014; Thomé, Ceryno, et al., 2016).

This tool uses a series of scientific publications to build a knowledge base in which the identity of each publication and the different elements (keywords, journals, references, etc.) are stored (Cobo et al., 2011; Oakleaf, 2009). It is based on the analysis of co-words and the h-index (Hirsch, n.d.) and incorporates methods, algorithms and measures for all steps in the workflow of general science mapping, from pre-processing to the visualisation of results (Cobo et al., 2011). SciMAT is based on the methodology defined by Cobo *et al*. (Cobo, López-Herrera, Herrera-Viedma, & Herrera, 2012) and establishes the following four stages **(**Figure 1) that allow the analysis of a research field (Cobo, Martínez, Gutiérrez-Salcedo, Fujita, & Herrera-Viedma, 2015a):

(i) **Detection of the research themes**. To obtain research subjects of great interest for the studies in each period, firstly SciMAT apply a co-word analysis to raw data for all the published documents in the research field (Callon, Courtial, Turner, & Bauin, 1983), secondly uses an equivalence index, which builds a standardized bibliometric network of keywords, and third applies the simple center algorithm to cluster the keywords into themes (Callon et al., 1983; Callon, Courtial, & Laville, 1991a).

(ii) **Low dimensional space layout of research themes.** In this second stage, the themes detected are displayed using two-dimensional strategic diagrams based on their centrality (degree of interaction of a research theme with other research themes) and density (internal strength value of the research theme) (Callon, Courtial, & Laville, 1991b). A strategic diagram is divided into four quadrants (Figure 2a):

- **Motor themes** are in the upper-right quadrant. They are well-developed and important for the structure of the research field.
- **Highly developed and isolated themes** are in the upper-left quadrant. They are well developed, but are of marginal importance for the research field.
- **Emerging or declining themes** are in the lower-left quadrant. They are poorly developed and marginally important.
- Finally, **basic and transversal themes** are in the lower-right quadrant. They represent important themes for the scientific field but are not well- developed.

As a complement to the strategic diagrams, the thematic networks show the relationship of each theme of the strategic diagrams with the keywords and their interconnections. Each thematic network is labelled using the name of the most significant keyword in the theme. Figure 2b shows an example of a thematic network. Here, several keywords are interconnected, where the size of the circle is proportional to the number of documents corresponding to each keyword, and the thickness of the link between two circles is proportional to the equivalence index.

(iii) **Discovery of the evolution of research themes.** At this stage, the evolving areas of the research field, their origins and inter-relationships are detected and analysed. The inclusion index (Sternitzke & Bergmann, 2009) is used to detect conceptual linkages between research themes in different periods and measure the strength of association between the themes. This analysis is represented by two graphs:

- **Overlay graph** (Figure 2c). The horizontal arrow represents the number of items shared by both time periods. The top entry arrow represents the number of new elements in period 2, and the top output arrow represents the elements shown in period 1 but not in period 2.
- **Evolution map** (Figure 2d). Solid lines indicate that related themes share a name, both themes having the same name, or the name of one of the themes being part of another one; a dotted line means that the themes share elements that are not the theme name. Finally, the line thickness is proportional to the inclusion index and the size of the circle is proportional to the number of documents associated with each theme.

(iv) **Performance analysis.** This analysis qualitatively and quantitatively measures the contribution of research themes to the entire research field by means of bibliometric measures such as number of published documents, number of citations and different variants of the h-index.

(v) **Visualisation phase**. Following the science mapping workflow, visualisation techniques are used to produce a scientific map and show the results of the different analyses.

3. Results

The method of SLR and bibliometric analysis described above was applied to perform an exhaustive analysis of the research field of building sustainability assessment methods and sustainable building, results that are reflected in the following sections.

3.1. A systematic literature review

Below the SLR methodology is described. It includes the definition of the research questions, the search process, the scope of the SLR, as defined by the inclusion and exclusion criteria, and how the data and corresponding search results were collected.

(i) **Planning and formulation of the problem.** The research questions were determined before starting the search. The SLR of this study addressed the following research questions:

- RQ1: What is the *objective* of this review?
- RQ2: What is the *status* of this study field?
- RQ3: Who are the most prolific authors in the research field?
- RQ4: What is the most influential work in the research field?
- RQ5: What are the major themes in the research field?

(ii) **Selection of the database.** In this study, the ISI Web of Science (ISIWoS) and Scopus (Elsevier's abstract and citation database) were selected due to the high number of international high impact scientific and technical publications they contain from all disciplines.

(iii) **Selection of keywords.** This review addressed two concepts: building sustainability assessment methods and sustainable building; therefore, it was necessary to ensure that both concepts were captured by keywords. An advanced search was performed using keywords related to both concepts as well as those satellite materials directly related to the research field. In addition, two search strings listed in Table 1 were included. The search was performed using the field "Title/Abstract/Keyword" through the inclusion of the terms indicated, as well as the inclusion of the keywords "sustainability"* and "building"* (to detect any words beginning with "sustain" or "build").

(iv) **Final selection of the literature.** After using the selected keywords and search strings to search the Scopus and ISIWoS databases, the records obtained were collected and filed. Once the previous records had been compiled, we applied the PRISMA flowchart guidelines (Figure 3), where the number of relevant documents finally identified is shown.

A total of 5678 bibliographic records were retrieved from the two selected databases. After eliminating 987 duplicates, 356 of the remaining 4691 records were excluded by analysing the title and summary and applying the exclusion criteria, such as document type, if it is a complete document and the relationship with the research field. A full text examination was done of the remaining 4335 records and 132 additional records were excluded since they did not cover the topics included in this review. This left 4203 relevant documents for the study.

