

Review

How BIM Contributes to a Building's Energy Efficiency throughout Its Whole Life Cycle: Systematic Mapping

Tatjana Vilutienė ^{1,*}, Rasa Džiugaitė-Tumėnienė ², Diana Kalibatiėnė ³ and Darius Kalibatas ¹

¹ Department of Construction Management and Real Estate, Faculty of Civil Engineering, Vilnius Gediminas Technical University, 10223 Vilnius, Lithuania; darius.kalibatas@vilniustech.lt

² Department of Building Energetics, Faculty of Environmental Engineering, Vilnius Gediminas Technical University, 10223 Vilnius, Lithuania; rasa.dziugaite-tumeniene@vilniustech.lt

³ Department of Information Systems, Faculty of Fundamental Sciences, Vilnius Gediminas Technical University, 10223 Vilnius, Lithuania; diana.kalibatiene@vilniustech.lt

* Correspondence: tatjana.vilutiene@vilniustech.lt; Tel.: +370-61-29-07-00

Abstract: This paper presents a systematic mapping (SM) study with the aim to determine how Building Information Modeling (BIM) methodologies and technologies contribute to energy-related analyses over the course of the entire building life cycle. The method adopted in the study is based on a set of seven research questions. We used a mixed technique combining co-citation analysis and bibliographic coupling in order to analyze the publications' datasets for the period 2010–2020. The main advantage and novelty of this study are that the joint dataset from the Scopus and Web of Science databases was used to develop the keyword map. The main findings of this study indicate that many BIM-based applications can be used to analyze the building energy performance at all stages of the building life cycle. However, the applications of BIM in conjunction with other information technologies are limited and are still in the initial stage. In the future, the main improvements should be focused on process, model, system, tool, use and information modeling. The most promising long-term solution is an open BIM framework based on open standards, which allows the integration of BIM and energy simulation tools and satisfies specific data exchange requirements.

Keywords: energy analysis; building life cycle; BIM; Building Information Modeling; systematic mapping

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1. Introduction

For several decades, the large share of global energy consumption devoted to creating an indoor microclimate has been of significant interest among the worldwide community and has often been a policy focus. The energy efficiency in buildings has increased in recent years. The most significant and economically promising area for energy savings is residential and public buildings [1]. However, the comprehensive and ambitious energy efficiency improvements in buildings require an understanding of real energy needs and the analysis of a large amount of data. Therefore, Building Information Modeling (BIM), as a working method, together with energy modeling tools, has been intensively applied over the last decade. Building Information Modeling (BIM) refers to an information management methodology that has, at its core, the adoption of a standard-based approach to managing information across the whole life cycle of built assets [2]. BIM is still an optional working method in many countries, except for cases of specific public buildings [3]. In some countries [4], the BIM methodology just recently became mandatory for all works of a certain value.

The main motivations for integrating BIM and energy analysis are the presentation of building geometry and material information [5,6], the integration and visualization of

energy-related information [7–9], the estimation of energy efficiency [10–14] and the optimization of energy consumption [8,13,15–17]. BIM can be used to optimize building management (operation and maintenance) by aiding building managers, who scan, analyze and process building information in a digitized 3D environment [15]. Such integration offers the opportunity to increase the efficient use of energy resources in buildings, improve employee productivity and create better working conditions for tenants [16,18–20]. IoT real-time sensing data (energy, air temperature, relative humidity and CO₂ concentration) represented in a BIM-based building management system help the user to identify the indoor climate, determine the level of thermal comfort and indoor air quality and even change occupancy behavior [21]. The application of BIM technologies involves not only the planning, design, construction and monitoring of new buildings to increase their energy efficiency, as open BIM technologies can efficiently integrate energy conservation measure data into BEP simulation models during the refurbishment of buildings [10]. Therefore, the optimal solution for the retrofitting scenario can be obtained more efficiently [22,23]. Furthermore, 3D urban-scale building energy prediction platforms are used to provide faster and better design solutions with improved building energy efficiency for urban planning, new constructions and building retrofits [24]. In addition, using data mining publicly available sources for 3D modeling, LCA results can be obtained that could be used for urban-scale life cycle modeling, in order to increase the sustainability of the built environment [25]. However, the wider use of integrated BIM and energy analysis lacks well-established interoperability strategies between BIM and energy simulation tools [15,16,20,26–32].

The initial stage of applying BIM in energy management involves providing basic building information for the energy analysis [6,7,14,29,30,33,34]. The integration of BIM and energy analysis is essential in designing and developing highly energy-efficient buildings [19,35]. Combining BIM and value engineering technologies optimizes the green building envelope in terms of energy savings and life cycle costs [36]. Integrating LCA with BIM during the conceptual stage enables the designers to evaluate the building's environmental performance during its life cycle [37]. Moreover, by using BIM as an interface during building design, architects can improve the sustainable design process by visualizing the thermal performance of individual building components [7]. The integration of sustainability assessment into the BIM environment allows designers to assess the level and design of sustainability and implement energy-saving measures at an early design stage more reliably and in a shorter time [38–40]. BIM-based energy performance simulations improve the decision-making process regarding overall sustainability [41,42]. The BIM platform can be exploited to ensure the more sustainable design of buildings through the integration of technologies that use renewable energy sources, e.g., facilitating the design of complex PV layouts on facades [5]. Using IFC-based BIM data for the automated generation of control strategies when building energy systems increases the overall quality of the building operation and reduces operational costs [43].

Although many software tools can be used to perform dynamic energy modeling and analysis, the design goal and the actual energy efficiency do not coincide. A review of the studies [15,16,29] showed an increasing focus of energy modelers on the operation and maintenance (O&M) phase of the whole building life cycle. The O&M is the longest phase and has the highest energy demands; it includes the following key processes: maintenance planning, maintenance of engineering systems, energy cost analysis, asset and space management, sustainability, monitoring and analysis, and accident prevention [14,20,26,29,44]. It is essential to collect data on energy consumption during the operational phase in order to ensure the future energy-efficient design of buildings.

An analysis of the literature sources [29,45–47] showed that software compatibility and BIM data transformation in the management phase are still in their initial stages and most of the current studies are focused on energy resource management. It was found that the effective application of the building management systems used in the O&M phase is

still a challenge. More research is needed, covering the data requirements, areas of inefficiency and process changes. A review of the literature revealed the main issues arising during the recent development of the BIM methods. Due to the rapid changes in BIM technologies and the integration of BIM and energy analysis at all building life cycle stages, more researcher studies are required. Moreover, industry professionals are required to possess up-to-date knowledge on BIM implementation and research in buildings [11,12,14,17,29,32,48–51].

In this context, it should be noted that the contribution of the BIM working method to a building's energy efficiency at all stages of the building life cycle is still under discussion. A comprehensive review regarding the integration of BIM and energy analysis throughout the whole life cycle of the building is essential. The research hotspots can be identified in order to lay the foundation for future studies. Consequently, systematic mapping would help to identify more general research trends and topics within the analyzed field. Moreover, systematic mapping allows us to visualize the observed results and trends using bibliometric analysis tools.

The current paper aims to present a systematic mapping review focused on BIM and energy efficiency. Therefore, the main research question is the following: How do BIM methodologies and technologies contribute to a building's energy efficiency throughout its whole life cycle?

This study provides insight into the future development of solutions related to improving the integration of energy analysis and BIM working methods.

The contributions of this study are as follows:

- We provide an alternative approach to review the research progress regarding the integration of energy analysis and the BIM working method based on systematic mapping and bibliometric analysis;
- We identify the research trends through an analysis of bibliometric indicators, laying a foundation for future development in the integration of energy analysis and the BIM working method;
- We use extended data samples from the Scopus and Web of Science databases and provide a global view of the research topic and a more comprehensive perspective than other analyzed reviews.

This paper's main advantage and novelty are that the data for analysis are retrieved from the Scopus and Web of Science databases. Specifically, the keyword map was made based on the data taken from both databases and the thesaurus was developed for this purpose. The developed thesaurus can be used repeatedly to perform similar studies and to update the existing review. The main findings of this study indicate that many BIM-based applications can be used to analyze the building energy performance at all stages of building life cycle.

The paper is organized as follows: Section 2 presents the analysis of the related works on the integration of BIM and energy analysis and it discusses issues, limitations and drawbacks. Section 3 introduces the data sources, research questions and method for data analysis. Section 4 presents the results, including a keyword map and the number of publications, countries and subject categories. Section 5 summarizes the results, discusses the answers to the research questions and proposes future research directions.

