

Sustainability Analysis of Environmental Comfort and Building Information Modeling in Buildings: State of the Art and Future Trends

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Abstract: Environmental comfort involves creating comfortable and healthy indoor environments, taking into account the climate characteristics of the built environment. The novelty herein is to define the challenges of using Building Information Modeling (BIM) to assess the three dimensions of environmental comfort: thermal comfort, visual comfort, and acoustic comfort. This work conducts a bibliometric review, using the VOSviewer software (version 1.6.20) and the GPSV website, and a bibliographic review of recently published articles in the field. This paper aims to identify the dimensions of sustainability with a focus on environmental comfort and the themes associated with these dimensions, recognize the limitations of the research, and propose recommendations for future work. The results of this work define the limitations related to the three dimensions of environmental comfort and recommend establishing a reliable database, integrating BIM with parameters that could interfere with the quality of the indoor environment.

Keywords: environmental comfort; thermal comfort; visual comfort; acoustic comfort; BIM



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1. Introduction

The influence of environmental comfort on the vitality of urban areas must be considered in urban planning to improve the quality of life [1]. Environmental comfort is a comprehensive concept that involves creating comfortable and healthy indoor environments that promote relaxation, taking into account factors such as temperature, air quality, lighting, and noise [2]. According to Mataloto et al. [3], buildings play a significant role in global energy consumption and CO₂ emissions. Various tools for planning and designing sustainable buildings have emerged to adapt to specific climatic conditions and local variables.

Environmental comfort in buildings, involving thermal, acoustic, and visual aspects, is essential for the well-being of users and the energy efficiency of buildings [4]. Thermal comfort has been examined in the literature based mainly on parameters such as temperature and energy efficiency. Zahid et al. and Salgude et al. [5,6], for example, calculated the ideal temperature to guarantee thermal comfort in buildings using Building Information Modeling (BIM) tools. Ijasahmed et al. [7] presented simulations in which energy consumption and costs are significantly reduced.

Acoustic comfort has been examined in the literature based mainly on the calculation of reverberation time to analyze the acoustic performance of the building. Aguilar et al. [8] applied BIM tools to verify that the reverberation time presented in the simulations complies with local regulations. Nik-Bakht et al. [9] calculated the reverberation time using a BIM tool and algorithms and were able to conclude that the presence of furniture and the size of the room interfered with the calculation. Visual comfort has been examined in the

literature using parameters such as the daylight factor and energy efficiency. Teo et al. [10] presented simulations varying the levels of shelves in the window and analyzing the daylight factor. In this way, it was possible to increase performance and reduce energy consumption. Ratajczak et al. [11] used BIM tools and artificial intelligence techniques to carry out simulations to improve the building's performance. In this way, it was possible to improve the autonomy of natural light and consequently improve the building's energy performance.

Sustainable construction encompasses four pillars that are social, biophysical, economic, and technical [12]. The development of sustainable construction practices seeks to achieve a balance between these pillars during the implementation of construction projects [13]. The passive impact of buildings on the environment has driven the adoption of the concept of sustainable construction, centered on reducing the consumption of natural resources and energy efficiency [14]. According to Lebiéd et al. [15], one of the objectives of the sustainable construction project is to present solutions for improving the energy efficiency of buildings.

BIM is a tool that helps to achieve more effective solutions in the process of energy performance and building construction [16]. According to Habibi [17], BIM is used to solve complex problems and is very effective for assessing the sustainability of renovation projects. The integration of BIM with Internet of Things (IoT) technologies allows data to be analyzed in real time, making it possible to make adjustments to the built environment [18]. According to Malagnino [19], the integration of BIM with the IoT has the potential to enable sustainability management of the built environment, helping to minimize the environmental impact of the construction sector. The bibliographic review is an important methodology for advancing knowledge of the object of study [20]. The bibliometric review makes it possible to identify gaps in the research topic and explore areas for future research [21]. The construction process needs to transform in order to become sustainable and this includes improvements in the use of tools for this purpose.

The novelty of this study is to explore the challenges of applying BIM to the comprehensive assessment of the three dimensions of environmental comfort: thermal comfort, visual comfort and acoustic comfort. Understanding the application of BIM tools in the context addressed in this article is important for identifying existing gaps and guiding future research on the subject. In the course of the research carried out here, it was possible to identify that articles have comprehensively analyzed environmental comfort involving thermal, visual and acoustic comfort and BIM tools. Thermal comfort receives greater focus in the articles that deal with the three dimensions. Therefore, this subject needs due attention so that it can be dealt with in a balanced way.

This study presents a classification framework that defines the topics most covered in the literature on environmental comfort and BIM. The methodology adopted is presented in a flowchart based on a bibliometric analysis and a detailed bibliographic analysis. The bibliometric analysis makes it possible to identify research trends and patterns, while the bibliographic analysis provides an in-depth understanding of the topics studied. Tools such as VosViewer were used to carry out cluster analysis, identifying patterns and trends related to the topic. By reviewing the literature, it was possible to define the most frequently discussed topics on the subject, which provided a comprehensive view of the research. In this sense, this work aims to answer the following questions related to the topic:

- (i) What are the different dimensions that sustainability analysis of environmental comfort in buildings research focuses on?
- (ii) What are the research themes associated with these dimensions?
- (iii) What are the main limitations of current approaches?
- (iv) What are the promising recommendations for future works in the field?

2. Methods and Systematic Survey

This paper carries out bibliometric and bibliographic analyses to answer the declared research questions. This systematic literature review allows us to understand how research on the subject is being conducted. The bibliometric analysis enables a quantitative approach to be taken to the subject, making it possible to identify trends and the growth of knowledge. With the bibliographic analysis, using a qualitative approach, it is possible to identify, evaluate, and synthesize the evidence of environmental comfort by reading the content of selected articles. Hence, data are to be collected through database searches and a descriptive analysis of the selected articles. A classification structure is to be suggested for the reviewed papers. All the material obtained is to be analyzed to understand the behavior of research on the subject.

The flowchart of the method used for bibliometric and bibliographic analysis is illustrated in Figure 1. For the bibliometric analysis, keywords relating to the topic were initially chosen. Searches were then carried out on the selected databases, with some filter limitations. The papers resulting from the searches were downloaded in a standardized tag format developed by Research Information Systems (.ris), and these files were inserted into the VOSviewer software for subsequent analysis of the clusters generated by the program. With the data obtained from the bibliometric analysis, the GPS Visualizer (GPSV) website was used to generate maps of the countries from which the articles originated, helping to understand the global trend of the topic. It was then possible to define the dimensions of the subject. Articles were selected for the literature review. The selected articles were related to the identified dimensions and to BIM. After the analysis, the themes for each dimension were defined and the articles were classified. Figure 1 provides a summary of the methodology described here.

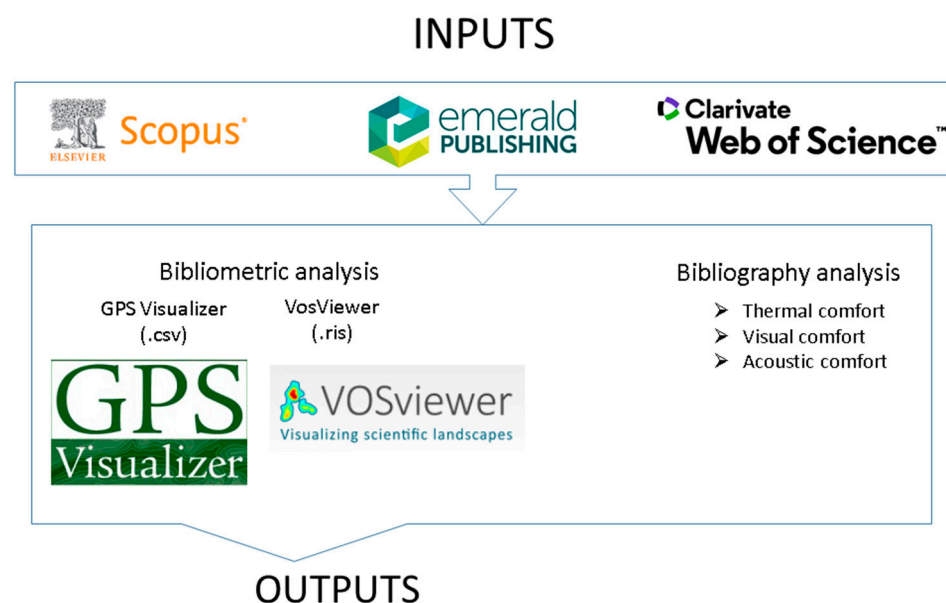


Figure 1. Flowchart of the method used in the research.

2.1. Bibliometric Analysis

This part of the study is divided into two main parts. The first concerns the collection of materials to conduct the required analysis in VOSviewer software, while the second concerns the GPSV analysis.

2.1.1. Collection of Materials

To collect the material, keywords related to the topic of this article were selected, and combinations of these were made for the search in three databases: Elsevier's Scopus, Emerald Insight and Web of Science. Seven keywords were used, divided into two groups. Group 1 used the keywords "environmental comfort" + "building" + "sustainability" in an attempt to have a general analysis of the topic. Group 2 used the keywords "thermal comfort", "visual comfort", "acoustic comfort" and "BIM", seeking to understand how environmental comfort has been related to BIM technology. The details of the research are listed below.

Initially, a search was carried out in the Scopus, Emerald Insight and Web of Science databases using the words in Group 1. The limitations used in this search were the period from 2019 to 2024, the English language, the type of article and book chapter and the words searched in all fields. As a result, this search returned 370, 47 and 15 files found in the Scopus, Emerald insight and Web of Science databases, respectively.

The second search carried out in the Scopus, Emerald insight and Web of Science databases was using a combination of keywords from group 2. The combination used was "thermal comfort" + "BIM". The limitations were the period from 2019 to 2024, the language in English, the type as article and book chapter and the words were searched in all fields. As a result, this search returned 1529, 117 and 133 files found in the Scopus, Emerald insight and Web of Science databases, respectively.

The third search was carried out using the second combination of keywords from Group 2. The words "visual comfort" + "BIM" were used. As a limitation, the search period was from 2019 to 2024, the language was English, the type was article and book chapter and the words were searched in all fields. As a result, this search returned 284, 33 and 11 files found in the Scopus, Emerald insight and Web of Science databases, respectively.

The last search carried out in this database was with the third combination of keywords from Group 2. The words "acoustic comfort" + "BIM" were used. As limitations, the search period was from 2019 to 2024, the language was English, the type was article and book chapter and the words were searched in all fields. As a result, this search returned 48, 13 and 2 files found in the Scopus, Emerald insight and Web of Science databases, respectively.

Figure 2 shows the results found in the respective databases. From this figure, it is possible to see that the database that returned the highest number of articles was Scopus. In addition, combination 1 of Group 2 returned the highest number of articles. This highlights the relevance of the Scopus database in research and points to a focus on studies related to thermal comfort.