(v) **Identification of the time horizon.** The time horizon was determined based on the main milestones and inflection points of the evolution of sustainable building and its assessment. Since the first attempts to assess the environmental performance of buildings took place in the 1970s (Cole, 1998), the time horizon used in this study was from 1975 to 2017. It was then subdivided into the following 4 periods, taking into account the number of documents selected as well as relevant milestones in order to analyse the trends in publication patterns:

- **First period** (1975-1989)**:** In the 1970s, the concept of sustainable building emerged, with special emphasis on energy conservation and efficiency. This was the beginning of research into assessment methods that looked at technologies that achieved more efficient energy performance (Macías, García Navarro, & Navarro, 2010).
- **Second period** (1990-1999): In the 1990s, and coinciding with the launch of the Building Research Establishment Environmental Assessment Method (BREEAM) in the United Kingdom in 1990 and the creation of the United States Green Building Council (USGBC) in 1993, there was extensive development of environmental assessment methods as effective instruments to achieve substantial reductions in the environmental impacts produced by buildings (Cole, 2006; Todd, Crawley, Geissler, & Lindsey, 2001). Special emphasis was placed on the impact of material manufacturing on the natural environment. An important milestone in this research field was the *Kyoto Protocol*, adopted in December 1997 in Kyoto and driven by the United Nations (UN) as a response to the threat posed by climate change. It provided a set of measures aimed at reducing greenhouse gas (GHG) emissions compared to 1990 levels.
- **Third period (2000-2009):** From the year 2000, coinciding with the expanding application of the Leadership in Energy and Environmental Design (LEED) rating system, numerous assessment methods began to emerge. This significant increase can be attributed to the growing recognition of sustainable architecture by industries and construction authorities around the world, as well as to the pioneering methodologies that were becoming widely accepted. As examples, the Green Standard for Energy and Environmental Design (G-SEED) in 2001 in South Korea, the Comprehensive Assessment System for Built Environment Efficiency (CASBEE) in 2002 in Japan, and the Green Building Tool (GBTool) in Canada.
- **Fourth period (2010-2017):** Finally, in the last period and coinciding with Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (*Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings*, n.d.), there was a marked increase due to concern over sustainable building assessment, which was in turn reflected by an increase in research in this field.

3.2. Bibliometric analysis. Science mapping

After the SLR was performed, 4203 documents were obtained that had been published within the time horizon (1975 - 2017). Finally, the following configuration in SciMAT for the bibliometric analysis was established: word as the unit of analysis, analysis of co-occurrence as the tool to build the networks, index of equivalence as the measure of similarity to standardise the networks, and the k-means clustering algorithm to detect the themes. Documents were analysed by year of publication, journals used, authors, and number of citations. The results obtained are summarised below.

3.2.1. Documents per year

In Figure 4, the distribution of 4203 publications by year is shown**.** An irregular distribution in the number of relevant articles published annually is observed, and the number is not typically high, with the exception of 2017, in which the number of published studies was more than double that of the previous year. Before 2012, there were fewer than 156 publications per year related to this research field, except for 1999, where a peak can be seen coinciding with adoption of the Kyoto Protocol in 1997. This agreement led the main

developed countries and transitioning economies to adopt legally binding commitments to reduce or limit greenhouse gas emissions. Since 2012, there has been a constant increase in the number of articles, demonstrating the attention given in recent years to assessment methods, which have become a vital part of sustainable building research.

3.2.2. Main publications contributing to the research field

565 journals were identified in the study. Table 2 shows the publications for 20.07% of the documents analysed, which are ranked in descending order by the number of citations. Most of them are research journals focusing on energy use and efficiency in buildings, the science of their construction, human interaction with the interior and exterior of built environments, and environmentally sustainable buildings and cities.

Table 2 also includes the most frequently cited document in each journal. As shown, the numbers of publications and citations are not closely related because only four of the major journals (identified in Table 2 with an *), in terms of number of articles, are also ranked among the top five in number of citations. In other words, the most prolific sources have not necessarily been those with the greatest impact in the research field.

3.2.3. Main authors contributing to the research field

A systematic literature review allowed the identification of 8581 authors who have published articles dealing with the topic of the study. Table 3 shows those authors with more than ten published studies, sorted by total number of documents published; it also incorporates the number of citations received, as well as the h-index (Hirsch index), a measure of the authors' professional quality according to the number of times that their scientific articles have been cited (Schreiber, 2015). According to the analysis, J. Kurnitski (Kurnitski et al., 2011) has published the most articles on the topic of building sustainability assessment methods; however, Danny H.W. Li (Danny H.W. Li, Yang, & Lam, 2012) has the highest index for the number of citations. It should be noted that M. Santamouris (Santamouris, 2007) has the highest h-index.

Table 3 also contains the most-cited document for each author, along with the keywords and the number of citations. As shown, a close relationship between the number of publications and the total number of citations does not exist, since only two of the top authors (identified with an *) in number of documents are ranked among the top five in number of citations. Regarding keywords, it should be noted that the concepts of energy, zero-energy building or zero-net-energy building are the most frequent among the authors, in addition to the assessment methods: the Comprehensive Assessment System for Built Environment Efficiency (CASBEE), Leadership in Energy and Environmental Design (LEED) and the Building Research Establishment Environmental Assessment Method (BREEAM).

3.2.4. Most-cited documents

The systematic literature review ended with the study of the most-cited documents. The 4203 documents analysed received 52582 citations. Table 4 lists the ten publications with the greatest number of citations, a total of 3110, which accounts for 5,91% of the total. The most-cited documents focus on different aspects of the thematic field analysed, revealing its diversity. These works range from the evolution of green building and the implementation of Life Cycle Assessment (LCA) in the construction sector to exhaustive reviews of the most common building sustainability assessment methods.

3.3. Content analysis

3.3.1. Strategic diagrams

To analyse the changes over time, strategic diagrams (shown in Figure 5) were generated for the four periods considered (1975-1989, 1990-1999, 2000-2009, and

2010-2017), where the size of the circle is proportional to the number of published documents associated with each research theme. In addition, Table 5 shows performance measures obtained for each theme and period in terms of number of documents, h-index, and values of centrality and density. An analysis of the results obtained for each period is shown below.

First period (1975-1989). According to the strategic diagram presented in Figure 5a, 8 research themes can be observed in the 720 papers selected in this period: environmental assessment tools, residential buildings, life-cycle cost, environmental impact, rating systems, energy resources, passive houses, and office buildings. Of these, 3 were considered motor themes (environmental assessment tools, residential buildings and energy resources), 1 a highly developed and isolated theme (rating systems), 2 emerging or declining (passive houses and office buildings) and finally, 2 others were considered basic (life-cycle cost and environmental impact).