2. Background and Related Works

Available studies have targeted different issues concerning BIM and energy efficiency. This section compares the current study with previous, similar reviews based on the following criteria: research domain, research questions, database from which the papers were retrieved, search keywords, number of analyzed papers, period in which the articles were published and the presence of a keyword map in the results of the reviews. As shown in Table 1, our study differs from previous reviews regarding all entries. Gao and Pishdad-Bozorgi [29] presented a literature review and content analysis focusing on

energy management issues in the building operation and management stage. They analyzed articles extracted from the WoS database for a ten-year period, from 2007 to 2018. Matarneh et al. [15] performed a bibliometric analysis and focused on data exchange and interoperability between BIM and FM systems. Papers were retrieved from the Scopus database and covered the period from 2008 to 2018. Wong et al. [16] presented a literature review on digital technologies used in the building operation stage for maintenance and facilities management. Articles were retrieved from the Scopus and Google Scholar databases and covered the period from 2004 to 2017. Andriamamonjy et al. [32] performed a scientometric analysis of papers retrieved from the WoS database. Papers focused on a narrow area of BIM applications within BEPS and covered the period from 2016 to 2018. Shirowzhan et al. [27] presented a systematic search of papers from 2012 to 2015, retrieved from the Scopus database, to analyze BIM compatibility issues. Meng et al. [52] performed a bibliometric analysis of papers published in 2020 retrieved from the Scopus and Google Scholar databases to reveal the most relevant issues related to building life cycle management, technology application and integration. Carvalho et al. [53] investigated BIM integration solutions with tools such as BREEAM, LEED and SBTool, in order to evaluate the performance of buildings and projects; the results were presented in papers published over a ten-year period from 2009 to 2019. Li et al. [54] performed a review and bibliometric search of WoS papers published from 2009 to 2019 that investigated energy inputs and outputs during the building life cycle. Murtagh et al. [50] reviewed the progress and potential for improvement in the construction sector as discussed in papers published in 2014–2020. Venkatraj et al. [17] performed a systematic literature review of papers published in the period from 1997 to 2020 focused on solving issues related to energy management during the building life cycle. Muller et al. [20] presented a systematic literature review and analyzed papers published in the Scopus, Engineering Village and Proquest databases in the period from 2016 to 2018. The review covered solutions for efficient interoperability within the life cycle, supported by BIM. Solaimani and Sedighi [55] performed a systematic literature review of papers focused on sustainability and lean and green construction, published in the Scopus database from 1998 to 2017. In most reviews, the articles were retrieved from a single database, mainly from WoS [29,32,52–54] or Scopus [15,16,20,27,55]. A few referred to Google Scholar [16,17,52] or Proquest [20]. Unlike those described above, our review analyzes a range of articles taken from two databases, WoS and Scopus. The research questions posed in this review do not replicate the research questions of previous studies, as the latter were mainly focused on separate building life cycle stages [15,16,29], different domains of energy analysis [15–17,29,54] and sustainability [17,20,50,53,55]. Most of the previous reviews [16,17,20,29,50,53,55] did not use a keyword map. On the contrary, this review presents the results obtained by analyzing a keyword map of BIM and energy analysis. Additionally, the present research analyzes the most recent papers, published in the period from 2010 to 2020.

Table 1. Summary of similar reviews on BIM and energy.

Ref.	Research Method	Research Domain	RQ ¹	Data-Base	Kwd. Map	No. of Papers	Year
[29]	Literature review and content analysis	Energy management in BIM-O&M	Yes	WoS	No	291	2007–2018
[15]	Bibliometric analysis	Data exchange and interoperability of BIM and FM systems	Partly	Scopus	Yes	502	2008–2018
[16]	Literature review	DT in FM	Partly	Scopus, Google Scholar	No	120	2004–2017
[32]	Scientometric analysis	BIM with BEPS	Partly	WoS	Yes	2662	2016–2018
[27]	Systematic search	BIM compatibility	No	Scopus	Yes	57	2012–2018

[52]	Bibliometrics statistical	Building life cycle management BIM in LEED, BREEAM,	Partly	WoS, Google Scholar	Yes	153	2020
[53]	Systematic review	BIM for SBTool, replicability level of applied procedures	Partly	WoS	No	41	2009–2019
[54]	Holistic review and bibliometric search	All energy inputs and outputs within the building life cycle	Partly	WoS	Yes	255	2009–2019
[50]	Editorial review	Progress and potential for improvement in the construction sector	No	VSI of Journal of Cleaner Production	No	34	2014–2020
[20]	Systematic literature review	Efficient interoperability within lifecycle supported by BIM	Partly	Scopus, Engineering Village, Proquest	No	230	2006–2018
[55]	Systematic literature review	Sustainability and Lean construction	No	Scopus	No	118	1998–2017
C.s.	Systematic literature review	Energy-related analysis within the lifecycle	Yes	WoS, Scopus	Yes	908	2015–2020

¹ This column indicates whether the research questions discussed in the analyzed review are similar to those presented in our review. Possible answers are No (i.e., research questions differ), Partial (i.e., research questions overlap partially) or Yes (i.e., research questions are the same).

A review of previous studies involving BIM-based energy analyses revealed the growing interest in energy simulation methodologies applied to various stages of the building life cycle, contributing to discussions on improving data exchange and interoperability. A summary of the research questions and issues, a complete list of keywords and the main results of similar reviews focused on BIM-based energy simulations are presented in Appendix S1 (https://github.com/DianaKalibatiene/BIM_Energy [Accessed on 12/09/2021]).

Future research directions discussed in recent studies include the information exchange and interoperability problems [15,20,27,28], energy management during the building operation stage and predictive analysis using BIM-aided building management systems [12,13,16,29,32,52,56,57]. These areas of interest are especially relevant, considering the issues introduced recently in the field of the BIM-based design and construction of new buildings or retrofitting of existing buildings as zero-emission, positive-energy or active houses [17,34,35,58–60].

Most studies emphasize the need for more accurate data transfer, including the following: site-to-BIM [15]; between the BIM model and various simulation environments and tools, such as building energy simulation tools [8,12,26,28,30–32,34,35,51,56,61]; GIS [16,44,62–64]; BIM-O&M applications [12,17,20,26,29,52]; building sustainability assessment tools [20,50,53,55]; between BIM and IoT [9,13,16,52,54]. Matarneh et al. [15] stated that future research could focus on the information exchange and interoperability issues that arise throughout the whole building life cycle, as well as easier BIM implementation in FM. The necessity of analyzing the interoperability of GIS and BIM-based information was mentioned in the review by Wong et al. [16]. Shirowzhan et al. [27] analyzed the compatibility and interoperability of BIM at the technical level and determined specific measures to predict the level of BIM compatibility in different contexts.

Li et al. [54] discussed the integration of technologies and methods in different areas and the possibility of improving operability amongst technologies (e.g., BIM, IoT, blockchain, AI and GIS).

The most recent research described above reveals the current research trends and shows the growing interest in BIM applications in energy management and related fields. However, the existing research is limited to a single database. The advantage of the present research is that its analysis is based on a combined set of articles from two databases, WoS and Scopus. Moreover, in this study, the publication period of the analyzed papers is longer and covers ten years, until 2020. During the last ten years, BIM technologies and methodology have evolved significantly. Through this study, the progress made over the last decade in BIM applications within energy analysis can be tracked.

3. Methods

Systematic mapping (SM) of BIM and building energy efficiency was employed as proposed in [65,66]; this method allows researchers to identify research trends, detect topics within the analyzed field [52,53] and visualize the findings [67]. The research method is presented in Figure 1. SM was systematically organized following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [48] such as planning, conducting and reporting. The main SM steps are explained in this section. The PRISMA checklist [55] provides a summary of SM, which is included in the Supplementary Materials (Document S2) (https://github.com/DianaKalibatiene/BIM_Energy [Accessed on 12/09/2021]). The present study uses systematic mapping (SM) but not a systematic literature review, which is narrower.

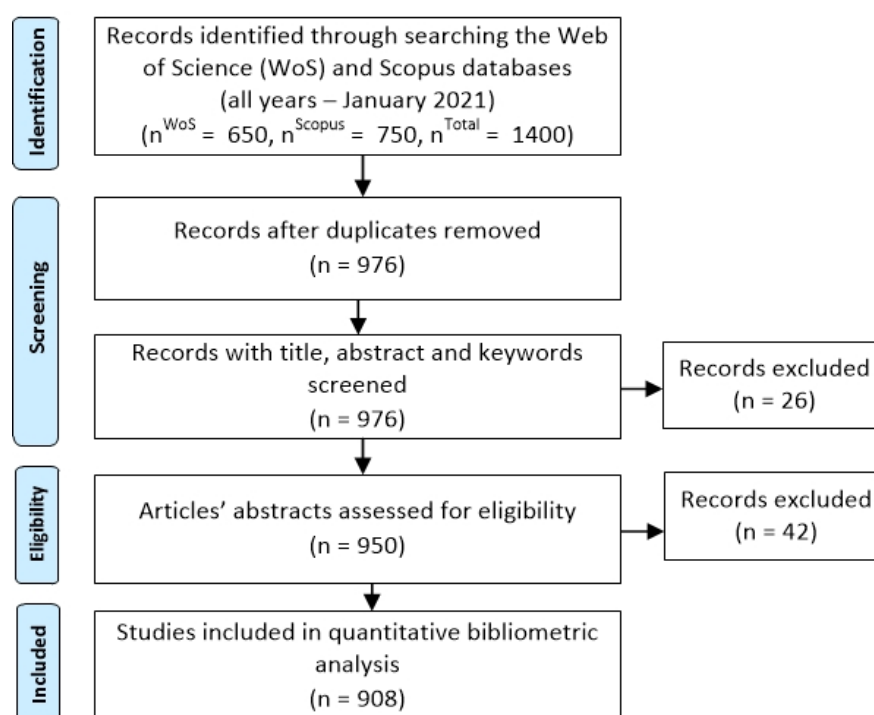


Figure 1. The PRISMA flow diagram.

The overall results of the paper selection procedure are illustrated in Figure 1 as a PRISMA flow diagram. Note that not all steps correspond to the original PRISMA flow diagram because we conducted SM.