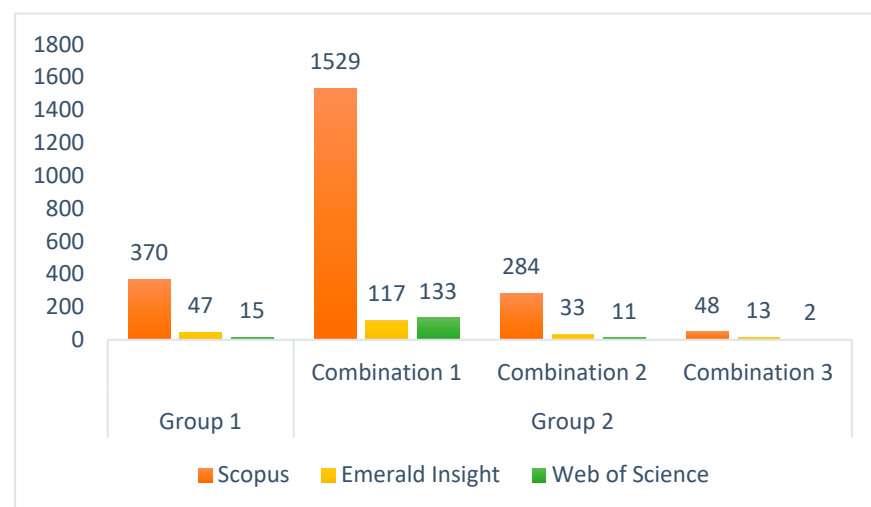


Figure 2. Summary of research results.

For the bibliometric analysis of the research carried out, VosViewer software, version 1.6.20, developed at Leiden University, Leiden, Holland, was used. The files were downloaded from the databases in (.ris) format so that they could be inserted into the software. With the software, it was possible to carry out analyses using cluster maps. Details of the research are listed below. Based on the bibliometric analysis carried out, it was decided to focus on future research.

2.1.2. GPSV Analysis

For the bibliometric review in this article, GPSV was used, an online tool that allows you to create maps and visualize geospatial data interactively.

The tool was used to generate a map containing the countries of origin of the articles extracted from the bibliometric review. Data such as author affiliations, titles, authors and the locations of the institutions were downloaded from the databases used in this article. The file was edited, leaving only the articles' countries of origin. These data were loaded into GPSV, where they were processed and a global map was generated. The tool allowed clear visualization of the geographical distribution of the articles, highlighting the countries with the most scientific production in the area of study, which makes it easier to identify global patterns and trends in research.

2.2. Bibliographic Analysis

This section analyses the most relevant articles on the subject based on the keywords elaborated in a word cloud, allowing greater refinement in the research. The analysis could be divided into three dimensions of environmental comfort—thermal, visual, and acoustic—based on the related themes carried out in the VOSviewer software used in the bibliometric analysis. For instance, the themes related to the thermal comfort dimension could be temperature, solar radiation, humidity, Predicted Mean Vote (PMV), energy efficiency, and building type. Themes related to the visual comfort dimension could be daylight factor, illuminance, energy efficiency, and building type. Themes related to the acoustic comfort dimension could be reverberation time, noise, and construction materials. In these terms, the bibliographic review could be conducted based on the analysis of the objective, methods, and results for each of the selected papers.

3. Results

This part of the study is divided into four sections. The first section gives an overview of the volume of articles extracted from the databases and the countries of origin of the Scopus database that returned the most results. The second section presents the results of GPSV, which generated a map showing the countries of origin of all the articles used in the bibliometric analysis. The third section describes the method used to develop the bibliometric analysis as well as the data analysis of the cluster maps generated by the VOSviewer software. The fourth and final section describes how the bibliographic analysis was carried out and presents the analysis of the articles selected in this analysis. In addition, this section presents the results of the questions proposed in the introduction to this article.

3.1. Descriptive Analysis of Materials

Based on the research carried out, the number of articles found was lower than expected. Figure 3 shows the number of articles found in the databases searched. The combination with the highest number of articles was “thermal comfort” + “BIM”. The relevance of this topic calls for more studies to be carried out, given that the number of buildings is increasing along with concerns about sustainability and comfort in the environment.

The articles included herein came from 75 countries. Figure 4 shows the distribution of the articles analyzed from the Scopus database by their various origins, highlighting China as the largest source of information on the subject. It is also important to note that only articles in English were considered, which may have had a direct impact on the research results.

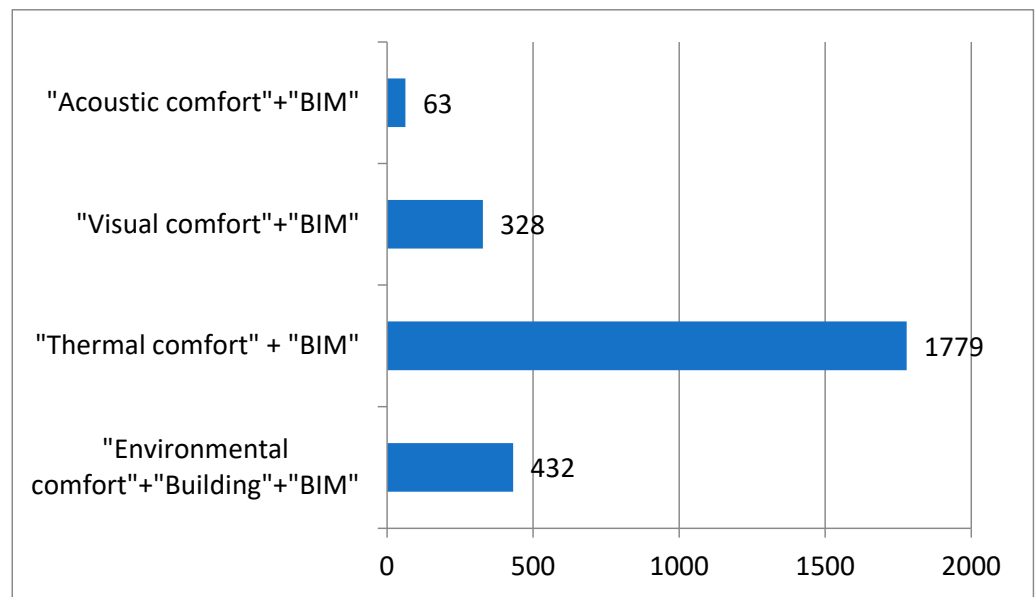


Figure 3. Files extracted from the database searches.

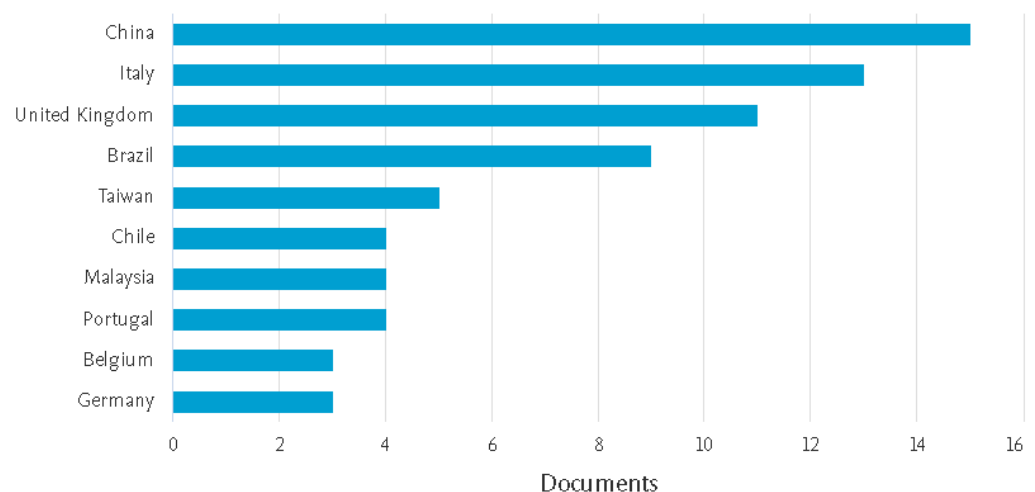


Figure 4. Number of articles related to your country of origin.

3.2. World Publications

The online tool GPSV, created by Adam Schneider in 2002, is used to generate the map with the countries of origin of the articles resulting from the bibliometric analysis. The countries of origin of the articles extracted in the bibliometric analysis carried out in this article are highlighted in Figure 5. Although the origin of the articles is spread across several countries, China, Spain, Italy, and the United Kingdom appear as the main contributors in terms of the volume of publications on the subject. The greater volume of publications originating in China, despite the relatively low total number of articles returned in this research, reflects a continuous and permanent investment in the country's scientific and technological development. This trend suggests an important commitment to innovation and progress in areas related to the subject.



Figure 5. Documents' origins plotted with the GPSV.

3.3. Bibliometric Analysis

As part of the bibliometric analysis, the files (.ris) were uploaded to the VosViewer software. To insert the downloaded files into the databases, a new project was created in the software and the option to create maps based on text data was chosen. The data source chosen in the software for reading the files was the (.ris) format. To generate the maps, information from the titles and abstracts will be extracted from the articles. The method used to count the terms was complete counting. The first analysis carried out by the software returns several terms repeated in the documents. As some of the terms found by the software are not relevant to the analysis, a filter is made of the terms most relevant to the topic. General terms that had no connection with the topic, such as "participant", "comment" and "year", were excluded when generating the maps. The maps were analyzed in order to improve future research. It is worth noting here that, as this is a bibliometric analysis, the articles found in the different studies carried out may deal with the broader topic of environmental comfort involving its three aspects (thermal comfort, visual comfort, and acoustic comfort). Thus, some of the clusters formed for a particular study show terms referring to other aspects of the subject.

The first map was generated by inserting the file (.ris) exported from the first search using the terms "environmental comfort", "building" and "sustainability" into the software, which returned 432 documents. The software analysis resulted in 11,147 keywords. The minimum number of occurrences was limited to 10, reducing it to 410 keywords. The software's relevance calculation considered 246 relevant words out of the 410 limited keywords. After analyzing the results obtained by the software and removing the words that were not part of the topic, the first cluster map was generated, shown in Figure 6.

Six clusters were generated on this map. The first cluster, in red, is related to the variables that can interfere with environmental comfort, such as air humidity, air quality, natural ventilation, and room temperature. The second cluster, in green, encompasses the dimensions of environmental comfort, including words such as acoustic comfort, visual comfort, luminance, and satisfaction. The third cluster, in blue, is concerned with natural and energy resources, showing the importance of thinking about project solutions with the capacity to generate greater energy efficiency. This can be seen in the words "sustainable development", "climate change" and "recyclable material". The fourth cluster, in yellow, features words such as "energy consumption", "cost" and "energy demand" and, like the third cluster, shows a concern for the environment and energy reserves. The fifth

cluster, in lilac, brings examples of solutions that can be adopted in projects, with the aim of minimizing impacts and providing better comfort for the individual. Words like “green roof”, “green wall” and “internet of things”, generated in this cluster, show this importance. The sixth cluster, in light blue, brought terms such as “green building”, and “indoor environmental quality”, reinforcing, as in other clusters, the importance of the environment and individual comfort.