The performance analysis for each theme, as shown in Table 5**,** complements the information provided by the diagram that highlights how the two themes that present the highest performance measures are "environmental assessment tools" and " residential buildings". These themes attain a high impact rate and account for more than a thousand citations, also obtaining a higher h-index than the remaining themes. Environmental assessment tools are designed to assess different types of buildings and emphasise different stages in the life cycle (Haapio & Viitaniemi, 2008), but in this period these tools focused on products and not so much on buildings.

Second period (1990-1999). According to the strategic diagram presented in Figure 5b, in the 756 papers selected in this period, 12 research themes can be observed: energy efficiency, greenhouse gas emissions, life-cycle cost, construction materials, building design, environmental impact assessment, renewable energies, developing countries, rating systems, natural resources, green building, and heat loss. Four of these themes were considered motor themes (construction materials, building design, developing countries and heat loss), 3 highly developed and isolated themes (energy efficiency, greenhouse gas emissions and renewable energies), 2 emerging or declining (rating systems and natural resources) and, finally, 3 basic (environmental impact assessment, life-cycle cost and green building).

In accordance with the performance measures (Table 5), the following 3 themes can be highlighted: life-cycle cost, environmental impact assessment and rating systems. These research themes had a high impact rate and also achieved a higher h-index than the remaining themes. Within the context of the construction industry, life-cycle cost is a method used to assess the anticipated economic performance of a building throughout its life cycle, which includes design and construction, operation and maintenance, and disposal (J.W. Bull, 1992). A green building rating system provides the project team with a framework and a tool to help achieve better sustainable development (Awadh, 2017).

Third period (2000-2009). According to the strategic diagram presented in Figure 5c, in the 756 papers selected in this period, 11 research themes can be observed: building sustainability assessment methods, LEED, heating, BREEAM, CO_2 emissions, intelligent buildings, green building, energy, natural resources, economic aspects and life-cycle assessment. Three of these were considered motor themes (building sustainability assessment methods, LEED, heating and BREEAM), 2 highly developed and isolated themes (life-cycle assessment and intelligent buildings), 2 emerging or declining (economic aspects, natural resources and green building) and finally, 2 others were considered basic (CO_2 emissions and energy).

In accordance with the performance measures, the following 3 themes can be highlighted: building sustainability assessment methods, heating and energy. These research themes obtained a high impact score and also attained a higher h-index than

the remaining themes. The themes heating and energy are closely related topics. Energy use in buildings forms a large part of global and regional energy demand. The importance of heating and cooling in total building energy use is very diverse varying between 18% and 73% of the total (Ürge-Vorsatz, Cabeza, Serrano, Barreneche, & Petrichenko, 2015).

Fourth period (2010-2017). According to the strategic diagram presented in Figure 5d, in the 756 papers selected in this period, 12 research themes can be observed: sustainable building, LEED, heating, urban development, life-cycle cost, indoor environmental quality, construction materials, environmental impact, energy efficiency, Passivhaus Standards, building simulation and social aspects. Five of these were considered motor themes (sustainable building, LEED, heating, urban development and life-cycle cost), 2 highly developed and isolated themes (construction material and energy efficiency), 3 emerging or declining (*Passivhaus* standards, building simulation and social aspects) and finally, 2 others were considered basic (indoor environmental quality and environmental impact).

In accordance with the performance measures, the following four themes can be highlighted: sustainable building, LEED, heating and urban development. These research themes obtained a high impact score and also achieved a higher h-index than the remaining themes. It should be noted that the *emerging theme* social aspects appears in this period with modest performance indicators but it is the baseline for important themes in the future.

3.3.2. Thematic network

The sustainable building theme of the last period is worthy of mention as one of the most characteristic themes if it is analysed from the point of its thematic network. Thus, in Figure 6, we can observe that the already consolidated sustainable building theme in the last period is closely linked to keywords such as net-zero energy building (NZEB), intelligent buildings, building design and climate change. These are all closely related to each other and, in recent years, have been the focus of numerous studies. This indicates where the sustainable building assessment research field is heading, with an emphasis on the study of climate change in relation to the design and consumption of buildings.

3.3.3. Conceptual evolution map

The systematic literature review showed that a very large number of authors, journals and documents deal with the research field of assessment methods and sustainable building. Nonetheless, the strategic diagrams reflect the interest of the scientific community in certain key issues, in parallel with the development of the concept of sustainable building. In the early years, the review demonstrates the concern regarding the environmental impact generated by the buildings themselves, specifically residential buildings, without considering the social and economic aspects of sustainability. In the 90s, life-cycle cost, construction materials and renewable energy, including an interest in the economic aspect of sustainability by the main authors, drew the attention of the largest number of documents. From the year 2000, a great interest was shown in the two main methods used for building sustainability assessment, LEED and BREEAM. More recently, interest has focused on sustainable building and urban development. For this reason, a joint analysis of the evolution of keywords and the thematic evolution of the research field would be interesting. The results are shown in Figure 7ab.

Figure 7a represents the number of keywords per period and their evolution, as well as the number of outgoing and incoming keywords, and the number and percentage of keywords that are retained from one period to the next. The number of keywords clearly

grows throughout the periods, in parallel with the increase in document numbers over the years. The number of keywords increases from 179 to 944 between the first and last periods, a 527% growth rate. Specifically, out of 179 keywords that appeared in the first period, 49% (88) remain in the second period, and 155 words are added, giving a total of 243 words. In the third period, 188 words remain (77%), and 301 new words are included, representing a total of 489. Finally, in the fourth period, 421 (86%) keywords from the third period remain, and 523 new keywords appear, resulting in a total of 944. These results indicate that the number of new and transitional keywords is high but also that the number of keywords shared by successive periods has increased. Therefore, the growing thematic diversity of the research field of sustainable building assessment and the fact that the keywords reappeared with increased strength in the following periods could be indicators that this relatively new research field is gradually being consolidated.