3.1. Research Questions

Well-supported design decisions and an effective and accurate design process are required in order to achieve optimal building energy performance throughout the whole building life cycle. Therefore, nowadays, BIM is used as a data source for energy analysis during the early design stage [32]. During the operation and maintenance stage, BIM is

applied as a platform to integrate and visualize energy data from BMS, to simulate and forecast energy consumption, to monitor indoor climate parameters, to perform fault detection and diagnosis (FDD) and to assess the sustainability of the building [29]. Previous reviews [15–17,20,27,29,32,50,52–55] showed that the main gap in this area is the integration of BIM and energy analysis tools, including faulty data exchange and interoperability. Therefore, this mapping study aims to determine how BIM methods and technologies improve energy-related analyses performed during the whole life cycle of a building. The main research question (RQ) is as follows:

How do BIM methodologies and technologies contribute to a building's energy efficiency throughout its whole life cycle?

According to the main RQ, the following sub-questions are defined:

RQ-1: When have BIM and energy efficiency studies been published?

RQ-2: Which BIM and energy efficiency topics are covered?

RQ-3: Which BIM tools are used for energy analysis?

RQ-4: Which stage of a building's life cycle do the authors discuss in their research?

RQ-5: Which construction participants (stakeholders) are involved in BIM and are related to energy saving?

RQ-6: What are the main challenges in the application of BIM tools for energy analysis?

RQ-7: What are the future directions referred to in the studies?

Below, the search protocol is presented, which was developed by the third and fourth authors and later reviewed by the first and second authors.

3.2. Source Evaluation and Quality Assessment

Nowadays, there are a number of scientific databases and search systems. Therefore, a question arises—which databases are the most appropriate when performing a review. In [68], 28 databases were compared and it was found that only 14 of 28 were well suited to a systematic literature review since they met all necessary performance requirements. Among these 14 systems, emphasizing the Civil Engineering research area, the main databases were the following: BASE (multidisciplinary), ScienceDirect (multidisciplinary), Scopus (multidisciplinary), Web of Science (WoS) (multidisciplinary) and Wiley Online Library (multidisciplinary). These databases were compared according to the following criteria: the quality of the research and the ability to download (not separate) the full search results for systematic mapping analysis.

There is a common problem in assessing the quality of published research in which papers do not present in sufficient detail the approaches used because of the space limitation in journal volumes and, in particular, conference proceedings [69]. Therefore, in this study, we tended to include papers with a more significant volume. Considering this requirement, many articles in conference proceedings were excluded from the study. Consequently, BASE and Wiley Online Library, having many proceeding papers, were excluded from the study. The assessment of the ability to download the search results in full for systematic mapping found that WoS and Scopus contained the most thoroughly ordered bibliographic data and supported the most sophisticated search strings among the compared databases. They allowed us to download both the bibliographic data and abstracts of the selected papers (i.e., WoS, up to 500 items at once; Scopus, all search results at once).

After considering all the advantages and disadvantages, WoS and Scopus were chosen for this systematic mapping, taking into account the time and performance constraints. They index high-quality peer-reviewed papers. Other relevant papers reporting related systematic studies have also used these databases, e.g., Scopus in [15,16,20,27,55] and WoS in [29,32,52–54] (albeit separately).

3.3. Search Keywords

Population, Intervention, Comparison, Outcomes, Context (PICOC), proposed by [70], was used to develop an effective search strategy.

Population: In our context, the population covered papers on BIM and building energy efficiency.

Intervention: In the context of this study, we investigated how BIM methodologies and technologies contribute to the energy efficiency analysis during the whole life cycle of a building.

Comparison: In this study, a comparison was not made.

Outcomes: No measurable effect was considered, as we did not focus on the outcomes of the papers. We were focused on the relevant keywords and their systematic mapping.

Context: This study was conducted in an academic context by analyzing existing BIM and energy efficiency papers.

The identified keywords were “building information model” and “energy”. These keywords were divided into sets and their synonyms were considered in order to formulate the search string.

- Set 1: Establishing the search for building information modeling, i.e., “building information model” or “BIM” or “building information”.
- Set 2: Search terms related to energy efficiency and energy analysis. Therefore, we used the general keyword “energy”.

As the keywords identified from the RQs and PICOC criteria were similar, we grouped them into two sets. Each set of searches was performed on Web of Science (WoS) and Scopus, selected based on the source evaluation described in Section 3.3. The limitations (such as search string, document type, language and categories) used in the search can be found in Table 2. We limited the categories during the search (i.e., civil engineering, construction and engineering fields), so as to exclude medicine, chemistry, humanitarian and other fields that were unrelated to the present study.

Table 2. Search strings in WoS and Scopus.

Database	Search String	Document Type	Language	Categories	Search Results
WoS	(“building information*” OR BIM) AND (“energy”)	article OR review	English	WoS Categories ¹	650
Scopus	(“building information*” OR bim) AND (“energy”)	article OR review	English	Scopus Categories ²	750
Total ³ :					1400

¹ WoS Categories: Construction Building Technology OR Engineering Civil OR Green Sustainable Science Technology OR Environmental Sciences OR Urban Studies OR Engineering Environmental OR Environmental Studies OR Computer Science Software Engineering OR Engineering Multidisciplinary OR Materials Science Multidisciplinary OR Architecture OR Automation Control Systems OR Thermodynamics OR Computer Science Hardware Architecture OR Management OR Computer Science Interdisciplinary Applications OR Engineering Electrical Electronic OR Computer Science Artificial Intelligence OR Engineering Industrial OR Remote Sensing OR Computer Science Information Systems OR Engineering Mechanical OR Engineering Manufacturing OR Operations Research Management Science. ² Scopus Categories: Engineering, Energy, Computer Science, Materials Science, Mathematics, Decision Sciences, Multidisciplinary. ³ Duplicates are not excluded.

This study was conducted in January 2021 without year restrictions on the search. The document type was limited to articles and reviews, since conference papers rarely provide sufficient details of the methods used due to space limitations in conference proceedings [69]. Moreover, conference papers are often expanded in journal papers.

3.4. Study Selection and Quality Assessment

After downloading the search results from WoS and Scopus into Mendeley, they were checked for duplicates. An initial set of total references consisted of 1400 entities, in which Mendeley found 976 unique references. After excluding duplicates, a review of the abstracts of all papers was performed by all authors. During the analysis of the abstracts, non-relevant papers that used the BIM but did not refer to a “building information model” were excluded. Finally, a set of 908 relevant papers were obtained and translated to VOSviewer to develop a keyword map.

3.5. Used Tools

In this study, we used two main tools: 1) Mendeley, for managing bibliographic references, and 2) VOSviewer, for developing keyword maps.

As demonstrated in [59], scientists have used different mapping tools, including VOSviewer, BibExcel, CiteSpace, CoPalRed, Sci2, VantagePoint and Gephi, for the analysis, mapping and visualization of bibliographic data. A comprehensive review of visualization tools was not the main aim of this paper; therefore, we used VOSviewer (<https://www.vosviewer.com/> [Accessed on 29/01/2021]) as an analysis and mapping tool. VOSviewer produces a network from the given bibliographic data. All networks consist of nodes and links. Nodes, which can present papers, publications, authors, organizations, countries or keywords, with a higher number of occurrences, are more significant. Links show the relationships among the nodes. Thicker ties present closer relationships among nodes. For more details on VOSviewer, see [71,72].

3.6. Data Extraction

We used the authors’ abstracts to extract data from the identified studies, create a keyword map on BIM and building energy efficiency and perform the co-occurrence analysis. In VOSviewer, an automatic keyword identification technique is applied to identify the closeness and strength of existing links [73], providing a unified approach to keyword mapping and clustering [74].

A thesaurus of keywords related to BIM and building energy efficiency was created in order to refine the keyword extraction from the abstracts and obtain a more relevant set of keywords. Without the use of the thesaurus the risk of double counting the same terms/keywords appears. Therefore, a map created based on bibliographic data or text data needs to be cleaned [75]. This was compiled according to the following limitation rules:

- merge different spellings of the same word, such as “building information modeling” and “building information modelling”;
- merge abbreviated keywords with full keywords, such as “information foundation class” and “IFC”;
- merge synonyms, such as “component” and “building element”;
- exclude general keywords, such as paper, year, model, etc., since these keywords contain insignificant information and the usefulness of a map tends to increase when they are excluded.

The thesaurus consisted of 326 merged and excluded keywords and can be found here at https://github.com/DianaKalibatiene/BIM_Energy (Accessed on 12/09/2021). Finally, the keywords that appeared to be the most relevant and most interesting were selected for in-depth analysis (see Section 4). The thesaurus was developed by the third author and checked for correctness by the other authors.

3.7. Methods Used for the Analysis of the Results

The content analysis was used to perform the analysis of the obtained keyword map. It consisted of the following steps:

- Chronological occurrence analysis of keywords, which was based on the study of the keywords' year of occurrence;
- Keyword occurrence analysis, which was based on an evaluation of the frequency of the keywords' occurrence;
- Keyword co-occurrence analysis, which was based on the relationships between the keywords;
- Keyword clustering analysis, which was based on an evaluation of keyword clustering;
- Keyword occurrence analysis, which was performed according to the building life cycle stages.