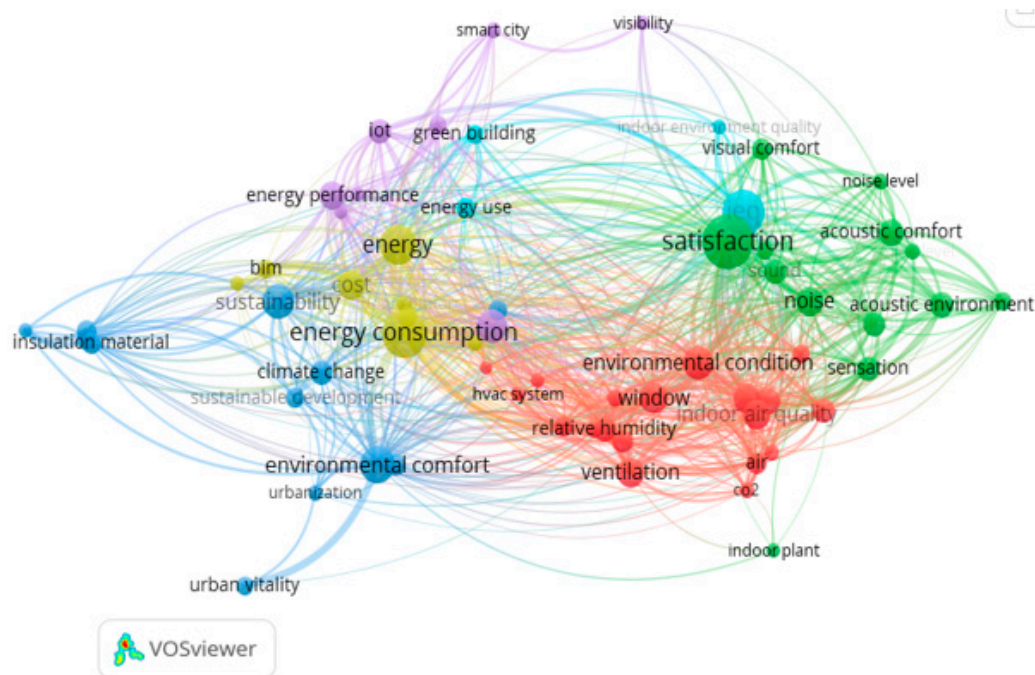


Figure 6. Cluster map generated by research results of the terms “environmental comfort”, “building” and “sustainability”.

The second map was generated with data from the search that used the terms “thermal comfort” and “BIM” and retrieved 1779 documents. The software analysis resulted in 35,806 keywords identified in the “title” and “abstract” fields. The minimum number of occurrences was limited to 22, reducing it to 600 keywords. The software’s relevance calculation considered 360 relevant words out of the 600 limited keywords. After analyzing the results obtained by the software and removing the words that were not part of the theme, the second cluster map was generated, which is shown in Figure 7. This map generated five clusters. The first and fifth clusters, in red and lilac, respectively, show parameters and systems that can be used in buildings to improve thermal comfort. This can be seen through words such as “air conditioning”, “internal temperature”, “relative humidity”, “ventilation” and “comfort level”. The second cluster, in green, shows the technologies and tools that can be used in the process of designing and building spaces, focusing on the theme of thermal comfort, showing the importance of planning throughout the process and using tools that add value and provide quality to the end product. This can be seen in the words “BIM technology”, “energy-efficient construction”, “artificial intelligence”, “facilities management” and “smart city”. The third cluster, in blue, features terms such as “climatic reduction”, “energy consumption”, “solar radiation” and “building orientation”, which show the external factors of the environment that directly influence the thermal comfort of the building, showing the importance of studies not only internal to the building. The fourth cluster, in yellow, shows the importance of studies involving life cycle analysis (LCA) in topics such as this, making it possible to choose systems and solutions that improve the building’s thermal performance. This can be seen through words such as “life cycle analysis”, “innovation” and “environmental impact”.

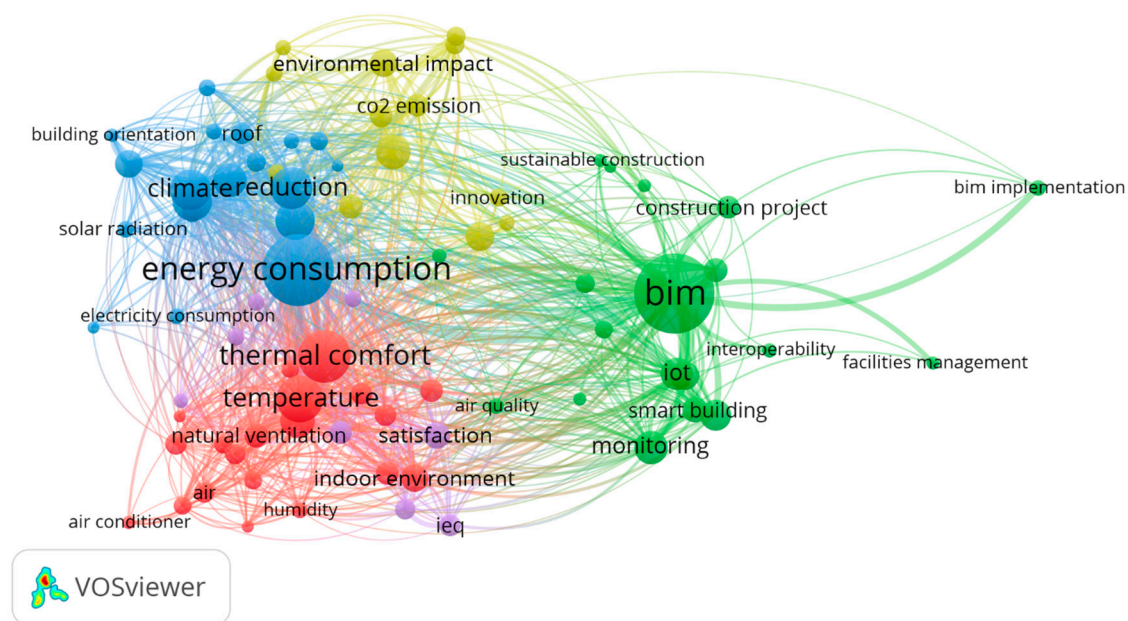


Figure 7. Cluster map generated by research results of the terms “thermal comfort” and “BIM”.

The third map was generated through a search using the terms “visual comfort” and “BIM”, which retrieved 328 documents. The software analysis resulted in 8467 keywords identified in the “title” and “abstract” fields. The minimum number of occurrences was limited to 10, reducing it to 242 keywords. The software’s relevance calculation considered 145 relevant words out of the 242 limited keywords. After analyzing the results obtained by the software and removing the words that were not part of the topic, the second cluster map was generated, shown in Figure 8. This map generated six clusters. The first cluster, in red, shows the importance of using technology to develop visual comfort. Technology in this area helps to implement innovative strategies and study the best parameters for the environment. This can be seen in words such as “technology”, “BIM”, and “virtual reality”. The second and third clusters, in green and blue, respectively, contain terms such as “climate”, “window”, “energy use”, “orientation” and “solar radiation”. These clusters deal with some variables that can influence visual comfort in environments. The fourth cluster, in yellow, shows the impacts generated during and after construction. This cluster shows the importance of studies aimed at mitigating these impacts, always seeking to maintain quality and comfort for the user. This can be seen in words such as “carbon emission”, “temperature” and “energy cost”. The fifth cluster, in lilac, contains terms such as “daylight factor”, “lux” and “light”. These words show the importance of studying lighting in terms of visual comfort, which can directly affect the user’s well-being and productivity. The sixth cluster, in light blue, has two words: “occupant comfort” and “building energy performance”. This cluster shows a concern with user sensations and the results that the building will generate through the application of the new technologies, materials and tools studied.

The fourth map was generated through a search using the terms “acoustic comfort” and “BIM”, which retrieved 63 documents. The software analysis resulted in 2081 keywords identified in the “title” and “abstract” fields. The minimum number of occurrences was limited to 4, reducing it to 208 keywords. The software’s relevance calculation considered 125 relevant words out of the 208 limited keywords. After analyzing the results obtained by the software and removing the words that were not part of the topic, the cluster map was generated, as shown in Figure 9. Due to the small number of articles found, this research did not result in many clusters or keywords, as can be seen in Figure 9. In addition, the results of the clusters showed a lack of studies that portray acoustic comfort in buildings and how this topic can be studied with the help of BIM tools since the keywords generated

in the clusters deal with more general topics, not specifically words related to acoustic comfort. The map generated four clusters. The first and second clusters, in red and green, respectively, contain words such as “acoustic performance”, “green building” and “energy performance”. These clusters show general characteristics of construction aimed at environmental comfort. The third and fourth clusters, in blue and yellow, respectively, deal with the importance of applying technology to the subject, with words such as “BIM”, “digital technology” and “facility management”.

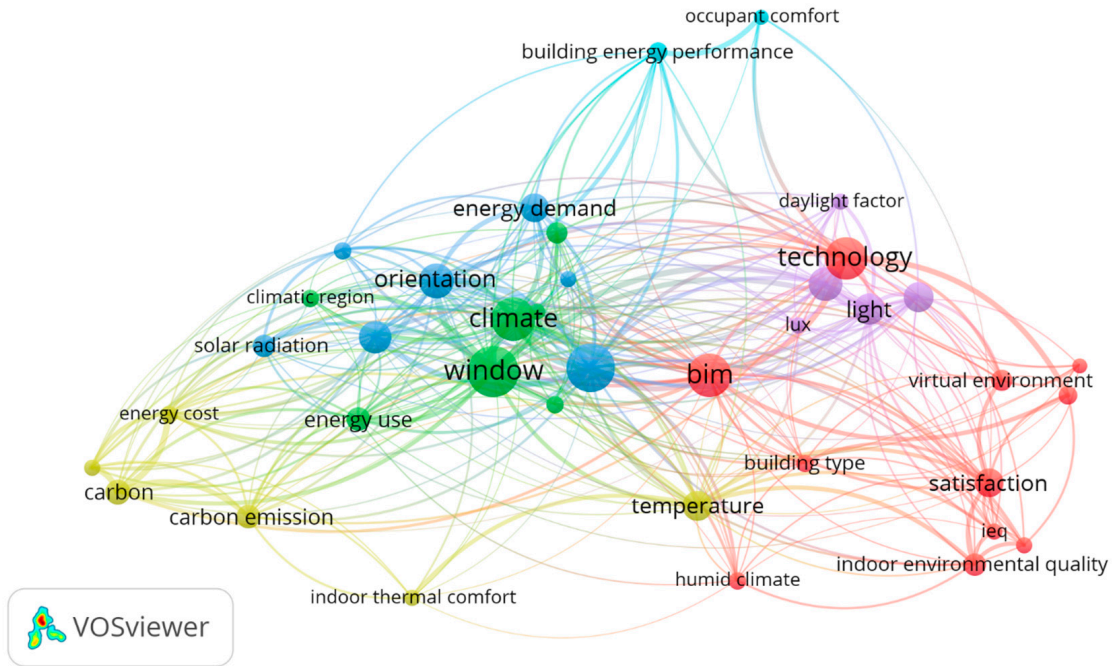


Figure 8. Cluster map generated by research results of the terms “visual comfort” and “BIM”.