Finally, Figure 7b shows the thematic evolution of the research field through the analysis of the themes' origins and inter-relationships. The thickness of the lines represents the strength of the association measured by the inclusion index. If the graph is analysed from the point of view of the number of documents, residential building appeared with the largest number of core documents in 1975–1989; it evolved into the themes of energy efficiency, life-cycle cost and building design in 1990-1999. Renewable energies appeared with the largest number of core documents in 1990-1999; it evolved into the themes of building sustainability assessment methods, CO_2 emissions, intelligent buildings and green buildings in 2000-2009. Building sustainability assessment methods appeared with the largest number of core documents in 2000-2009; it evolved into the themes of sustainable building, urban development, life-cycle cost, construction material and environmental impact.

It should be noted that the life-cycle cost thematic cluster from 1975 to 1989 continued to use the same label in 1990–1999. However, the number of core documents published on the theme increased and it merged with building sustainability assessment methods, CO_2 emissions, energy and economic aspects. It appeared again in the last period, with the largest number of documents, which shows that life-cycle cost is gaining considerable attention, particularly within the context of sustainable construction (Dwaikat & Ali, 2018). In the construction sector, it is used to compare different design alternatives for a building or a system, considering the life-cycle cost and saving associated with each design option, which explains its relationship with the building sustainability assessment method thematic cluster and the economic aspects thematic cluster. However, the application of life-cycle cost in the construction sector is still limited and is facing practical problems (Dwaikat & Ali, 2018). According to *Botelho et al*.(Botelho, Ferreira, Lima, Pinto, & Sousa, 2017) determining the economic value of environmental impacts is not a simple process, since there are no markets for the environmental goods and services impacted and, therefore, prices are not available. The rating system thematic cluster from 1975 to 1989 also continued with the same label in 1990–1999, but with a larger number of core documents published on the theme and it merged with building sustainability assessment methods, intelligent buildings, economic aspects and life-cycle assessment.

Finally, the green building thematic cluster from 1990 to 1999 continued to have the same label in 2000–2009, but with a larger number of core documents published on the theme. It merged with LEED, urban development, energy efficiency and social aspects, since these topics are closely related. Although there are several terms and meanings associated with what it is to be a green building, they are expected to have a reduced impact on the natural environment and create a more resource-efficient model with regard to building-related practices (Prum, 2010). Green buildings, however, do not only

address issues related to ecological protection; they also address issues related to social justice, public health, and productivity (Cidell & Beata, 2009).

4. Conclusions

The systematic literature review shown is based on the use of SciMAT for the bibliometric analysis of the evolution of the selected research field between 1975 and 2017, using the publications available through the ISI Web of Science (ISIWoS) and Scopus. Trends were analysed, considering an overview and a more specific analysis of four different time intervals during the period under review (1975-1989, 1990-1999, 2000-2009, and 2010-2017).

The analysis has shown that building sustainability assessment methods and sustainable building are significant themes, especially over the last five years, with a gradual increase in the number of studies on these topics published in international journals since 2012. Overlay graphs by periods have shown two main problems: a) the greater number of new and transitory keywords between sub-periods, a sign that this is a field of research in constant evolution that has not yet reached a stage of maturity; and, b) an evolutionary trend in each of the research topics in the field analysed.

Strategic diagrams by period and performance analysis by period also show that emerging studies focus on the inclusion of social and economic aspects. In the early years (from 1975 to 1989), there is a clear concern about the environmental impacts generated by buildings, specifically residential buildings, but not about the social and economic aspects of sustainability. In the 90s, the largest number of documents focused on life-cycle cost, construction materials and renewable energy, including a greater interest in the economics of sustainability by the most prolific authors. Since the year 2000, there has been great interest in the main building sustainability assessment methods, LEED and BREEAM, according to the studies. Finally, recently (2010-2017), interest has focused on sustainable buildings and urban development.

It can be seen how the evaluation instruments have evolved from tools that only looked at environmental aspects towards more complete instruments that include economic and social aspects in the evaluation of building sustainability. This is clearly reflected in the last period where environmental impacts are the basic, crosscutting issue, social aspects are emerging issues, and life-cycle cost is positioned as a motor theme.

The previous findings show that this study is a valuable contribution to research concerning building sustainability assessment methods and sustainable building, because it provides researchers and professionals in the field with a detailed understanding of the *status quo* and predicts the dynamic directions of this field.

Acknowledgments

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Figure 1. Materials and Methods