3.8. Validity Evaluation

Based on [76,77], the following types of validity were identified and discussed in this study: internal, external, construct and conclusion validity. Although we carefully followed the SM process to minimize any threats to the validity of the results and conclusions drawn, we encountered some issues, which are discussed below.

In determining the construct validity, we encountered three major problems in this SM. First, we used brainstorming, in which all the authors participated, to define the RQs and analyze similar reviews in the related work section. The research questions covered all the relevant aspects that characterized the existing research in our area of interest. The RQs were explicitly designed for the defined goal and were related to different aspects of BIM and building energy efficiency in the Civil Engineering field. The questions were systematically answered and finalized through several iterative improvement processes. Second, the inclusion of all the relevant works in the field could not be guaranteed. We addressed this problem by combining and manually searching previous literature reviews on BIM and building energy efficiency.

Moreover, WoS and Scopus were chosen to perform this study. Consequently, the search string was compiled regarding the defined RQs and PICOC. However, there was a risk of obtaining a limited selection of papers. Therefore, inclusion and exclusion criteria guided the selection in order to mitigate this risk and more than one researcher analyzed each article.

Regarding internal validity, a major problem was that most papers did not provide accurate and direct statements regarding BIM usage for building energy efficiency. A review of the related existing literature reviews was performed to address this issue. For the development of the keyword map, we used the abstracts of the papers rather than the titles, since titles present only a short description of a research study and only general terms rather than exact terms are typically used.

External validity refers to the results and conclusions of the SM. They are only valid for BIM and building energy efficiency in the research area of Civil Engineering and we do not attempt to generalize our conclusions beyond this scope. Therefore, any risks associated with external validity are minimized. We have explicitly described all of the steps performed in the systematic mapping by detailing the procedure as defined in the Research Methods (see Section 3). We have also referred to our created thesaurus, which is necessary to ensure reproducibility and provide evidence to support our findings.

4. Results

4.1. Time Series Analysis (RQ-1)

Figure 2 chronologically shows the number of papers published between 1985 and 2020, which totals 908. Consequently, this chronological distribution allows us to answer RQ-1 (“When have BIM and energy efficiency studies been published?”). The following preliminary conclusions can be drawn: research on BIM and building energy efficiency emerged in 1999 and has risen sharply since 2007. Figure 2 illustrates the increasing interest of scholars in this field of research over the past decade.

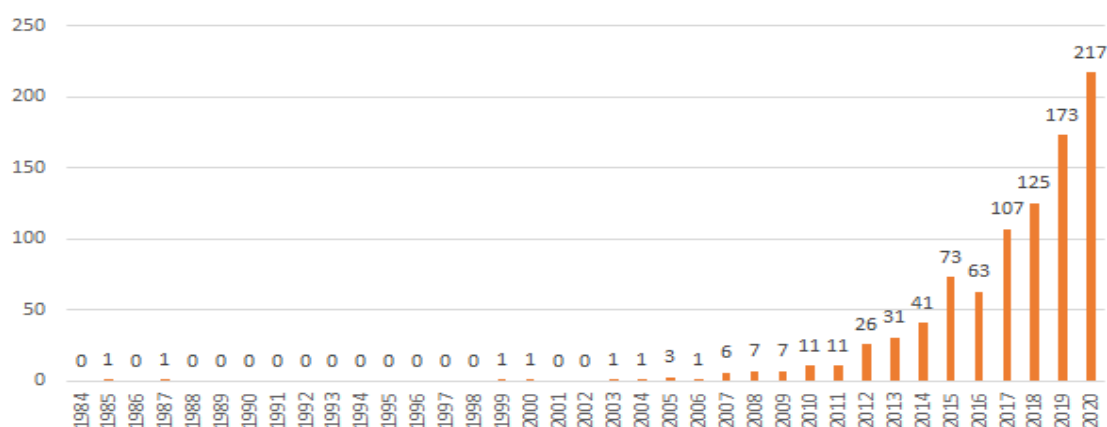


Figure 2. Relevant papers on BIM and building energy efficiency were published each year between 1985 and 2020.

4.2. Keyword Occurrence Analysis

Based on the analysis methods described in Section 3.7, three keyword maps were created as follows: 1) a map of the most common keywords (most commonly occurring in research papers) to identify the most analyzed areas in BIM and energy efficiency; 2) a map of moderately common keywords to identify the moderately analyzed areas in BIM and building energy efficiency; 3) a map of the least common keywords to identify the areas that are in the early development stage. Keyword analyses allow conclusions to be drawn about the dominant research and applied methods.

First, we created the map of the most common keywords, presented in Figure 3; when producing this map, we restricted the minimum number of keywords' occurrences to 50. Using VOSviewer, we identified 50 keywords that met the threshold. The ten most relevant keywords (RQ-2) were the following: BIM (561), building (550), model (315), energy (296), analysis (277), system (275), building design (262), tool (256), process (255) and information (235).

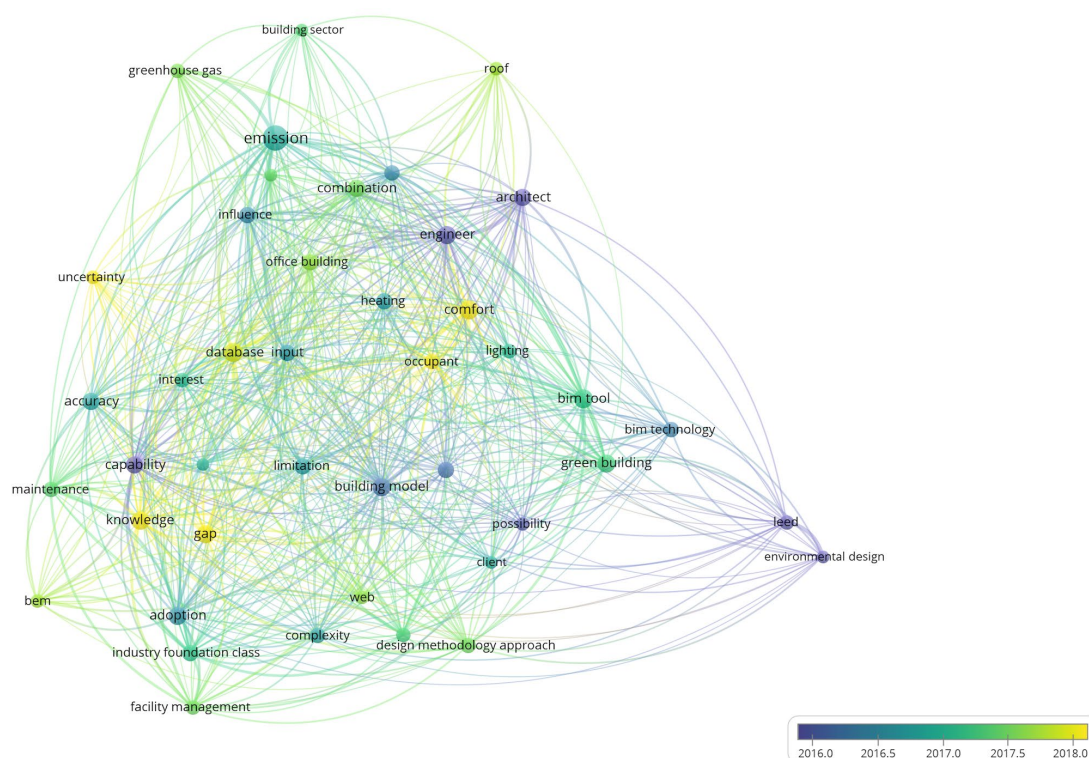


Figure 4. The moderately used keywords in BIM and building energy efficiency.

We can conclude that maintaining knowledge in the area of BIM and building energy efficiency is important, as BIM usage in building energy efficiency analysis influences facility management. Another dependency that can be observed in the map is that the occupants' comfort is the most studied and influential aspect of a green building. In addition, within the topic of BIM and building energy efficiency, the most important participants are identified as the engineer and architect, who should be familiar with and apply BIM technology for building energy efficiency analysis (RQ-5).

Third, we created a map of the least common keywords (Figure 5); to create this map, we restricted the number of keyword occurrences to the range from 10 to 20. The most relevant keywords (RQ-2) were the following: building project (19), facade (19), society (19), Autodesk Revit (18), building energy (18), construction process (18), documentation (18), investment (18), IT (18), public building (18), ratio (18), refurbishment (18), reliability (18), Revit (18), specification (18) and team (18). As can be seen in Figure 5, the APY varied in the interval 2014–2019. The newest keywords (RQ-8), whose APY was 2019 or 2018, were the following: questionnaire, IoT (Internet of Things), global warming, thermal comfort, sustainable construction, sensitivity analysis, air conditioning, correlation, classification, smart building, Autodesk Revit, BIM data, life cycle cost and operational energy.