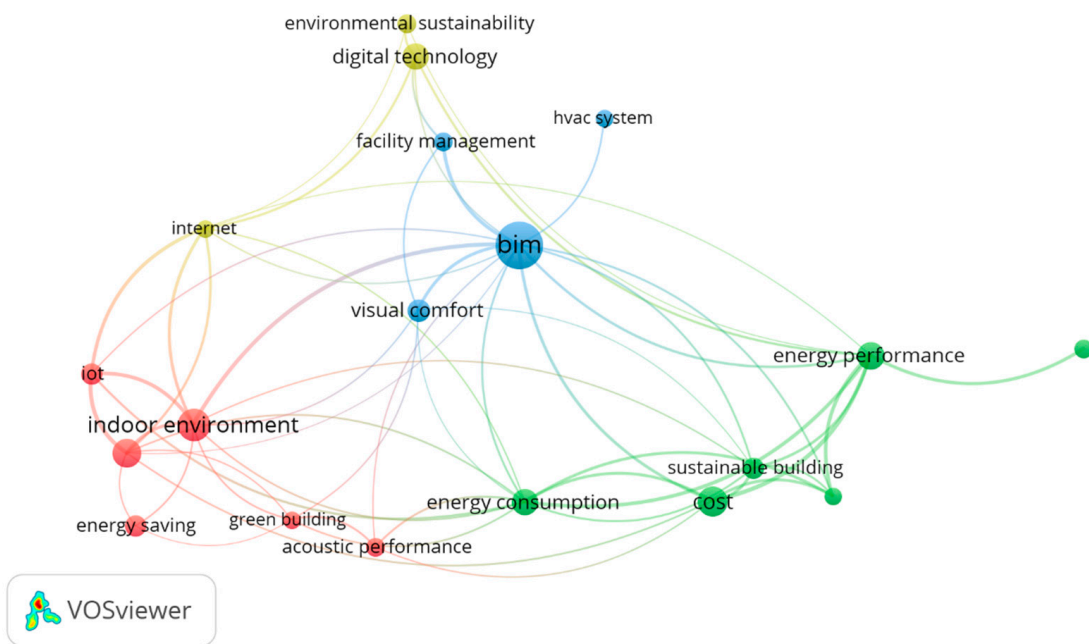


Figure 9. Cluster map generated by research results of the terms “acoustic comfort” and “BIM”.

Table 1. Dimensions and themes related to environmental comfort.

Dimensions		Themes	
Thermal Comfort	35	Parameters (temperature, solar radiation, humidity, sensors, PMV)	16
		Energy efficiency	9
		Building type	10
Visual Comfort	23	Daylight factor, illuminance	12
		Building type	8
		Energy efficiency	3
Acoustic comfort	13	Reverberation time	10
		Noise	2
		Material	1

The articles presented in Table A1 have been classified into three themes. The first theme, “Parameters”, shows the articles that presented the application of BIM tools, mostly in conjunction with other tools, and provided results such as the ideal internal temperature of a building [5], identifying the level of internal comfort and discomfort [22], as well as signaling these levels to building managers [23,24], comparing the calculated parameters with the normative parameters [25], calculating the incidence of sunlight inside the building, analyzing thermal comfort considering the temperature of the occupants or their thermal preference [26–31], analyzing the thermal transfer of the building envelope [32] and analyzing the level of thermal comfort through the analysis of the PMV (Predicted Mean Vote) [33–36]. The second theme, “Energy efficiency”, presents articles that have applied BIM tools, mostly in conjunction with other tools, and provides results such as parameters that cover the thermal comfort and energy efficiency of the building [37], the calculation of energy consumption by varying insulation materials, cooling systems and other parameters [7,38–40], the factors that interfere with the energy performance of the building [41,42], such as the climate zone [43], and how the level of thermal comfort and energy consumption interfere with the behavior of the occupants [3]. The third theme, “Building type”, presents articles that have applied BIM tools, most of them in conjunction with other tools, and provides results such as calculating indoor environmental quality based on variations in the building envelope’s constructive characteristics [6,44–48], improving the use of space, thermal comfort and the cost of construction [49], identifying construction techniques and materials to improve thermal comfort [50,51] and analyzing thermal comfort considering cooling systems, constructive systems, and environmental conditions [52].

Table A2 in Appendix A highlights the publications that evaluated the visual comfort in the literature and reveals that the studies focus on parameters such as daylight factor and illuminance. In addition, several studies simulate architectural features that favor natural lighting and visual comfort simultaneously.

The articles presented in Table A2 were classified into three themes. The first theme “Daylight factor/illuminance” presents the articles that presented the application of BIM tools, mostly in conjunction with other tools, and presented results such as the improvement of visual comfort through natural lighting [11,53–61], the calculation of ideal artificial lighting considering visual comfort [62], the relationship between illuminance levels and the performance of the building occupants’ tasks [63]. The second theme, “Building type”, presents the articles that brought up the application of BIM tools, mostly in conjunction with other tools, and brought up results such as the interference of construction characteristics on visual comfort [64–70], and the ideal façade systems for the best use of natural light [71]. The third theme, “Energy Efficiency”, presents the articles that brought the application of BIM tools, mostly in conjunction with other tools, and presented results such as the interference

of the application of energy systems in the energy performance of the building and in the improvement of visual comfort [72] and the integrated analysis of energy performance and natural lighting [10,73].

Table A3 in Appendix A presents the publications that evaluated the acoustic comfort in the literature and reveals that these studies focus on calculating reverberation time and on materials that can contribute to a better result in acoustic comfort in buildings.

The articles presented in Table A3 were classified into three themes. The first theme, “Reverberation Time”, shows the articles that applied BIM tools, mostly in conjunction with other tools, and showed results such as identifying and analyzing reverberation time in order to improve the acoustic performance of an environment [8,9,74–81]. The second theme, “Noise”, presents the articles that applied BIM tools, mostly in conjunction with other tools, and resulted in the calculation of the sound pressure level of noise in work environments and its interference with acoustic comfort [82,83]. The third theme, “Material”, presents articles that have applied BIM tools, mostly in conjunction with other tools, and show results such as the impact of certain construction materials on the acoustic performance of buildings [84].

The literature found in the research carried out in this article highlights the importance of developing further studies in the area of environmental comfort, especially with the use of BIM methodology. The integration of BIM in environmental comfort studies is a growing trend, recognized for its ability to provide a detailed and integrated analysis of various parameters that affect the well-being of building occupants. The BIM tool most commonly used in this topic was Autodesk Revit in conjunction with other plug-ins or other software.

4. Discussions

A general analysis of the articles presented in the tables in Appendix A reveals that the dimensions of environmental comfort require more in-depth studies when studied in conjunction with the BIM methodology. Based on the literature review carried out, it was possible to answer the questions proposed at the beginning of this article. These questions will be discussed below.

- a. What are the different dimensions that sustainability analysis of environmental comfort in buildings research focuses on?

This analysis highlights three fundamental dimensions in the analysis of environmental comfort: thermal comfort, visual comfort, and acoustic comfort. However, research that addresses these three dimensions in conjunction with the BIM methodology tends to focus predominantly on thermal comfort. For example, visual comfort and acoustic comfort are often treated superficially in a small number of studies. Furthermore, there is little research that explores visual comfort and acoustic comfort in conjunction with the BIM methodology.

This trend indicates that a high level of maturity still needs to be reached in integrating the BIM methodology with the three dimensions of environmental comfort. Many studies use BIM to model buildings and develop specific plug-ins or use other software to analyze the performance of environmental comfort in buildings. However, a lack of comprehensive studies that fully integrate the use of BIM tools in the analysis of the three dimensions of environmental comfort is perceived.

In addition, it is important to note that environmental comfort is not just restricted to thermal, visual, and acoustic aspects. It also encompasses factors such as indoor air quality and ergonomics, which are essential for the well-being of a building’s occupants. Integrating these factors with the BIM tools could provide a comprehensive and accurate analysis of environmental comfort.

The lack of studies on the visual and acoustic dimensions, especially when combined with the use of BIM tools, points to an area of research that has yet to be explored. It is crucial to develop more detailed and integrated studies that consider all the comfort dimensions integrated with BIM tools to reach a full potential environmental comfort analysis.

There is an urgent need to broaden the scope of research to more robustly include the dimensions of visual and acoustic comfort. This would not only improve the quality of built environments but also provide a more solid basis for applying BIM to create more comfortable and sustainable buildings.

b. What are the research themes associated with these dimensions?

By analyzing the literature, it was possible to understand the main points relating to environmental comfort in buildings. These are solar radiation, building orientation, climate classification, daylight factor, sound, and reverberation time.

Articles related to the thermal comfort dimension focus mainly on parameters such as temperature, building orientation, and PMV (Predicted Mean Vote). The most frequently used software for thermal comfort analysis was Autodesk Revit, usually in combination with plugins or other software. In addition to Autodesk Revit, other BIM software used in the research included EnergyPlus (i.e., version 8.9, version 9.2 and version 9.4), DesignBuilder (i.e., version 6.1 and version 6.5), and Grasshopper (i.e., version 0.9, version 1.0.0007 and version 4.0). These programs are used for energy performance simulations, solar radiation analysis, and optimization of the building's thermal design.

Visual comfort studies often address parameters such as the daylight factor, building design, and materials used, especially on facades. Autodesk Revit stands out in visual comfort analysis, often combined with plugins or additional software. In addition, EnergyPlus (i.e., version 8.9, version 9.2 and version 9.4), DesignBuilder (i.e., version 6.1 and version 6.5), and Grasshopper (i.e., version 0.9, version 1.0.0007 and version 4.0) are widely used in research to carry out daylighting simulations and evaluate the effectiveness of design solutions in terms of visual comfort.

Articles dealing with acoustic comfort focus on parameters such as reverberation time, noise level, and materials used. Similar to the other comfort dimensions, Revit is the most widely used software, often in combination with plugins or other programs. Other BIM software mentioned in the surveys include EnergyPlus (i.e., version 8.9, version 9.2 and version 9.4), DesignBuilder (i.e., version 6.1 and version 6.5), ComSol (i.e., version 5.3 and version 5.4), EASE (i.e., version 4.4), and I-Simpa (i.e., version 1.3.4). These programs are used for acoustic simulations, analysis of the acoustic performance of materials, and optimization of the building's acoustic design.