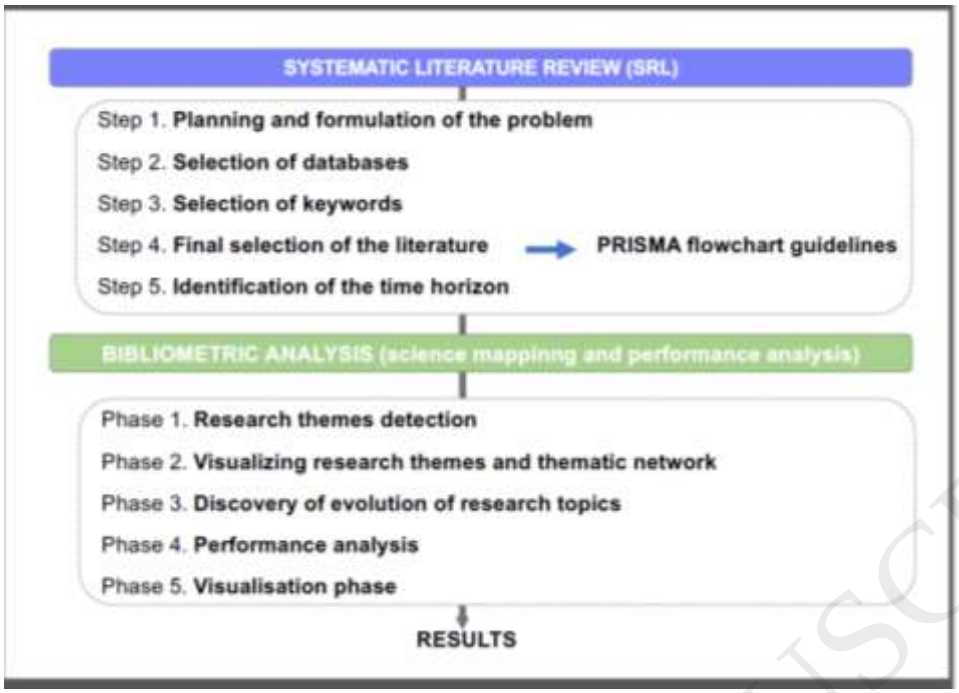

Figure 2. PRISMA flowchart

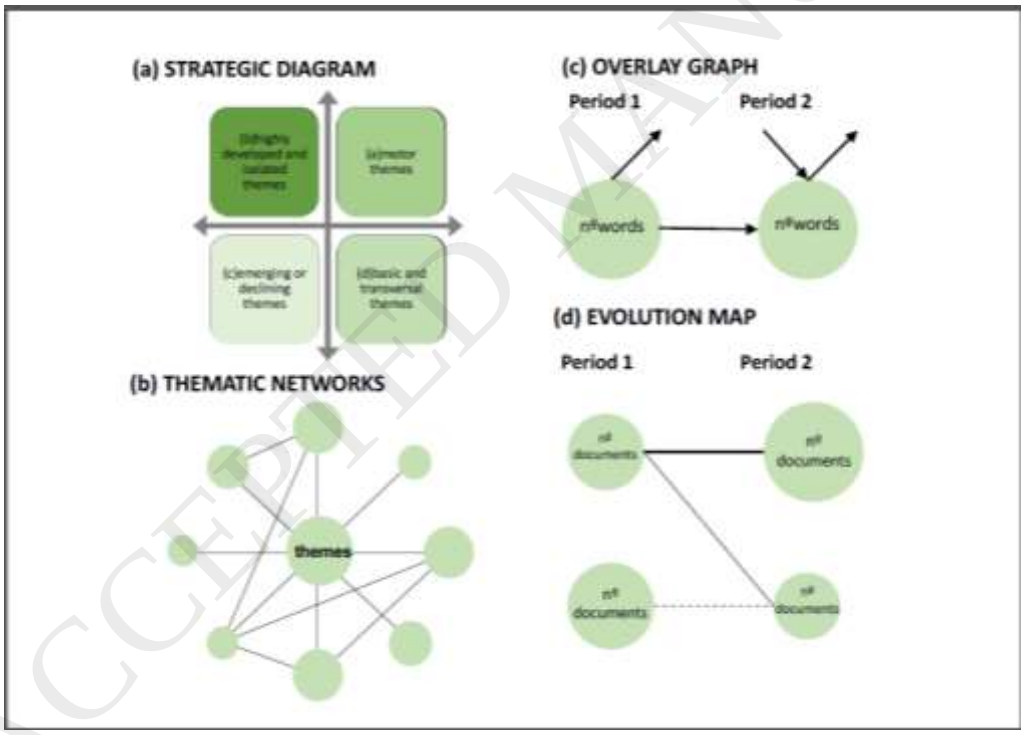

Figure 3. Example of a strategic diagram (a), thematic network (b), overlay graph (c) and evolution map (d)