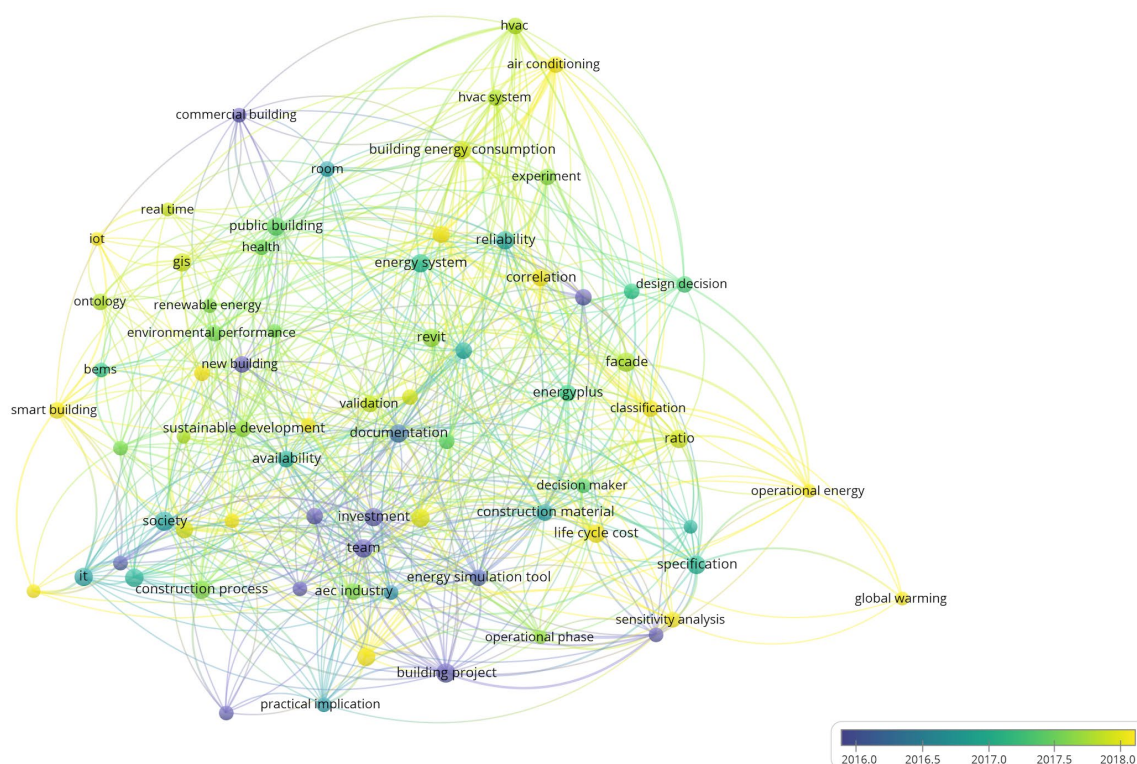


Figure 5. The least common keywords in BIM and building energy efficiency.

From the above, we can conclude that the topic of BIM and building energy efficiency is discussed in terms of global warming, thermal comfort, sustainable construction, sensitivity analysis, air conditioning, smart building and operational energy. Moreover, the data were analyzed (RQ-2, RQ-3) by drawing upon the following concepts: 3D model, classification, correlation, energy simulation, experiment, questionnaire, sensitivity analysis, design decision, green building design and sustainable building design.

Software or computational tools used for BIM and building energy efficiency analysis (RQ-3) could be found in the analyzed papers. The most-used BIM authoring software included the following: Autodesk Revit, ArchiCAD, OpenBuildings, Sketchup, ArcGIS and Allplan, as well as energy simulation tools such as Autodesk Green Building Studios (GBS), Autodesk Ecotect Analysis, OpenStudio, Energy Plus, IES-VE, DesignBuilder, BEopt, eQuest, TRNSYS and IDA-ICE. In addition, the use of these tools enabled the collection of data on building energy systems and HVAC systems from existing BEMS, using IoT and integrating them into the common BIM environment.

To answer RQ-4 (Which stage of the building's life cycle do the authors discuss in their research?), we analyzed all the keywords found in the three keyword maps. Extracted keywords were classified into three categories: (1) building life cycle stage; (2) BIM use case; (3) activity of a building life cycle stage.

Note that, in the table, synonyms for the roles of participants are indicated with a slash ("/"). Consequently, we found thirteen keywords representing various life cycle stages (see Table 3) mentioned regarding the topic of BIM and building energy efficiency. The found keywords are presented according to their occurrence in sources. As can be seen in Table 3, the three most frequently occurring keywords were the following: building design (248), implementation (79) and early design (62). The newest keywords (RQ-8) were the following: sustainable construction (APY 2019), facility management (APY 2018), construction process (APY 2018), green building design (APY 2018) and operation phase (APY 2018).

Table 3. Stages of a building's life cycle as analyzed in papers on BIM and building energy efficiency.

Keywords	Occurrences	APY
building design	248	2017
implementation	79	2017
early design	62	2017
planning	40	2017
facility management	27	2018
construction project/building project	44	2017
architectural design	21	2016
construction process	18	2018
sustainable building design	11	2015
sustainable construction	11	2019
green building design	10	2018
operation phase	10	2018

According to the most commonly used classification proposed by the Royal Institute of British Architects in the RIBA Plan of Work 2020 [78], there are eight stages in a building's life cycle, which are as follows: (0) strategic definition; (1) preparation and brief; (2) concept design; (3) spatial coordination; (4) technical design; (5) manufacturing and construction; (6) handover; (7) use. The keywords related to the building's life cycle stages could be found in the relevant papers reviewed in this study, which are presented in Table 3. They coincide with the RIBA stages as follows: stages (0) and (1) represented as "planning"; stages (2) and (3) represented as "early design", stage (4) represented as "building design", "architectural design", "sustainable building design" and "green building design"; stages (5) and (6) represented as "implementation", "construction project/building project", "construction process" and "sustainable construction"; stage (7) represented as "operation phase" and "facility management". The preliminary conclusion can be made that the most analyzed life cycle stages are building design and construction. The least studied life cycle stages are strategic definition, preparation and brief, concept design, spatial coordination and use.

Table 4 presents the BIM use cases of a building's life cycle. The most frequently occurring BIM use cases (RQ-4) were the following: analysis/energy analysis (295), assessment/evaluation (216), simulation/energy simulation (200), management (115) and energy efficiency (111). As can be seen from Table 4, some of the presented keywords seem to be similar, such as "building model", "3D model" and "modelling". Although there are similarities, those terms, along with the number of years and occurrences, reflect the evolution of BIM concepts. In 2015, the "3D model" implied a technique that refers to 3D drawing. Later this concept evolved to "modeling" and "building model" that include more variables, such as time and cost. The newest keywords (RQ-8) were the following: sensitivity analysis (APY 2019), simulation/energy simulation (APY 2018), management (APY 2018), consumption (APY 2018), optimization (APY 2018), scenario (APY 2018), modeling (APY 2018), accuracy (APY 2018), energy demand (APY 2018), estimation/life cycle cost (APY 2018), energy model (APY 2018), uncertainty (APY 2018), energy management (APY 2018), correlation (APY 2018), environmental impact/environmental performance (APY 2018) and real-time (APY 2018). Therefore, in the last three years, in order to increase the sustainability of the new and built environment, optimize the design of green buildings and NZEB and extend the use of BIM-based energy analysis, a number of assessment/evaluation methods, simulation methods and tools have been used.

Table 4. BIM use cases found in the topic of BIM and building energy efficiency analysis.

Keywords	Occurrences	APY
analysis/energy analysis	295	2017
simulation/energy simulation	200	2018
assessment/evaluation	216	2017
management	115	2018
energy efficiency	111	2017
decision making	99	2017
integration	97	2017
building energy performance/lighting	125	2017
consumption	85	2018
quality	68	2017
efficiency	67	2017
interoperability/interaction	88	2017
optimization	61	2018
energy saving/energy conservation	80	2017
environmental impact/environmental performance	69	2018
scenario	52	2018
building model	44	2016
modelling	39	2018
accuracy	38	2018
influence	36	2017
energy demand	35	2018
monitoring	34	2017
exchange	33	2017
estimation/life cycle cost	46	2018
visualization	29	2017
prototype	25	2017
collaboration	24	2017
energy model	24	2018
uncertainty	24	2018
environmental design	22	2015
design alternative	21	2017
energy management	20	2018
documentation	18	2016
investment	18	2016
reliability	18	2017
specification	18	2017
correlation	16	2018
3D model	14	2015
total energy consumption	14	2017
sensitivity analysis	13	2019
real-time	10	2018

Figure 6 (based on the data presented in Appendix A) presents the stage–use case co-occurrence matrix. The columns and the rows of the matrix present keywords and the cells indicate the co-occurrence strength of the two keywords. Moreover, the intensity of the green color indicates that keywords tended to appear together—the more intense the green color, the stronger the co-occurrence. If the cell at the intersection of two keywords is blank, then a co-occurrence between them was not found. Figure 6 shows that strong co-occurrences existed among the following keywords: building design–analysis/energy

analysis (83), building design–assessment/evaluation (51), implementation–analysis/energy analysis (30), early design–decision-making (22) and implementation–assessment/evaluation (20). Figure 6 confirms previously obtained research findings based on the analysis of the building life cycle stages and the most common BIM use cases. The analyzed period’s research studies mainly focus on energy analysis and simulation during building design and construction. The most recent studies focus on identifying energy management and optimization solutions using sensitivity and scenario analyses, as well as real-time simulations.