An analysis of the literature shows that although Autodesk Revit is the predominant software used for environmental comfort analysis, it is often used only for modeling and, in most of the reviewed papers, is complemented by other specialized programs to meet the specific needs of each comfort dimension. Integrating these tools within the BIM environment allows for a more comprehensive and accurate approach to assessing and optimizing environmental comfort in buildings.

c. What are the main limitations of current approaches?

The main limitations of current approaches to the study of environmental comfort using BIM tools are diverse and cover both technical and methodological aspects. Most of the studies and applications of BIM in the context of environmental comfort focus on the thermal comfort dimension. In this sense, the other dimensions of environmental comfort (visual and acoustic comfort) end up being treated superficially or even inadequately. This scenario can be verified by the difficulty of finding published studies that deal only with acoustic or visual comfort applied to the BIM tools. Thus, one can perceive a notable lack of studies that develop a comprehensive approach, taking into consideration the three dimensions of environmental comfort in an integrated manner.

Another limitation of the subject is that many studies use external software or additional plug-ins to develop environmental comfort analyses, which can create interoperability challenges and increase the complexity of the design process. The quality and accuracy of the data are also a limitation since the accuracy of environmental comfort analyses depends on the quality of the data entered into the BIM model. Inaccurate or

incomplete data on climatic characteristics, building materials, and occupancy profiles can compromise the results of the analyses carried out.

Many studies also require multidisciplinary professionals to be behind them. For example, multidisciplinary teams are made up of architects, engineers, and specialists in environmental comfort and BIM. These limitations emphasize the need for continuous development and deeper integration of BIM tools with all dimensions of environmental comfort. Comprehensive and balanced development studies, together with the design of new tools, are fundamental to overcoming these limitations and advancing the creation of more comfortable and sustainable built environments.

d. What are the promising recommendations for future works in the field?

The recommendations aimed at advancing the integration of environmental comfort with the BIM tools include a balanced approach between the dimensions of environmental comfort, the improvement of techniques, and further study of tools. The development of studies that address all the dimensions of environmental comfort (thermal, visual, and acoustic) in an integrated way, together with BIM tools, will help provide a complete and coherent understanding of the impact of environmental comfort on buildings. The development and application of combined assessment methodologies that use BIM modeling to integrate aspects of environmental comfort, energy efficiency, sustainability, and ergonomics are also recommendations on the subject.

Another recommendation is the creation and maintenance of reliable and comprehensive databases that provide the necessary parameters for accurate environmental comfort simulations, including climate data, building materials, and occupancy profiles. Research into how sustainable practices can be incorporated into BIM to improve environmental comfort, considering factors such as energy efficiency, the use of ecological materials and passive design, as well as the use of sustainable materials, especially green infrastructure, and the analysis of the impact of environmental comfort on building requires more attention and is part of the recommendations for future research.

In addition, in-depth studies of BIM tools that allow for a broad analysis of the dimensions of environmental comfort are recommended. These topics represent promising areas for future research that can contribute significantly to advancing the integration of environmental comfort with BIM tools. By exploring these topics, researchers can develop innovative and practical solutions that improve the quality and sustainability of built environments.

5. Conclusions

Environmental comfort analysis has a vital impact on the well-being of a building's occupants. Analyzing this topic in conjunction with BIM tools helps to develop the application methods, selection of building materials and adapt the building design to improve the performance of the building. The bibliometric analysis carried out in this study contributes to understanding the growth trends related to the topic, as well as helping to investigate the gaps related to environmental comfort and BIM.

This work conducts a deep analysis of the clusters created with the VOSviewer software and presents the need to conduct a comprehensive and structural analysis of the three dimensions related to environmental comfort: thermal, visual, and acoustic. For instance, the clusters generated by the visual and acoustic comfort dimensions provided insufficient information on the topics due to the small number of articles returned from the research carried out.

The bibliographic analysis carried out in this article contributed to a more in-depth knowledge of the subject and how studies have been developed. An analysis of 72 articles was carried out to highlight the main dimensions and topics covered in studies on environmental comfort and BIM. Four main research questions were addressed in this review, namely:

- (i) What are the different dimensions that sustainability analysis of environmental comfort in buildings research focuses on?
- (ii) What are the research themes associated with these dimensions?
- (iii) What are the main limitations of current approaches?
- (iv) What are the promising recommendations for future works in the field?

By proposing a classification structure and carrying out comprehensive bibliometric and bibliographic analyses of articles published in the last five years, different research trends related to environmental comfort and BIM were revealed. The bibliometric analysis conducted for this study identified six major keyword groups that dominate research into environmental comfort: “solar radiation”, “building orientation”, “climate classification”, “daylight factor”, “sound” and “reverberation time”. The bibliographic analysis herein helped to understand how studies on this topic are being conducted, revealing a scarcity of research carried out on visual or acoustic comfort in conjunction with BIM. In addition, the most widely used BIM software is Revit, used in most studies in combination with other compatible software or plug-ins.

The analyses developed in this study suggest a path for future research, aligning environmental comfort with the BIM tools in a set of well-defined dimensions and categories. One limitation associated with the proposed dimensions is the lack of studies that address the three dimensions in a balanced and holistic way. In addition, few studies seek to use sustainable materials and green infrastructure, analyzing their performance concerning environmental comfort with BIM software.

As a limitation of the research, it was difficult to obtain a sufficient number of articles related to particular groups of keywords. For some of the topics explored, the databases consulted returned a few number of available articles, which limited the scope of the bibliometric and bibliographic review. Furthermore, in the context of the study on Building Information Modeling (BIM) applied to environmental comfort, few studies that integrated these two fields were found, which also represented a significant limitation for the comprehensive analysis of the topic.

Based on the recommendations derived from the framework developed, the study indicates that future research should focus on approaches that integrate BIM, environmental comfort, energy efficiency, and sustainability. In this scenario, studies focused on the use of sustainable materials, especially green infrastructure, and the analysis of the impact on the environmental comfort of buildings, are also pertinent. Finally, as a central theme, the in-depth study of BIM tools that analyze thermal, visual, and acoustic performance in a balanced way is an important investigation for future studies.

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Nomenclature

CO ₂	Carbon dioxide
BIM	Building Information Modeling
LCA	Life Cycle Analysis
PMV	Predicted Mean Vote
IoT	Internet of Things
Ris	Research Information Systems
GPSV	GPS Visualizer website

Appendix A

Table A1. Literature review-based thermal comfort analysis.

Ref.	Objective	Methodology	Results
[5]	This article presents an optimization approach to achieve the ideal indoor temperature in a building with the highest energy efficiency.	It uses IoT tools to measure environmental data, BIM using parametric information considering other environments, and DynamicPMV to visualize the 3D model in real time.	As a result, through the simulations carried out, this article provides the ideal temperature to guarantee thermal comfort inside the building.
[37]	The aim of this article is to evaluate individual thermal comfort by combining improved energy efficiency with increased human comfort.	A system combining BIM tools and an artificial neural network was used. The ANN model takes into account environmental, human state and body parameters. The BIM model helped to evaluate thermal comfort combined with changes in the various parameters and suggested energy-saving optimizations in the various scenarios proposed.	This article resulted in guidelines and parameters for creating a thermally comfortable and sustainable environment.
[23]	The aim of this article is to propose the integration of a sensor-based alert system with BIM models in order to improve the management of environmental monitoring of buildings.	A prototype was created encompassing a BIM platform, temperature and humidity sensors and a database for an environment that was part of the case study. In this way, an updatable model was created, with real-time information that detects the levels of comfort and discomfort in the environment.	Levels of comfort and discomfort were detected in the case study environment and the system was able to issue alerts to managers. Thus, the proposed monitoring model proved to be ideal for managing the internal environmental conditions of a building.
[24]	The aim of this article is to monitor thermal comfort levels using sensors integrated with BIM tools.	BIM and IoT tools were used. The model created for the case study allows the visualization of thermal comfort data in real time, based on ASHRAE. The measured room temperature and humidity are fed into a MySQL database. BIM and the database are integrated so that monitoring can be visualized in BIM.	With the methodology adopted, 13 levels of thermal discomfort were generated in a given hour of analysis. In addition, alarms were issued to the building managers in real time.
[33]	This article evaluates and improves the level of thermal comfort and productivity of users in an educational building. It also analyzes how these conditions affect the building's energy consumption.	EnergyPlus (version 9.4) and DesignBuilder (version 6.1) software were used to analyze the environmental conditions, control strategies and annual heating and cooling loads. Thermal comfort was evaluated using the PMV index. The effect of room temperature, air flow, air conditioning and shading on thermal comfort and user productivity was verified.	It was found that the time of discomfort was reduced by 17.6%. However, annual energy consumption increased by 11.7%. The effect on productivity (typing and reasoning) was very significant, increasing by 46%.

Table A1. Cont.

Ref.	Objective	Methodology	Results
[34]	The aim of this article is to propose a system that will help increase indoor comfort levels and operate equipment in order to minimize energy consumption.	Tools were used to help managers develop plans for space demand and the use of electrical equipment. The BIM tool was used to reduce the discrepancy between the real conditions and the simulated models.	Based on the measurements taken, the article suggests that in closed spaces used for public meetings, a system should be installed to help with air exchange between the internal and external environments. It was also found that the comfort temperature, according to the PMV indicator, varied between 26 °C and 27.5 °C. This parameter will help managers to change the cooling equipment.
[44]	This article aims to parametrically analyze the influence of building openings, considering the urban morphology of Egypt's new communities, on improving indoor environmental quality (IEQ).	The methodology used parametric assessments based on spatial and environmental information and the BPS as a tool to support the study in the field.	The evaluation showed the difficulty of achieving indoor environmental quality considering only the openings specified in the urban morphology of Egypt's new communities, suggesting reconsidering their legislation and urban rules.
[35]	The aim of this article is to evaluate different strategies for retrofitting air conditioning without damaging historic heritage buildings.	As the methodology was applied, a structure was generated using BIM tools to generate a building energy model (BEM) of a historic building in a museum. The study focused on the deterioration of air conditioning systems, taking into account their replacement or maintenance.	The proposed retrofit strategy reduced the PMV index of the entire building by up to 31% during the cooling period.
[49]	This article aims to improve the use of space, thermal comfort, constructability and rental value of buildings through a BIM-based optimization framework in the initial design phase.	The BIM tool is used for volumetric data of the environment to be built. MOO is used to optimize the data extracted from BIM, taking into account space utilization, thermal comfort, rental value and construction cost. The case study is an architecture school construction project.	The study resulted in significant figures. There was a 30% increase in space utilization, thermal comfort improved by 20%, construction costs fell by 10% and rents increased by 33%.
[50]	The aim of this article is to find the best parameters for improving thermal comfort inside modern Coptic Orthodox churches.	A systematic literature review was carried out with the aim of listing the passive techniques used in Coptic Orthodox churches and a comparison between two case studies consisting of a historic church and a modern one. Simulations were also carried out with the modern church using Design Builder software, analyzing thermal comfort using the techniques found in the literature.	A list of techniques used to improve thermal comfort was obtained from the literature review. Simulations showed that the use of triple glazing was more effective for internal thermal comfort.
[30]	The aim of this article is to use BIM tools to improve the energy efficiency and internal comfort of already-occupied buildings.	A platform using IoT was developed, testing prototypes with algorithms using real data relating to internal temperature and meteorology, and the body temperature of the occupants.	The platform developed (Symbiotic Data Platform) is applicable to all BIM tools and can be operated by any user without prior knowledge of these tools.
[52]	This article takes a new approach by predicting the level of comfort using four parameters: HVAC, building system performance, room conditions and user behavior.	Data was collected from a case study project, using BIM tools, regarding information on the construction systems used and the building's energy efficiency. Environmental conditions were assessed using the FP-Growth Algorithm and Clustering methodologies and compared with Revit.	The results obtained from the combinations can be propagated to other buildings, taking into account the thermal performance to be achieved.