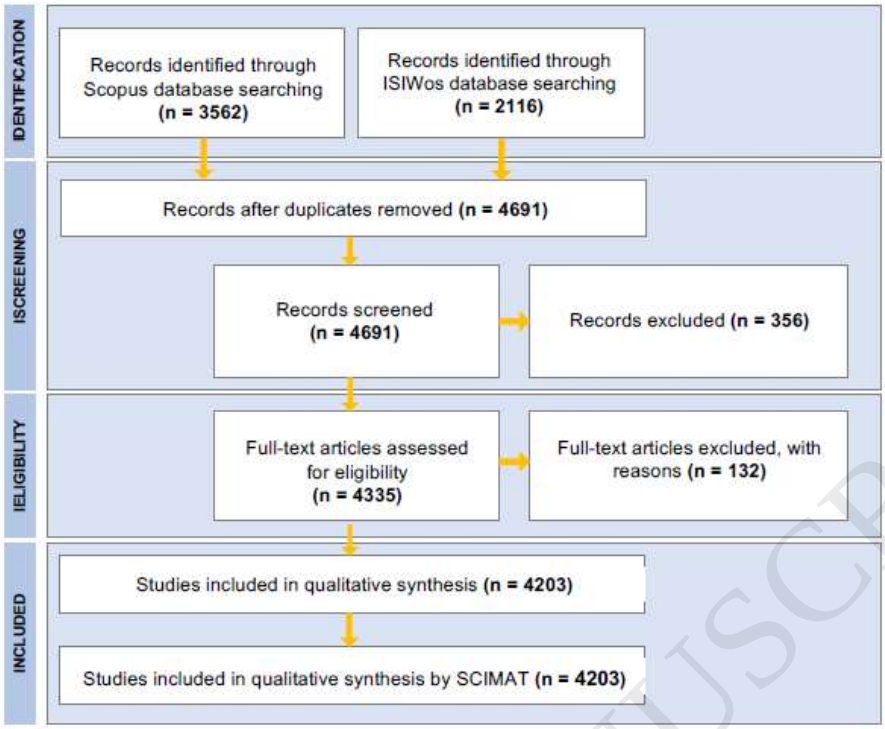

Figure 4. Documents per year

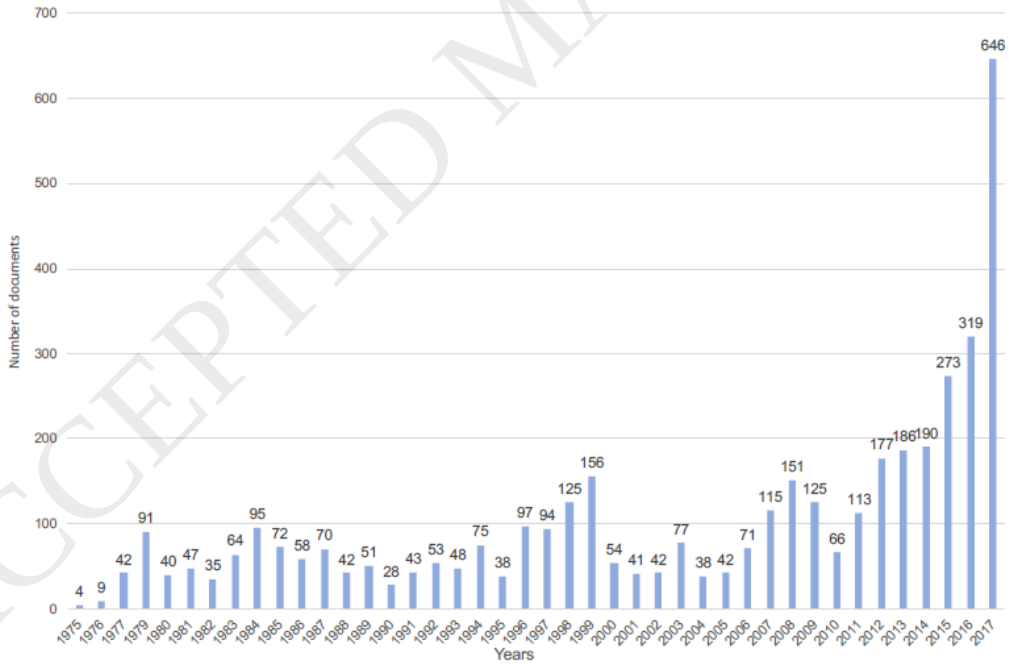

Figure 5. Strategic diagrams by period

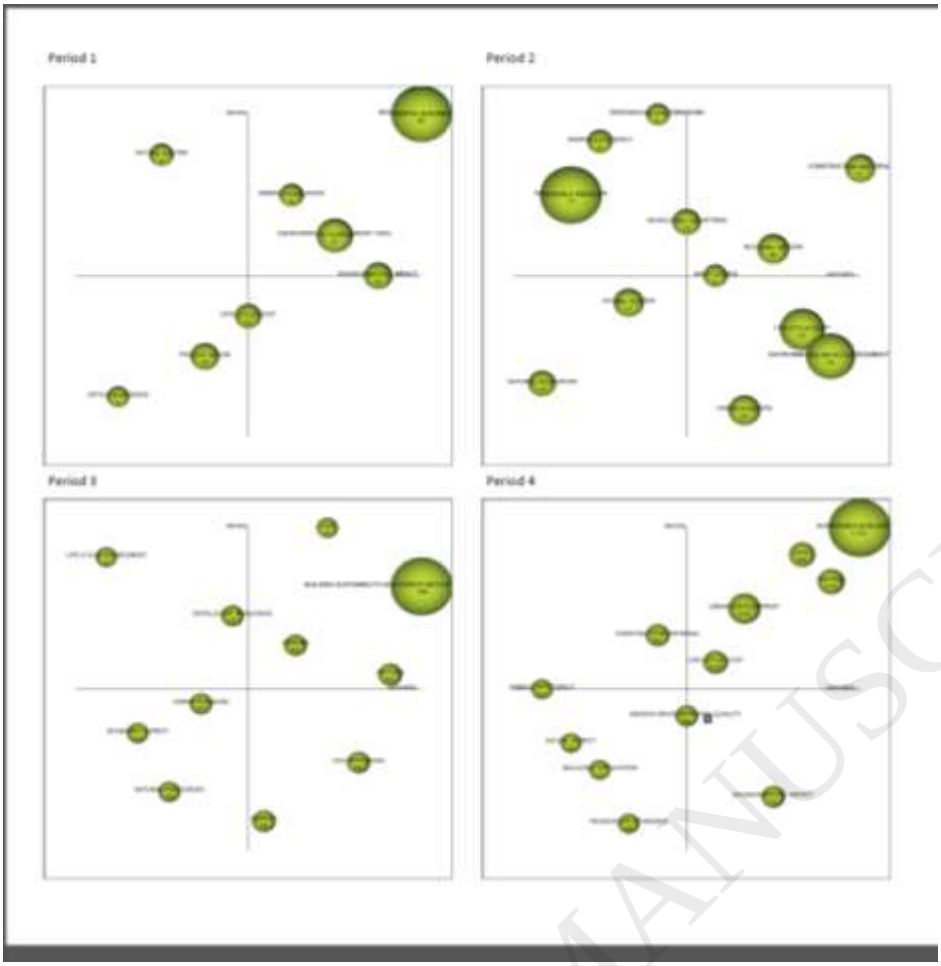

Figure 6. Thematic Network “sustainable building” of fourth period

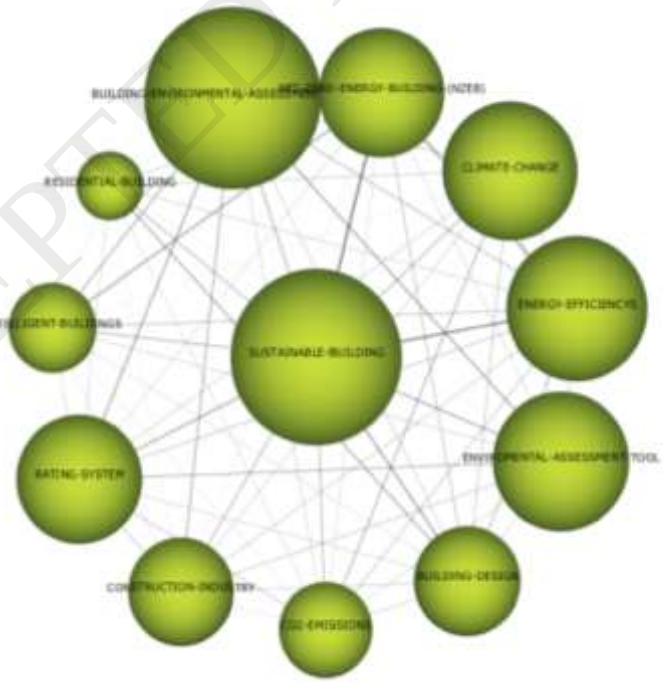

Figure 7. Overlay graph (a) and thematic evolution map (b) of the research field by periods.