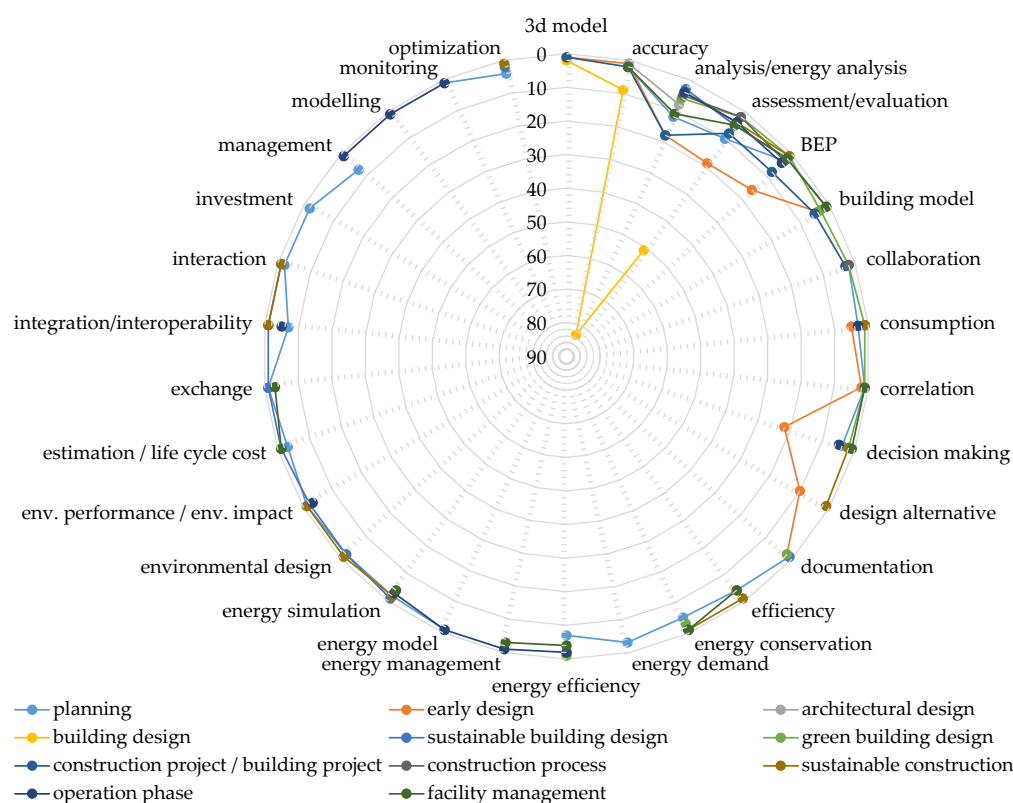


Figure 6. The stage–use case co-occurrence matrix in BIM and building energy efficiency analysis. Note: values of keywords co-occurrence are presented in reverse order to improve legibility.

Based on the keyword analysis, it was possible to identify the most common activities related to energy modeling during the various stages of the building life cycle. Table 5 presents the activities of the building’s life cycle. As can be seen in this table, the most frequently occurring activities (RQ-4) were the following: information modeling (202), development (177), engineering (56), improvement (56) and control (43). The newest keywords (RQ-8) were the following: questionnaire (APY 2019), control (APY 2018), renovation/refurbishment (APY 2018), classification (APY 2018) and validation (APY 2018). To obtain greater insight into the links between activities and BIM use cases and to draw conclusions, an additional co-occurrence analysis was performed.

Table 5. Activities of the building’s life cycle as found in BIM and building energy efficiency analysis.

Keywords	Occurrences	APY
information modelling	202	2017
development	177	2017
engineering	56	2017
improvement	56	2017
control	43	2018

maintenance	32	2017
measurement	26	2017
regulation	26	2017
collection	24	2017
renovation/refurbishment	42	2018
communication	22	2016
classification	14	2018
design decision	14	2017
validation	14	2018

Figure 7 (based on the data presented in Appendix B) presents the activity–use case co-occurrence matrix. It shows that strong co-occurrences exist among the following keywords: information modeling–analysis/energy analysis (78), information modeling–assessment/evaluation (63), development–analysis/energy analysis (57), development–assessment/evaluation (28), development–decision-making (27) and information modeling–energy efficiency (27). This analysis reveals that, in this context, simulations and scenario analysis are preferable to ensure efficient decision-making and increase the robustness of results.

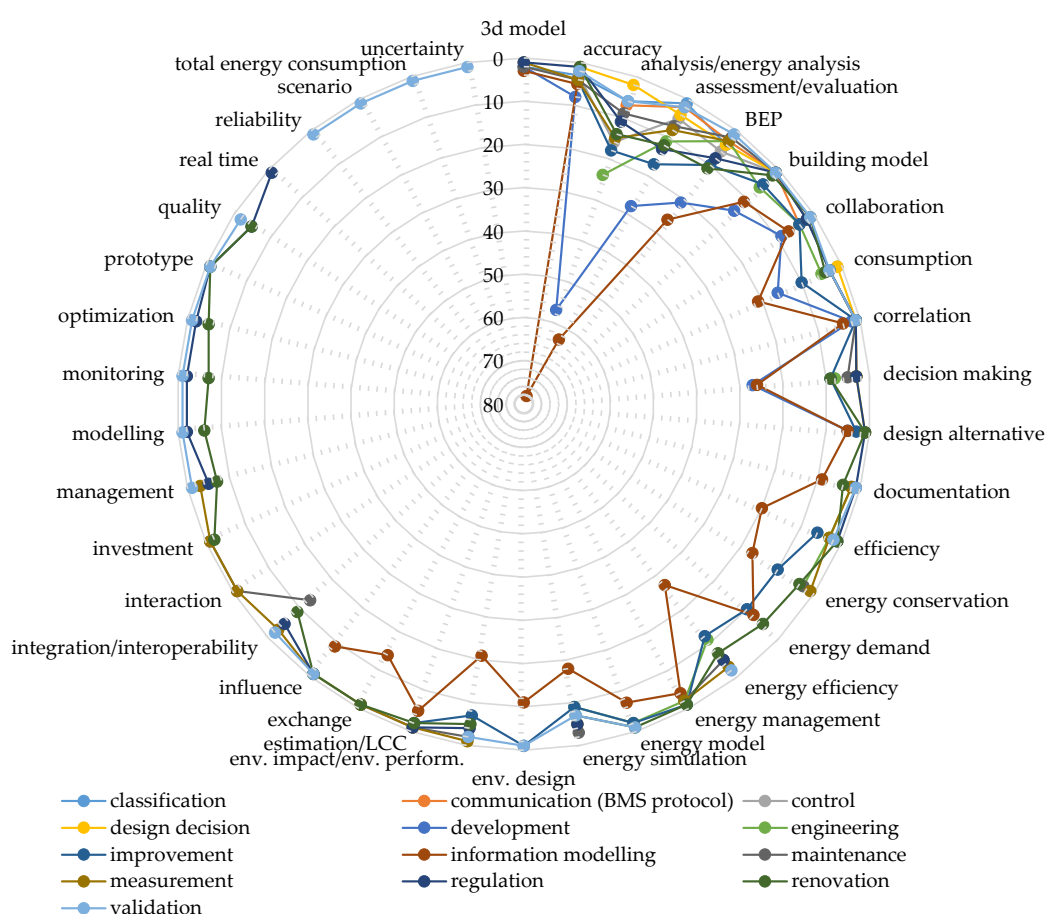


Figure 7. The activity–use case co-occurrence matrix in BIM and building energy efficiency analysis. Note: values of keywords co-occurrence are presented in reverse order to improve legibility.

Based on the keyword maps, the identified roles of participants in the topic of BIM and building energy efficiency are presented in Table 6 (RQ-5). Note that, in the table, synonyms for the roles of participants are indicated with a slash (“/”). The three most frequently occurring participants were the following: project/team (181), designer/architect/design team (111) and industry/sector (99). The participants having the most recent

APY (RQ-8) were as follows: government (APY 2018) and facility manager (APY 2018). This tendency was probably due to the recent active participation of public clients (governmental institutions) in the legal regulation of BIM activities.

Table 6. Participants in the topic of BIM and building energy efficiency analysis.

Participants	Occurrences	APY
project/team	181	2016
industry/sector	99	2017
designer/architect/design team	111	2015
user/occupant	83	2017
engineer	44	2016
owner/client	47	2016
professional	25	2017
researcher/university	25	2017
government	20	2018
society	19	2017
operator	15	2016
facility manager	12	2018
contractor	11	2015

We next sought to determine the main challenges (RQ-6) related to BIM and building energy efficiency analysis. First, the keywords and their synonyms associated with the main challenges were extracted from the developed keywords map, such as the following: challenge (83), problem (83), improvement (56), gap (45), limitation (34), complexity (31), uncertainty (24), difficulty (13) and interoperability issue (11). Second, a co-occurrence matrix was developed to analyze the main challenges, as in Figure 8 (Appendix C).