Table A1. Cont.

Ref.	Objective	Methodology	Results
[6]	This article seeks to analyze the characteristics of a building that interfere with optimizing energy consumption.	Autodesk Insight 2020 software is used to verify energy optimization. 125 models are analyzed using BIM tools, combining different orientations of the building and different types of window glass and window-to-wall ratio (WWR).	The study found the best relationship between the parameters analyzed: 90-degree orientation, 15% WWR and triple glazing. This combination resulted in a 7% reduction in energy consumption, energy costs and CO ₂ emissions.
[45]	The aim of this article is to verify the impact of the application of green construction in buildings on the energy use index.	Using Revit software, simulation models are created by varying the orientation of the building, the material used in the construction, the thermal insulation and the treatment used.	As a result, it was found that the use of double-glazed windows and a green roof brought significant improvements in the energy use index.
[46]	The aim of this article is to investigate how the orientation of a building interferes with the design of each façade.	Simulations were carried out in a test room, where the variables were the type of glass, the relationship between the wall and the window and the use of shading devices. The study was carried out for buildings that are occupied all year round.	As a result, the article provided parameters that can be applied to a building without worrying about its orientation. The parameters were: for a window wall ratio of less than 50%, the angle to the north between 0° and 10° and to the east between 85° and 95°; for a window wall ratio of less than 40%, the angle to the south between 170° and 180° and to the west between 265° and 275°. The results do not apply to buildings that are not occupied all year round.
[7]	The aim of this article is to analyze the retrofiting techniques to be employed in an existing building in India in order to achieve energy efficiency.	Autodesk Revit 2017 software was used to make the comparisons between the established models. The energy performance of the existing building was measured and compared with the performance of the model by varying the insulation characteristics, type of glass and cooling system, and by adding a photovoltaic system to the building.	As a result, there was a reduction in energy consumption per year. From 193 kWh/m ² /year to −150 kWh/m ² /year. It was also found that the return on investment in the building is up to 9 years.
[51]	The aim of this article is to analyze the performance of five thermal insulators when installed in the external walls of buildings.	The materials analyzed are rock wool, vermiculite, phenolic foam, extruded polystyrene (XPS) and polyethylene. The apartment, part of the case study, was modeled using DesignBuilder software (version 6.5).	As a result, the thermal insulator that maintained thermal comfort for the longest time during the year was XPS. This material also reduced annual energy consumption by 9.27%.
[25]	The aim of this article is to develop an automatic structure that allows the evaluation of the comfort and performance of a building.	The case study consists of an office located in Hong Kong and used by 10 people. The site was modeled in BIM and the internal data and equations used are defined using the SD-ABM platform. The data from this platform is integrated into the BIM using Dynamo-Excel. The occupancy, comfort level, temperature and CO ₂ presence indicators in the environment were calculated.	As a result, it was observed that most of the data obtained remained within the tolerance limit based on the ASHRAE Guideline. The methodology and structure used in this study can be used in other environments.
[47]	The aim of this article is to analyze the effect of shading on the energy performance of buildings in China.	Grasshopper (version 0.9) and EnergyPlus (version 8.9) software were used. A total of 93,114 simulations were carried out, considering seven cities and four climate zones. The study was applied to independent buildings and also to neighboring buildings.	As a result, the study found that shading has a strong influence on the thermal performance of buildings, with cooling loads being overestimated by 45% and heating loads underestimated by 21%. The study can contribute to local urban planning.

Table A1. Cont.

Ref.	Objective	Methodology	Results
[43]	The aim of this article is to investigate the influence of the orientation of buildings on their energy performance using optimization techniques.	Using the IES VE 2023 and Rhino/Honeybee tools, simulations were carried out to investigate the influence of building orientation on energy use intensity, cooling and heating load, solar heat gain and air exchange.	This study found that in addition to the orientation of the building, factors such as the climate zone and the size of the building also affect its energy performance. Furthermore, it was concluded that the orientation of the building does not have a strong influence on the intensity of energy use.
[38]	The aim of this article is to investigate design parameters applicable to university buildings in China to improve energy performance and indoor thermal comfort.	Grasshopper software (version 1.0.0007) and the Ladybug and Honeybee plug-in were used to model the simulations, covering variables such as building form, orientation, building structure and building components (window, wall, roof and shading).	As a result, it was found that the parameters adopted as a model reduced annual energy consumption by 58% compared to the real building. It was also found that the duration of the feeling of thermal comfort was 53%.
[31]	The aim of this article is to develop an indoor thermal comfort model, integrating BIM, IoT, Machine Learning and user experience.	Revit 2021 software was used to model and integrate the IoT devices and the users' thermal needs, specified via a mobile app. The Predicted Mean Vote (PMV) and Personal Vote (PV) were calculated and these parameters were used to create a logistic regression model.	As a result, it was possible to visualize the thermal conditions in the mobile application and in the BIM, making it possible to make adjustments according to the users' preferences.
[48]	The aim of this article is to evaluate the effect of different orientations and shading on the energy performance of a building in Afghanistan.	Simulations and modeling were carried out, based on on-site data and dynamic simulation, varying the orientation of a residential building and the levels of shading on it.	As a result, the study showed that the arrangement around the building interferes with cooling demand and that the best orientation for the glazed façade would be south, which would reduce cooling costs by up to 7.4% and heating costs by up to 9.7%. It was also found that the shading devices that had already been installed helped to reduce the energy load by 19% in the summer.
[26]	The aim of this article is to analyze the impacts of a hypothetical house with a glazed façade, subjected to the effects of latitude and orientation on the level of solar illuminance.	BIM and BEM methodologies were used to carry out simulations in five different countries: Brazil, Italy, the Dominican Republic, the United Arab Emirates and Australia. The analyses carried out on the models generated were related to the solar trajectory, calculation of the natural light autonomy factor and analysis of natural light illuminance levels.	As a result, it was found that although the greatest incidence of sunlight occurs in the upper part of the house, 67% of the spaces do not receive natural light within the 2% limit. The back rooms are the ones that reach levels higher than 300 lux most of the time. The methodology applied in this study helps to improve projects that consider better energy performance and also in the retrofit phase of a building.
[41]	The aim of this article is to evaluate the energy efficiency and environmental comfort level of an existing Traditional Public Market building.	Revit 2018 was used to model the design of the market and its surroundings and Integrated Environmental Solutions Virtual Environment (IES VE 2018) software was used to carry out the simulations.	The results showed that energy consumption is mainly affected by thermal radiation in the building. Problems were also found with ventilation and the incidence of sunlight inside the market. These results provide a basis for retrofitting or new sustainable building projects.
[42]	The aim of this article is to investigate parameters for introducing sustainability and sustainable energy into a building.	AutoCad 2021 was used to create the 2D project, Scketchup 2021 to model the 3D project and Revit 2021 for the redesign.	Simulation results were compared with the real building and the building combined with sustainable parameters.

Table A1. Cont.

Ref.	Objective	Methodology	Results
[27]	The aim of this article is to evaluate the impact of using Growblocks on the incidence of solar radiation and on users' visual comfort.	The incidence of solar radiation was calculated using the Revit Insight 2020 plugin. Natural lighting performance was simulated using a Velux Daylight Visualizer. The results obtained from the simulations were compared with the real values.	As a result, it was found that there was a 53% reduction in the incidence of solar radiation in the environment. The natural lighting and ventilation requirements were met in several scenarios.
[22]	The aim of this article is to develop a method that integrates thermal data from a building in space and time.	Revit 2015 and Rhinoceros software (version 6.0) are used as tools. Sensors are used to collect air temperature and other thermal data. This data is georeferenced in the BIM model. With this data, the thermal comfort variables are automatically calculated using equations. The 4D visualization is conducted with the Grasshopper (version 0.9) script.	As a result of the system developed, it was possible to detect altered thermal information. In addition, the method calculates the thermal comfort values for the environment. The method only allows for a visual analysis of thermal comfort levels.
[39]	The aim of this article is to develop a methodology that integrates BIM, AI and NSGA II to analyze the impact of building factors on energy use.	A case study was carried out in a school in Norway. Revit 2021 software was used for modeling and the Dynamo plugin. This model was exported to IDA ICE, which allowed simulations to be created analyzing energy use. 11 algorithms were used to jointly analyze the building envelope, HAVC systems, shading parameters, lighting and air infiltration.	As a result, the algorithm with the most accurate results was GLSSVM. There was a 37.5% decrease in energy consumption and a 33.5% increase in thermal comfort.
[36]	The aim of this article is to study the integration of BIM, virtual reality and IoT in the analysis of thermal comfort in real time.	The software used to model the prototype was Revit 2020. The prototype consists of a dynamic thermal environment, where the average radiant temperature was measured in real time using a semi-automatic method. PMV and PPD were calculated	As a result, it was found that the results obtained for PMV and PPD in the proposed model are in agreement with those obtained by an online thermal comfort analysis tool. In addition, there was agreement between the users' thermal sensations and the results of the methodology applied. It is worth noting that the results of the methods used here may vary, mainly due to the uncertainties of the measuring equipment used.
[28]	The aim of this article is to develop a vector-based spatial model (Build2Vec) that identifies the indoor environmental preferences of building users.	Build2Vec (version 0.0.1) was used to incorporate spatial and indoor location data from BIM. EcologicalMomentary Assessments (EMA) were used to collect subjective data on thermal comfort. All this data was integrated into a graphical network.	As a result, it was found that the Build2Vec model showed an improvement in accuracy of between 14% and 28% over conventional methods of predicting thermal preference.
[32]	The aim of this article is to develop a building information modeling (RBIM) retrofit method that reduces overall thermal transfer (OTTV) and the cost of retrofitting, taking into account the thermal performance of the building envelope.	Revit 2021, Dynamo (version 2.1) and NSGA-II tools were used, applied to an office that is part of the case study. Heat transfer through the building envelope was analyzed using the OTTV metric.	As a result, the proposed system was found to have a higher level of automation than conventional methods. In addition, the case study approach showed that the method was effective, which would make it easier for managers to make design decisions.
[40]	The aim of this article is to optimize energy-efficient automated systems in terms of thermal comfort parameters, energy use, and workloads.	The methodology used Revit 2023 software and energy optimization algorithms. IoT was used to calculate the performance of an indoor environment. In addition, the Personal Comfort System (PCS) was used as user voting data.	As a result, it was possible to verify the critical levels of energy use and the capabilities of thermal comfort control systems. The model used helped to understand and predict user activities and thermal comfort levels for well-being.