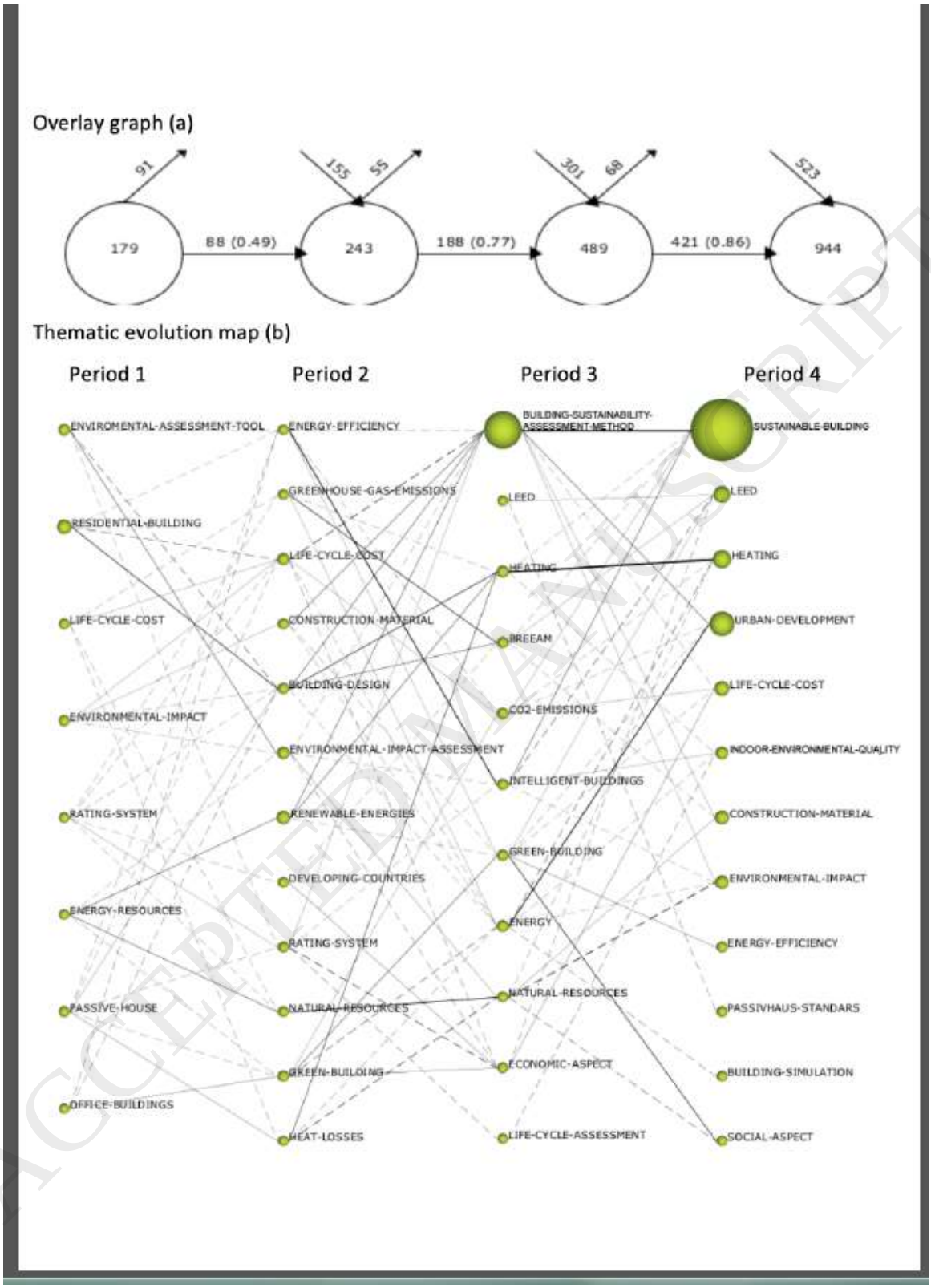

Table 1. Keyword search strings

Concepts	Keyword search strings
building sustainability assessment methods	"assessment methods", "assessment tools", "assessment systems", "indicators", "environmental impact", "social impact" and "economic impact"
sustainable building	"environmental impact", "social impact" and "economic impact"

Table 2. Main publications contributing to the research field

	Name	No. Number of citation indexes of the journal	No. of documents	Most cited document	Number of citations in the document**	Ref.
1	Energy and Buildings*	5451	175	Re-inventing air heating: Convenient and comfortable within the frame of the Passive House concept	184	(Feist, Schnieders, Dorer, & Haas, 2005)
2	Building Research and Information*	4300	114	Are users more tolerant of 'green' buildings?	165	(Leaman & Bordass, 2007)
3	Building and Environment*	3186	163	Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification	301	(Zabalza Bribián, Aranda Usón, & Scarpellini, 2009)
4	Landscape and Urban Planning	1885	38	Applying landscape ecological concepts and metrics in sustainable landscape planning	478	(Botequilha Leitão & Ahern, 2002)
5	Journal of Cleaner Production*	1569	163	Advancing sustainable urban transformation	126	(McCormick, Anderberg, Coenen, & Neij, 2013)
6	Energy Policy	1247	32	Environmental impacts of energy	175	(Dincer, 1999)
7	Applied Energy	973	44	Towards sustainable-energy buildings	168	(Chwieduk, 2003)
8	Energy	727	36	Impact of climate change on energy use in the built environment in different climate zones - A review	114	(Li, Yang, & Lam, 2012)
9	Renewable Energy	641	63	Evaluation of the cost efficiency of an energy efficient building	25	(Gieseler, Heidt, & Bier, 2004)
10	Sustainable Cities and Society	340	35	Sustainable building assessment tool development approach	69	(Alyami & Rezgui, 2012)

* Journals with a large number of articles published which are also among the top five in number of citations

** Number of citations up to 29/10/2018

Table 3. Authors with more than ten published studies in the research field

	Name	No. of documents	Total citations in this work	h-Index	Most cited document	Number of citations in the document**	Ref.
1	**Kurnitski, J. ***	**16**	**281**	**19**	**Cost optimal and nearly zero (nZEB) energy performance calculations for residential buildings with REHVA definition for nZEB national implementation**	**127**	**(Kurnitski et al., 2011)**
2	**Murakami, S.**	**14**	**60**	**6**	**Development of a comprehensive city assessment tool: CASBEE-City**	**28**	**(Murakami et al., 2011)**
3	**Ikaga, T.**	**13**	**38**	**6**	**Development of a comprehensive city assessment tool: CASBEE-City**	**28**	**(Murakami et al., 2011)**
4	**Santamouris, M. ***	**12**	**573**	**60**	**Heat island research in Europe: The state of the art**	**180**	**(Santamouris, 2007)**
5	**Kalamees, T.**	**11**	**175**	**18**	**Cost optimal and nearly zero (nZEB) energy performance calculations for residential buildings with REHVA**	**127**	**(Kurnitski et al., 2011)**