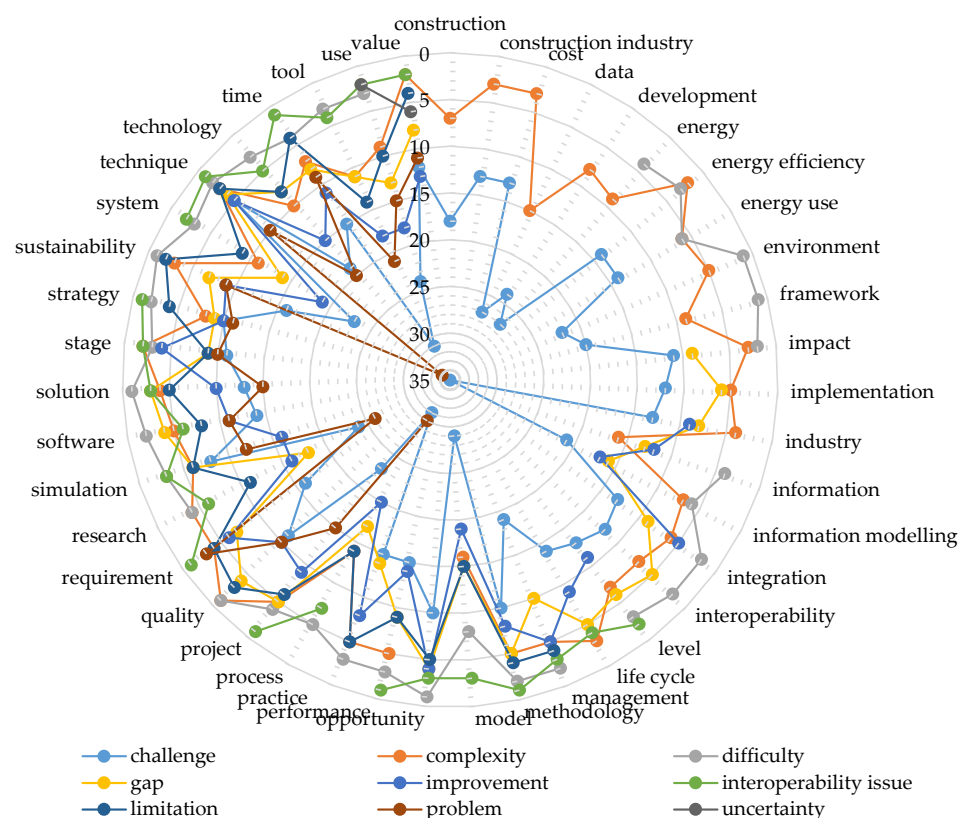


Figure 8. The challenges co-occurrence matrix in the BIM and building energy-efficient topic. Note: values of keywords co-occurrence are presented in reverse order to improve legibility.

As can be seen in Figure 8, the most frequently occurring pairs were the following: challenge–information (35), problem–system (34), challenge–tool (31), challenge–process (31) and problem–process (30).

5. Discussion

The main aim of this mapping study was to determine how BIM methods and technologies contribute to a building's energy efficiency throughout its whole life cycle. Following the analysis and systematic mapping of the literature, as presented in Section 4, this section presents an in-depth discussion of the findings relating to BIM and energy analysis during the whole life cycle of a building.

The chronological analysis of papers published on BIM and building energy efficiency (RQ-1: When have BIM and energy efficiency studies been published?) shows that this topic has gained momentum in recent years due to its promising application in BIM-based building analysis. The most analyzed topics (RQ-2: Which BIM and energy efficiency topics are covered?), found in the map of the most commonly occurring keywords, are quite general, such as building (i.e., the corresponding keywords are the following: building design, process, etc.), energy efficiency (i.e., energy, analysis) and BIM (i.e., model, tool, system, information, etc.). Papers on these general topics analyze specific problems, which fall into subtopics, found in the map of moderately occurring keywords, such as emission, database, comfort, gap, adoption, engineer, green building, etc. The analysis of the least common keywords allowed us to identify topics that are developing, which include the following: building project, facade, society, Autodesk Revit, construction process, documentation, investment, IT, public building, refurbishment, reliability, specification and team. Increasing attention is being paid to the development of renovation projects [34,58], digitalization of the management process of public sector buildings [13,16,51] and investment in sustainability assessment initiatives [41,52,61]. Problems related to data collection, storage, reliable transfer and analysis also remain relevant. Starting from 2018, the topics deal with topical issues: the use of intelligent technologies, such as IoT and machine learning; modeling, evaluating and predicting the parameters of the indoor climate of the building; and the behavior of building users. Therefore, energy simulation throughout the whole life cycle of the building has become particularly relevant.

To promote sustainable construction and achieve high-performance buildings with less embodied energy and a low impact on the environment, a detailed energy analysis must be carried out throughout the whole building life cycle. According to the keywords identified in this study, the possible applications of the integration of BIM and energy analysis during the four stages (planning, design, construction, operation and maintenance) of the building life cycle are summarized in Figure 9.

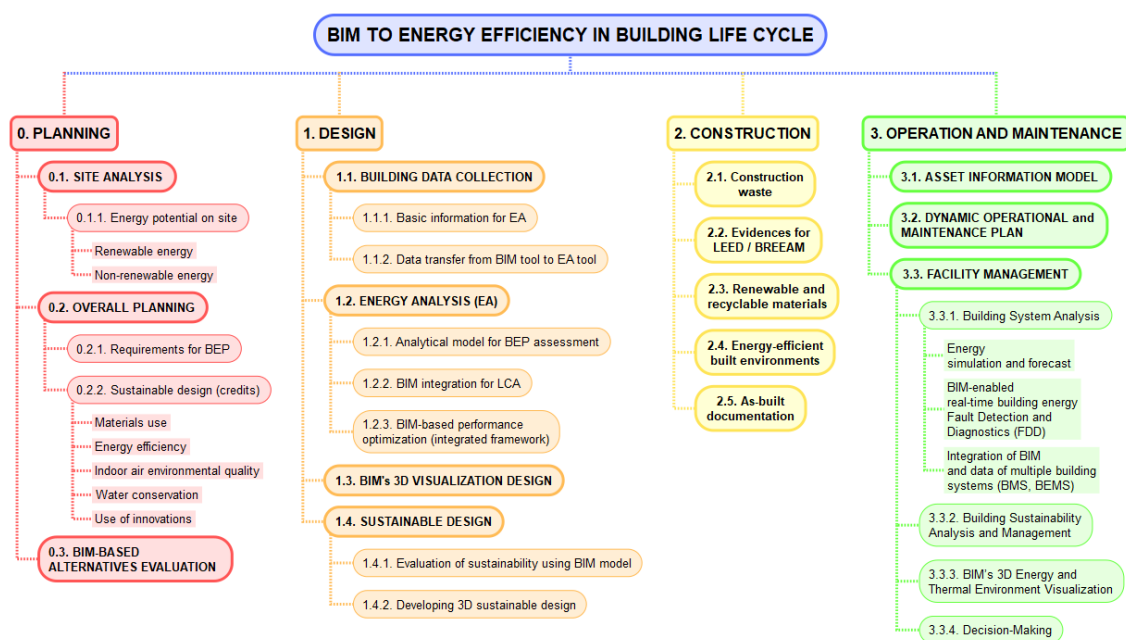


Figure 9. BIM contribution to energy efficiency during the building life cycle.

As shown in Figure 9, the main BIM model can be used for site analysis, overall planning and BIM-based alternative evaluation at the planning stage. At this stage, the BIM model is mainly used for primary energy analysis and the assessment (evaluation) of the energy efficiency of selected alternatives. At the design stage, the BIM model is used for building data collection, energy analysis (EA), the BIM's 3D visualization design and the assessment/evaluation of sustainable building energy performance. This study showed that BIM is mainly applied for energy analysis during the design stage of the building. At the construction stage, BIM technologies are used to obtain evidence for sustainable construction by implementing the estimation of the construction waste, the assessment of the quantities of renewable and recyclable materials, the evaluation of the energy efficiency and environmental performance and obtaining high-quality “as-built” documentation. At the operation and maintenance (O&M) stage, the BIM model is used to create an asset information model, a dynamic operational and maintenance plan and perform facility management. During the operation stage, BIM is used for energy monitoring, simulation, analysis and management to optimize the building performance. The data exchange between BIM technologies and building management systems has the highest importance during the O&M stage. As can be seen in Figure 9, different types of BIM-based energy analysis and building performance assessment/evaluation are performed at each stage of the building life cycle. Therefore, increasing numbers of scientific papers are examining the possibilities of applying BIM tools (RQ-3) to solve energy analysis tasks at separate building life cycle stages. In the context of BIM, many software simulation applications can be adopted analyze the building energy performance at all stages, starting from the initial stages of planning to the final stage of operation and maintenance (the most used one are mentioned in Section 4.2).

The results of RQ-4 show that the most analyzed life cycle stages of a building are the early design and design stages. The least analyzed life cycle stage is the operation and maintenance of the building. This finding can be explained by the fact that the application of BIM in building energy management is not highly developed and future studies are needed in this regard.

During the evaluation of energy efficiency at each life cycle stage of a building, many problems arise and many challenges (RQ-6) between commonly used energy simulation

and BIM tools need to be overcome. As shown in Figure 8, the main problems are related to the keywords: system, process, lack of research, tools and technology. At the planning and design stages, the main issues are the efficient exchange of different models, missed components and information errors during the information exchange between BIM and energy analysis tools. During the operation and maintenance stage, BIM facilitates the acquisition, storage and processing of energy-related information. Therefore, the BIM tools and technologies must be integrated with other big data technologies. The applications of BIM in conjunction with other information technologies are limited and are still in the initial stage [54]. As shown in Figure 8, the most complex elements are process, model, information and data. Therefore, the main challenges are related to the keywords information, process, tool, model, data and energy. The main improvements should be focused on process, model, system, tool, use and information modeling. According to Andriamamonjy et al. [32], the most promising long-term solution is an open BIM framework based on open standards, which allows BIM and energy simulation tools to be integrated and satisfies specific data exchange requirements. In summary, the integration of BIM with other information technologies (IoT, blockchain, AI and GIS) and the improvement of processes, such as the real-time collection, processing and exchange of data and operability amongst the tools, should be the main focus in future research.