Table A1. Cont.

Ref.	Objective	Methodology	Results
[29]	The aim of this article is to develop a new methodology for analyzing the structural performance and environmental comfort of historic buildings.	As a methodology, a new Python-based software (version 3.11), H2BIM, was developed to implement the proposed approach in Revit. A case study was carried out on a recently renovated historic building in Italy. The building was monitored as part of the GEOFIT Horizon 2020 project.	As a result, it was found that the vibration data and the thermal perception of the occupants were within the normative limits adopted due to the energy-efficient retrofit of the building.
[3]	The aim of this article is to develop an approach for monitoring and interacting with users in an environment, providing information through graphic descriptions of energy consumption and environmental parameters.	The methodology involved real-time monitoring of temperature, luminosity and humidity. BIM software was used to model the environment and represent the data collected. Environmental comfort and energy consumption parameters were depicted.	As a result, it was found that the environmental comfort and energy consumption indices induced user commitment, as well as increased their participation in energy-saving actions.

Table A2. Literature review-based visual comfort analysis.

Ref.	Objectives	Methodology	Results
[53]	The aim of this article is to investigate parameters for improving the visual comfort of an apartment in South Korea.	BIM was used to model the apartment and Computer-Aided Design 2019 software was used to carry out simulations involving natural light. A new layout and modeling were developed for the apartment in question with the aim of reducing energy demand.	It was found that the proposed model resulted in a 15% improvement in the daylighting factor and a 30% improvement in daylight autonomy.
[64]	The aim of this article is to improve the visual comfort and reduce the energy consumption of a building by considering window layouts.	Models were built considering components of the window-to-wall ratio and the shape and positioning of the window on each façade.	As a result, it was found that the 30% window-to-wall ratio, with a square and horizontal window shape, positioned in the center or at the top of the façade had the best performance. Other results were obtained for visual comfort, lighting and energy consumption.
[65]	The aim of this article is to analyze an Egyptian palace, proposing sustainable solutions related to improving energy and natural light.	A simulation was carried out using the Diva-grasshopper (version 4.0) software with the Octopus plugin. Thermal and daylight conditions were analyzed in order to minimize energy consumption.	Various skylight configurations were proposed, combined with other techniques that resulted in optimal energy performance for the palace. The techniques used in this study can be applied in similar cases.
[72]	The aim of this article is to analyze photovoltaic energy systems integrated with buildings in order to improve energy performance and increase the level of visual comfort for users.	New photovoltaic panel design alternatives were proposed, with curved and flat sections. The Honeybee and Ladybug plugins were used to analyze the thermal and visual comfort of the building's users. The Octopus plugin for Grasshopper (version 2.9) was used to optimize the model.	As a result, the simulations showed that there was an annual saving of 29% in energy consumption, as well as improving the thermal and visual comfort of users.

Table A2. Cont.

Ref.	Objectives	Methodology	Results
[10]	The aim of this article is to propose a daylighting project for an office with sloping windows, in order to improve the energy performance and visual comfort of the environment.	Photorealistic and natural light simulations were carried out combining different levels of shelving in the sloping windows.	As a result, it was found that the use of shelves offers a better reflection of natural light in the environment, with an increase in performance of 34%. In addition, there was a reduction of more than 25% in energy consumption. There was no heating in the chiller loads. The cost of this project is low, which increases its potential for execution and operation.
[66]	The aim of this article is to present design solutions involving the structure of a building in China that improves visual and thermal comfort and energy consumption in all five of the country's climatic regions.	The Taguchi method is used to optimize the system. The variables considered in the process were the shape of the building and the characteristics used in construction.	As a result, it was found that the building shape that suits all climatic regions is cylindrical and the ideal glass window would be the triple-glazed window. With regard to insulation, the thickness of 150 mm suited three climates and 90 mm suited the rest. The window-to-wall ratio (façade) that met the four climatic regions was 10%.
[71]	The aim of this article is to analyze different proposals for shading systems applied to façades, investigating their impact on natural lighting inside a commercial building in Kerala.	Autodesk Revit 2019 software was used to model a commercial building in Kerala and create simulations in six scenarios that differ from each other due to the shading systems used on its façade. Internal lighting levels were calculated using the software.	As a result, it was found that the ideal internal natural lighting was achieved by combining vertical and horizontal shading devices. Facades located to the north and south allow more natural light in. Two ideal façade systems were obtained, taking into account efficiency, lightness, aesthetics and architectural features already used in local buildings. These results comply with the local building code and the user's visual comfort.
[54]	The aim of this article is to apply an optimization method to improve energy performance in a student house at the University of Athens.	Revit 2021 software was used to model the environment and EnergyPlus (version 9.2.0) software to carry out dynamic energy simulations. Simulations were carried out using lightweight shelving systems, varying their geometry, material and type of finish.	As a result, it was found that the most viable solution would be one that uses external shelves in an elevated position. An ideal model was also obtained that would cause the least discomfort to the user. In this model, the level of illumination would increase by 59% and the level of illuminance by 25 to 32 times, improving the visual comfort of users.
[67]	The aim of this study is, using BIM tools, to analyze an ideal typology considering the level of natural lighting in the environment.	Revit 2019 software and a BIM plugin were used to carry out simulations on five buildings. Simulations were carried out considering illuminance, LEED and natural light autonomy.	As a result, it was found that the tower typology is the best in terms of natural light performance and the worst typology was the one where the housing units are arranged in rows on either side of a central corridor.
[68]	The aim of this article is to classify user visual comfort indicators and predict the appropriate individual illuminance.	The indicators were classified using a cloud model and FMEA. Four types of algorithms were used to train the models. A BIM plugin considering environmental data and personal choices was used to predict individual vertical illuminance.	As a result, it was found that among the models analyzed, the random forest model showed the best prediction performance. Furthermore, with the help of the BIM plugin, it is possible to adjust the lighting levels to suit the individual visual comfort of the users.

Table A2. Cont.

Ref.	Objectives	Methodology	Results
[69]	The aim of this article is to analyze the energy performance of a mosque building in Egypt.	Data was collected using 3D laser scanning. The case study building was modeled using Revit. The building's energy analysis was carried out using IESVE 2020 software. New modification systems were proposed and their performance was evaluated in comparison with the existing one. The impact of the proposed changes was analyzed and a decision-making model was created using Analytical Hierarchy Process (AHP) techniques and the Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS).	As a result, it was found that daylighting performance would improve by changing the existing type of glass and keeping the skylights. The addition of a modern cooling system would improve the room's thermal performance. The use of LED lamps and dimmers would significantly improve the space's energy consumption. Using the AHP and TOPSIS techniques, it was found that the ideal scenarios are those that consider using double glazing, applying insulation to the roof, adding a cooling system, using LED lights with dimmers and changing the mosque's operating profile.
[55]	The aim of this article is to use BIM tools to develop a method for analyzing natural lighting that can be used in the various stages of a project.	The proposed method is based on the sky factor, which is measured by the angle formed between the calculated point and the light opening in the wall. The data required for this calculation is extracted from the model made in BIM tools.	The proposed method makes it possible to calculate the side and top lighting of a building. This method was developed to be applied as a tool to find the best design solution considering visual comfort, thermal comfort and safety.
[56]	The aim of this study is to verify whether the buildings that form part of the case study meet the natural lighting and ventilation requirements of the Islamic residential concept.	Simulations of three buildings were carried out using Revit 2022 and the Insight Lighting Analysis resource to assess the level of natural lighting in the projects.	As a result, it was found that building 1 meets the Islamic housing criteria due to the presence of an open space in the middle of the building. The changes made to the design of this building resulted in an increase in the incidence of natural light inside the room from 2.8 to 3%.
[57]	The aim of this article is to propose a method for analyzing natural lighting levels in real time using BIM tools.	Revit 2016, 3Ds Max 2016, Unreal Engine 2016 and Dynamo 2016 software were used to develop the BLDF system. Various scenarios of an environment were compared using virtual reality in order to analyze energy performance.	As a result, it was found that the method developed helps designers and building managers make decisions, taking into account the best natural lighting performance in an environment and energy savings, while also ensuring the user's visual comfort.
[11]	The aim of this article is to analyze the energy and daylight performance of a building in order to propose optimal design solutions.	BIM tools, visual programming and Artificial Intelligence techniques were used. In the case study, the Spatial Daylight Autonomy metric was used to improve daylighting performance and the Energy Use Intensity metric was used to reduce energy consumption. The window-to-wall ratio of the rooms was also checked.	As a result, optimizing the project showed that the spatial daylight autonomy could be improved by 7.39 to 10.01% by increasing the window-to-wall ratio. Increasing the autonomy of natural lighting also guarantees good energy performance for the building.
[70]	The aim of this article is to evaluate visual comfort inside mosques.	The software Autodesk-Insight-360 2023 for Revit-2023 and SolemmaClimateStudio for Rhinoceros-6 were used. The level of visual comfort was calculated using illuminance and the natural light and glare factor.	As a result, it was found that buildings with courtyard lighting reduced the level of internal glare. In addition, windows installed in vertical rows increased the incidence of natural light. This study contributes to the evaluation of visual comfort in various mosques depending on their morphology.

Table A2. Cont.