					6definition for nZEB national implementation		
6	**Wang, X.**	**10**	**41**	**25**	**A decade review of the credits obtained by LEED v2.2 certified green building projects**	**20**	**(Wu, Mao, Wang, Song, & Wang, 2016)**
7	**Carlucci, S.**	**10**	**161**	**11**	**Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design**	**135**	**(Attia, Hamdy, O'Brien, & Carlucci, 2013)**
8	**Rezgui, Y.**	**10**	**167**	**27**	**Sustainable building assessment tool development approach**	**69**	**(Alyami & Rezgui, 2012)**
9	**Attia, S.**	**10**	**175**	**10**	**Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design**	**133**	**(Attia et al., 2013)**
10	**Li, D.H.W**	**10**	**644**	**40**	**Impact of climate change on energy use in the built environment in different climate zones - A review**	**105**	**(Li, Yang, & Lam, 2012)**

* authors with a large number of articles published which are also among the top five in number of citations

** Number of citations up to 29/10/2018

Table 4. Most-cited documents

	Title	Authors	Journal	Year	Number of citations of the document *	Percentage of total citations (%)	Ref.
1	Adaptive thermal comfort and sustainable thermal standards for buildings	Nicol, J.F., Humphreys, M.A.	Energy and Buildings	2002	669	1,27	(Nicol & Humphreys, 2002)
2	Sustainable construction-The role of environmental assessment tools	Ding, G.K.C.	Journal of Environmental Management	2008	472	0,89	(Ding, 2008)
3	Sustainable development and climate change initiatives	Damtoft, J.S., Lukasik, J., Herfort, D., Sorrentino, D., Gartner, E.M.	Cement and Concrete Research	2008	385	0,73	(Damtoft, Lukasik, Herfort, Sorrentino, & Gartner, 2008)
4	A critical review of building environmental assessment tools	Haapio, A., Viitaniemi, P.	Environmental Impact Assessment Review	2008	320	0,60	(Haapio & Viitaniemi, 2008)
5	Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification	Zabalza Bribián, I., Aranda Usón, A., Scarpellini, S.	Building and Environment	2009	301	0,57	(Zabalza Bribián, Aranda Usón, & Scarpellini, 2009)
6	Trends in European cultural landscape development: Perspectives for a sustainable future	Vos, W., Meekes, H.	Landscape and Urban Planning	1999	224	0,42	(Vos & Meekes, 1999)
7	Green building research-current status and future agenda: A review	Zuo, J., Zhao, Z.-Y.	Renewable and Sustainable Energy Reviews	2014	199	0,37	(Zuo & Zhao, 2014)
8	Life-cycle assessment and the environmental impact of buildings: A review	Khasreen, M.M., Banfill, P.F.G., Menzies, G.F.	Sustainability	2009	199	0,37	(Khasreen, Banfill, & Menzies, 2009)
9	Developing a green building assessment tool for developing countries - Case of Jordan	Ali, H.H., Al Nsairat, S.F.	Building and Environment	2009	178	0,33	(Ali & Al Nsairat, 2009)

10	Building environmental assessment methods: Applications and development trends	Crawley, D., Aho, I.	Building Research and Information	1999	163	0,30	(Crawley & Aho, 1999)
Total					3110	5,91	

* Number of citations up to 29/10/2018

Table 5. Performance analysis by period

Name	No. of documents	No. of citations	h-Index	Centrality	Density
PERIOD 1 (1975-1989)					
1. Enviromental assessment tool	37	154	8	23.48	12.52
2. Residential building	97	88	5	38.92	43.23
3. Life cycle cost	13	9	2	12.78	6.45
4. Environmental impact	19	47	4	37.49	11.06
5. Rating system	8	6	2	10.31	35.09
6. Energy resources	9	103	3	14.66	17.71
7. Passive house	19	12	2	11.62	2.88
8. Office buildings	4	1	1	2.22	2.26
Period 2 (1990-1999)					
1. Energy efficiency	8	46	5	31.25	35.88
2. Greenhouse gas emissions	5	58	4	34.74	69.07
3. Life cycle cost	43	865	16	59.43	10.45
4. Construction material	17	271	8	102.36	24.19
5. Building design	20	356	7	54.84	13.44
6. Environmental impact assessment	50	1,616	21	78.23	8.48
7. Renewable energies	73	2,075	18	29.4	17.3
8. Developing countries	13	233	8	37.89	14.86
9. Rating system	17	1,003	13	32.77	10.72
10. Natural resources	12	847	5	28.62	5.39
11. Green building	20	278	9	49.44	2.92
12. Heat losses	6	325	3	44.48	12.93
Period 3 (2000-2009)					
1. Building sustainability assessment method	590	16,947	69	126.26	0.82
2. Leed	9	84	5	33.99	1
3. Heating	43	1,714	20	40.53	0.55
4. Breeam	26	847	15	33.94	0.64
5. Co_2-emissions	34	773	12	37.57	0.27

6.	Intelligent buildings	25	488	7	31.46	0.73
7.	Green building	27	623	11	19.8	0.45
8.	Energy	36	988	17	33.57	0.09
9.	Natural resources	16	597	7	18.41	0.18
10.	Economic aspect	12	258	7	13.8	0.36
11.	Life cycle assessment	3	200	3	1.2	0.91
Period 4 (2010-2017)						
1.	Sustainable building	1,122	11,574	46	148	41.32
2.	Leed	140	3,133	22	45.25	9.83
3.	Heating	172	2,147	26	60.53	9.45
4.	Urban development	316	2,407	25	36.55	9.37
5.	Life cycle cost	103	863	13	35.55	7.74
6.	Indoor environmental quality	56	314	8	21.31	7.55
7.	Construction material	81	660	10	17.9	8.63
8.	Environmental impact	71	649	14	36.83	1.95
9.	Energy efficiency	17	51	4	3.97	7.72
10.	Passivhaus standars	16	95	6	9.82	1.58
11.	Building simulation	7	137	4	5.31	2.42
12.	Social aspect	9	132	5	5.16	3.28