The future directions (RQ-8) identified in our study are following: the use of open BIM frameworks to solve the information exchange, interoperability and compatibility issues; the integration of LCA databases into BIM models for the assessment of the entire building at the early design or design stages; easier BIM implementation at the operation and maintenance stage.

6. Conclusions

This study is designed to contribute and complement existing research findings in the field of BIM with energy efficiency published in the Scopus and Web of Science databases. The area has attracted much interest. Some research efforts have been described in the literature that focus on related questions, such as specific interoperability issues between BIM and energy simulation tools, the integration of BIM-based technologies, etc. Nevertheless, this study offers an insight into the body of BIM knowledge concerning energy efficiency issues, which requires further development. The study contributes to this area of research by providing insights into issues related to the technical aspects of energy efficiency assessment, which are hindered by the challenges of implementing BIM working methods and the deployment and application of the required technology. The study provides an understanding of the explored BIM areas in terms of energy efficiency and presents the areas that require further research. The findings here presented contribute to the field by identifying the gaps to be addressed, trends to be redefined and main areas of focus for future research. In methodological terms, the study draws upon a quantitative analysis of citation networks, which involves minimal subjective judgment, making the findings reliable. Our findings reveal that research on BIM's application in energy efficiency modeling still encounters many issues; much work remains to be conducted to make this a well-established area of research.

BIM-related issues, such as interoperability issues between BIM and energy simulation tools, have limited the potential of BIM. Existing studies have overlooked the technical issues to be resolved in information exchange using the BIM. Moreover, the existing literature on the topic presents fragmented research efforts from isolated groups of researchers. These issues are rooted in the research problems, researchers and their institutions. These trends should be reassessed and redefined, as highlighted by the findings of the study.

Future work in energy efficiency and BIM must target the issues of energy modeling to be addressed and solved by applying BIM capabilities. There is a need for future research that involves forming collaborative networks, which will improve the discussion and exchange of experience, debates and cross-border communication and initiatives.

Despite the contributions of the present study, it had limitations. First, the analysis only covered the literature in English, using a certain set of keywords for searching. Due to space limitations, the study was focused on providing a broad picture of the available literature on BIM for energy modeling through a bibliometric analysis of citation networks. It was less concerned with an in-depth content analysis of the available studies. The authors performed an in-depth qualitative analysis of the retrieved papers before performing the bibliometric analysis of citation networks. A complementary study to analyze the content of some available studies on the topic was conducted. Second, the analysis was based on the dataset retrieved from the WoS and Scopus databases. There is currently no suitable tool to automatically combine data from different databases and prepare them for analysis (remove duplicates, unify the format, etc.). Therefore, more complex analyses, such as the analysis of co-authorship by countries, were performed separately for the WoS and Scopus datasets. Thus, the findings may not fully reflect the entire available set of BIM literature related to energy modeling. Consequently, a combined analysis of articles from several databases is needed in the future. This would provide a global picture of the issues under consideration.

Supplementary Materials: The following are available online at https://github.com/DianaKalibatiene/BIM_Energy, Thesaurus, Appendix S1: Summary of the research questions, issues and main results of the similar papers.

Author Contributions: Conceptualization, T.V., R.D.-T. and D.K.(Diana Kalibatiene); formal analysis, T.V., R.D.-T., D.K.(Diana Kalibatiene) and D.K.(Darius Kalibatas); methodology, T.V., D.K.(Diana Kalibatiene) and D.K.(Darius Kalibatas); resources, T.V., R.D.-T., D.K.(Diana Kalibatiene) and D.K.(Diana Kalibatiene); supervision, T.V.; writing—original draft, T.V., D.K.(Darius Kalibatas) and R.D.-T.; writing—review and editing, T.V., R.D.-T. and D.K.(Darius Kalibatas). All authors have read and agreed to the published version of the manuscript.

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

Abbreviations:

AI	artificial intelligence
APY	average publication year
BEMS	building energy management system
BEP	building energy performance
BEPS	building energy performance simulation
BIM-O&M	BIM-based Operation and Management
BMS	building management system
C.s.	current study
DT	digital technologies
EA	energy analysis
EE	embodied energy
env	environmental
FDD	fault detection and diagnosis
FM	facility management
GIS	geographic information system
IFC	Industry Foundation Class
LCA	life cycle assessment

documentation	1	2		1	2				
efficiency	4						1		4
energy conservation/ energy saving	5				3		1	1	1
energy demand	3								
energy efficiency	7				1		2	2	4
energy management								1	3
energy model	1							1	
energy simulation/ simulation	2			1	2		2	3	4
environmental design	2			2			1		
environmental performance/en- vironmental impact	1			2			1	3	
estimation/life cycle cost	3			1					1
exchange	1			1					3
integration/interoperability	7			1			1	5	
interaction	2			1			1		
investment	2								
management	7							1	
modelling							1	1	
monitoring	1							1	
optimization	4			2			1		

Appendix B. The Activity–Use Case Co-Occurrence Matrix in BIM and Building Energy Efficiency Analysis. (Note: Yellow and green colors allow visualizing co-occurrences: the dark green color presents the keywords' highest co-occurrence; light green color presents medium occurring keywords; yellow color presents less occurring keywords)

Activity												
Use Case	communication	control	design decision	development	engineering	improvement	information modelling	maintenance	measurement	regulation	renovation	validation
3D model				2			3	2	1	1		
accuracy		3	1	8		4	5	4	4	1	1	2
analysis/energy analysis	7	16	2	57	24	18	78	9	15	11	14	6
assessment/evaluation	2	5	4	28	11	17	63	7	8	13	12	2
building energy performance/lighting	3	6	4	21	3	10	26	2	3	8	11	1
building model	1	1	1	14	6	5	11	1		1	2	1
collaboration	4			9	4	4	7	2		2	1	1
consumption		1	1	16	5	10	21	3	3	3	4	3
correlation			1	2		1	4	1	1	1		1
decision making			3	27	8	9	26	5	3	3	9	
design alternative			1	5		3	5			1	1	
documentation					2		9	2	2	1	4	1
efficiency					3	6	20		3	1	1	2
energy conservation/energy saving					3	10	17	3	1		4	
energy demand						10	8				5	
energy efficiency					11	12	27	5	3	5	7	2
energy management					2	1	4	2	2		1	
energy model					2	2	7				1	1
energy simulation/simulation					9	9	18	3	5	5	7	7
environmental design						1	11					1

environmental impact/environmental performance	7	21	2	1	4	5	2
estimation/life cycle cost	2	5	1	1	1	2	
exchange		14	1	1		1	
influence		9		1	1	1	1
integration/interoperability			13	3	5	9	2
interaction			1	1			
investment			1	1		2	
management				3	5	7	1
modelling					2	6	1
monitoring					2	7	1
optimization					2	5	1
prototype					1	1	1
quality					5	5	2

Appendix C. The Challenges Co-Occurrence Matrix in the BIM and Building Energy-Efficient Topic. (Note: Yellow and green colors allow visualizing co-occurrences: the dark green color presents the keywords' highest co-occurrence; light green color presents medium occurring keywords; yellow color presents less occurring keywords)

Keywords	challenge	complexity	difficulty	gap	improvement	interoperability issue	limitation	problem	uncertainty
construction	18	7							
construction industry	13	3							
cost	13	3							
data	27	15							
development	24	8							
energy	27	9	4						
energy efficiency	14	2	3						
energy use	14	6	6						
environment	22	5	1						
framework	20	9	1						
impact	11	3	2	9					
implementation	12	5		6					
industry	13	4		8	9				
information	35	16	4	13	12				
information modelling	21	7	6	16	17				

integration	13	6	2	9	5				
interoperability	12	7	2	5					
level	13	7	3	6	11	2			
life cycle	14	3		5	9	4			
management	19	5	2	10	5	3	4		
methodology	10	5	2	5	8	1	4		
model	29	16	8	15	19	3	15		
opportunity	10		1	4	4	3	5		
performance	15	5	3	9	14	1	9		
practice	15	5	3	14	8		5		
process	31	14	5	17	20	7	14	30	
project	23	5	4	5	9	1	6	15	
quality	11	1	1	4	10		3	10	
requirement	16	4		7	6	1	4	3	
research	24	4	4	18	16	6	11	26	
simulation	8	6	3	6	16	3	6	12	
software	14	5	2	4	11	6	8	11	
solution	13	4	1	3	10	3	5	15	
stage	11	2	3	9	4	2	9	10	
strategy	10	8	2	9	10	1	4	11	
sustainability	16	3	1	7	9		2	9	
system	23	11	3	14	19	2	9	34	
technique	5	3	2	4	5	1	3	10	
technology	19	10	3	8	15	5	8	20	
time	15	7	4	8	11	1	4	9	
tool	31	11	3	11	18	4	14	21	
use	24	9	3	13	18	2	10	15	2
value	12	2		8	13	2	4	11	6

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