Ref.	Objectives	Methodology	Results
[62]	The aim of this article is to evaluate indoor visual comfort in offices in Malaysia and the level of user satisfaction.	A case study was carried out in three offices in Malaysia. The modeling and simulations were carried out using Revit software and took into account factors such as brightness, illuminance and office layout. In addition, a questionnaire was carried out with one hundred users of the spaces.	As a result, the questionnaire showed that users were visually uncomfortable. The ideal lighting for the space would be LED with a brightness level of 400 lux.
[58]	The aim of this article is to analyze the performance of natural lighting in an educational building and an office.	Revit 2021 software and the Integrated Environmental Solutions Virtual Environment (IESVE 2021) were used to model and simulate natural lighting performance in the case study.	As a result, the building was found to have favorable daylighting for more than 50% of the time it was occupied by users, according to the Illuminance Engineering Society of North America (IESNA). In addition, the ratio of 1:14 window to wall is the ideal ratio, maintaining visual comfort for users.
[73]	The aim of this article is to analyze the energy and daylighting performance of a new building on a university campus.	DesignBuilder (version 6.1) and Revit 2019 software were used to perform the modeling and simulations for the case study. ASE and sDA daylighting metrics were used. The simulation should be carried out on the entire building to avoid errors in the results.	It was found that applying the methodology discussed in this article allows decisions on energy performance and daylighting to be made at the design stage of the project, guaranteeing a good result in terms of operation and user comfort.
[63]	The aim of this article is to verify whether Correlated Color Temperature (CCT) and illuminance levels can be accurately reflected in lighting simulations in immersive virtual environments (IVEs).	Nine lighting scenarios were created in IVEs. Some users were subjected to these scenarios, and evaluations were carried out on their visual perception and task performance. The variables used in the simulations were CCT and illuminance levels. Revit 2021 software was used to model the environment for part of the simulation and other plugins and software were used to calculate the parameters.	As a result, it was found that the use of head-mounted displays affected the perception of visual comfort in some aspects for users. In addition, the performance of the tasks carried out by the users improved as the illuminance was increased. No specific relationship was found between CCT and task performance.
[59]	The aim of this article is to present a digital solution and a new plugin (AftabRad), developed to export 3D models from BIM tools to Radiance, allowing the simulation of natural light and the presentation of the results back to the BIM software.	As a methodology, the AftabRad plugin was developed to export 3D models from the BIM software to Radiance. The natural light simulation is carried out in Radiance. The results are integrated with the BIM software for continuous analysis.	As a result, it was found that AftabRad increases the likelihood of achieving a well-lit, thermally comfortable and visually pleasing space, meeting daylighting requirements. This approach allows the quality of natural light to be checked throughout the process.
[60]	The aim of this article is to study how the BIM methodology can be applied to accurately analyze natural light in buildings and its impact on energy costs, materials and design.	Revit 2011 software was used for modeling. Natural light analysis was carried out using tools such as Ecotect and 3D Studio Max Design 2011. Bim was used as a tool to improve the natural light performance of buildings before construction.	As a result, it was found that the methodology applied here has savings potential, as it reduces the need for design changes, energy costs, material changes and modernizations. In addition, it is possible to improve the aesthetics of the building, improve levels of visual comfort and reduce the use of electric lighting.

Table A2. Cont.

Ref.	Objectives	Methodology	Results
[61]	The aim of this article is to evaluate the use of BIM tools in the development of building performance simulations, with a focus on daylighting analysis, and to verify the challenges and benefits of this integration.	As a methodology, a prototype was developed to integrate Revit 2013 with the Radiance and DAYSIM tools used for daylighting simulation. The prototype automates the process of creating input files for the simulations, ensuring high efficiency and accuracy.	As a result, it was found that BIM does not contain all the data needed to create the input files for the simulations. However, options are offered for incorporating the necessary information. In addition, it was found that the representations of building elements vary between Revit and Radiance/DAYSIM, requiring adaptations. This methodology facilitates informed decision-making in building design.

Table A3. Literature review-based acoustic comfort analysis.

Ref.	Objective	Methodology	Results
[74]	The aim of this article is to propose the use of a BIM tool to improve the acoustic performance of an educational building, taking into account its architectural features.	The authors developed a BIM tool that takes reverberation time, sound pressure level, and critical distance into account in its simulation. From the simulations carried out, it was possible to assess how speech perception and general comprehension are affected by acoustic conditions.	From the simulations carried out, it was possible to see that the authors have developed a BIM tool that can be used in other cases to improve the acoustic performance of the environment through parameters such as reverberation time, sound pressure level, and critical distance.
[8]	The aim of this article is to propose a structure using BIM tools to improve the acoustic performance of buildings by taking reverberation time into account.	The proposed structure, applied to a case study of a classroom, makes it possible to assess whether the reverberation time of the room in question complies with specific regulations and its location. If the result is not compliant, changes are proposed to the finishing materials of the room's structures.	The proposed method does not require the use of other tools. From the structure developed, it is possible to calculate the reverb time automatically. This result helps professionals make decisions, especially in the design phase, if this value does not comply with regulations. In addition, it is possible to reduce costs and improve the room's acoustic performance by identifying these parameters in the early stages of the project.
[75]	The aim of this article is to compare, using BIM methodology and a passive acoustic technology (IPRAT), various scenarios with normative acoustic standards in classrooms in Australia.	Simulations were carried out using I-Simpa (version 1.3.4) software. A total of 20 scenarios were analyzed, taking into account reverberation time, sound clarity and sound intensity. Firstly, these parameters were measured considering the current state of the classrooms, and compared with the values after applying passive acoustic technology.	As a result, using IPRAT technology resulted in an average reduction in reverberation time of 0.56 s, an increase in sound clarity of 4.49 dB and a reduction in sound intensity of 2.46 dB. However, it was found that the methodology applied in this article can be extended to other countries and other environments.
[84]	The aim of this article is to analyze the impact of new subfloor systems on noise levels in individual residential units.	As a methodology, prototypes of 30 square meters each were built, simulating the subfloors. The subfloors used are made from construction and demolition waste and are finished with materials such as ceramic tiles, porcelain tiles and wood laminate, among others. For the simulations, the CYPE AcouBAT 2023 software was used, which provided the results of the impact sound insulation calculation.	It was found that the simulated models with subfloors made from construction and demolition waste achieved acoustic performance results equivalent to traditional subfloor systems. The most favorable result of the research, without considering flooring, achieved a reduction of 23 in the impact sound pressure level. Considering the application of glued laminate flooring, the reduction found was 32.

Table A3. Cont.

Ref.	Objective	Methodology	Results
[82]	The aim of this article is to assess the impact of noise suffered by maintenance workers on offshore platforms.	The methodology used Revit 2019 and Comsol (version 5.4) software to carry out 4D simulations, enabling a spatial-temporal analysis of the sound pressure level suffered by workers. The acoustic diffusion equation (ADE) is used to calculate the sound pressure level of the noise. The impact of noise is quantified using an equation based on the daily noise dose. The simulations take into account the duration of the noise and its sound power. A maintenance schedule is generated using an optimization algorithm.	As a result, it was found that the methodology adopted helps to manage the health and safety of the workers involved, since the spatio-temporal analysis provided by the software helps to optimize maintenance schedules. This methodology can be applied to other activities.
[9]	The aim of this article is, through a case study in an educational building, to use Revit software to create a method for calculating acoustic performance.	Revit 2020 was used in conjunction with Dynamo (version 2.5) for various scenarios and the reverberation time (TR60) was calculated using an algorithm. This algorithm takes into account the geometry of the space, the existing furniture and its properties such as surface and material, characteristics that can affect the TR60. The TR60 is calculated using the Sabine equation.	As a result, it was observed that the presence of furniture reduces TR60 values. This reduction is more significant in larger rooms, where this result can decrease by up to 7.87 s at higher frequencies.
[76]	The aim of this article is to develop a software prototype that extracts data from a BIM model to evaluate the acoustic performance of a classroom.	The software used was Revit 2013, DirectX 11 and C# programming in Visual Studio. The parameters used in the simulation were reverberation time and sound intensity level. These parameters make it possible to assess how the sound behaves for the audience. The geometric characteristics of the environment and the components, the absorption coefficients and the position of the sound sources and the audience are taken from Revit. DirectX is used to adjust the sound intensity level.	The result is a software prototype, using BIM, capable of evaluating the acoustic performance of environments by calculating the reverberation time and the sound intensity level. In this way, the software can help designers make decisions on choosing the best materials and space layout for the best acoustic performance in the environment.
[83]	The aim of this article is to use BIM software to create noise maps that make it possible to assess the need for barriers and acoustic insulation systems to mitigate noise levels in environments and workplaces.	GIS (version 3.1), SoundPlan (version 5.0), Autodesk Revit 2018 and Navisworks 2018 software were used. Terrain data (elevation) is exported from GIS to SoundPlan. SoundPlan must be fed with noise source parameters. From the data entered, a noise map is generated, which must be exported to Civil 3D 2018. In Civil 3D, surfaces with equal noise levels are created. This file is exported to Navisworks, where it is possible to assess the areas of the room or building that are exposed to the highest noise levels.	Based on the evaluation of the noise maps and the analysis, through Navisworks, of the locations exposed to these noises, this methodology helps designers to implement measures to minimize these noises in the design phase, and can also help in the adoption of protection measures in existing environments and buildings.

Table A3. Cont.

Ref.	Objective	Methodology	Results
[77]	The aim of this article is to use BIM technology, together with other software, to calculate the reverberation time of concert halls.	The study environment is modeled in Revit. An IFC file, which contains data such as the geometry of the room, the location of objects and the types of elements in the project, is exported from Revit. For the acoustic analysis, the COMSOL (version 5.3) software is used, which uses the geometry data, the location of the sound sources and the materials used, extracted from the IFC file. Various scenarios are created, changing the position of the sound sources and the materials with acoustic absorption and, using COMSOL, the reverberation time of the environment is calculated.	From the simulations carried out with the various scenarios created, it was found that, for the case study in this article, changing the position of the sound sources did not significantly alter the value of the reverberation time. Changing the geometry of the room reduced the reverberation time by 29 s. It was also found that the covering materials that make up the walls and seats are decisive in the result of the reverberation time.
[78]	The aim of this article is to develop a calculation model, using BIM modeling information, to analyze the acoustic performance of an environment.	The calculation model was developed in Visual Studio and follows regulatory guidelines. On-site measurements were taken and the results of these measurements were entered into the Measurement Partner Suite 2019 software. Once the BIM model has been coded, an xml file extracted from Measurement Partner Suite is exported. This association is made using the ArchLineXP BIM authoring tool.	The case study showed that the coding system plays a significant role in interoperability between different tools. It was also found that the use of BIM tools speeds up the process of studying the acoustic performance of environments.
[79]	The aim of this article is to analyze energy and acoustic performance by applying the proposed method to an educational building.	The educational building in the case study was modeled using Revit 2021 software. For the energy performance analysis, the Design Builder and IES VE 2021 software were used. The acoustic performance analysis was carried out using Dynamo. Two parameters were considered for the acoustic analysis: reverberation time and Schroeder frequency.	As a result, it was observed that Revit, in conjunction with other scripts, is a good tool for acoustic analysis of environments. It is possible to calculate acoustic parameters and simulate environments that meet comfort levels. One limitation of the tool is that it considers all the windows to be made of a single material, as well as the walls. The model is only valid for rooms with a simple format.
[80]	The aim of this study is to analyze the acoustic performance of environments using BIM tools and authoring software.	The building is modeled in Revit 2019 software. Acoustic comfort is assessed using reverberation time. The program developed is able to identify rooms and calculate the reverberation time using the Sabine equation and an external database of acoustic materials called OpenMat. The results are shown in Revit using different colors for each acoustic level.	As a result, it was found that the development of closed cycles in BIM, without the need to involve other software for acoustic analysis, demonstrates an alignment to achieve a high performance of BIM maturity in organizations.
[81]	The aim of this article is to analyze the interoperability of BIM tools with acoustic performance analysis programs.	Revit 2013 and EASE (version 4.4) software were used to model and analyze a performing arts hall, part of the case study. An integration model between these tools was developed.	The simulations carried out helped managers, designers and engineers choose the best solution to achieve optimum acoustic performance in the room. Integration between the tools increased project quality and team productivity.

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