sustainability

Systematic Review

The Use of Energy Simulations in Residential Design: A Systematic Literature Review

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Abstract: The Industrial Revolution and technological advancements have led to the densification and expansion of cities. In urban environments, residential buildings are common, and optimizing energy use in these structures is achieved by focusing on key parameters during the early design phases. These parameters can be tested through simulations. This study aims to define the scope of energy simulations in residential design to contribute to design optimization and reduce energy consumption. A systematic literature review and qualitative analysis were employed, using the PRISMA protocol for data collection and Vosviewer and Bibliometrix tools for bibliometric analysis. The keywords obtained were subjected to qualitative analysis. The research revealed the absence of a standardized approach in simulation studies. To address this, a nine-step framework has been proposed. A discrepancy between the objectives of certain studies and the keywords used was identified. Themes were created based on the studies' objectives, and keywords were recommended accordingly. Several studies have determined the energy potential of buildings during the occupancy phase. Simulations should be integrated into the early design phase to facilitate pre-design optimization. A framework for residential simulation methodology was developed, believed to enhance the validity of studies and facilitate result comparisons. Minimizing energy consumption is a primary objective in residential buildings. The recommendations developed align with the United Nations' Sustainable Development Goal 11: Sustainable Cities and Communities.

Keywords: energy simulation; EnergyPlus; DesignBuilder; sustainable development goals; energy efficient; thermal performance; HVAC; systematic review

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1. Introduction

Energy consumption in residential buildings represents a significant portion of daily energy demand. Energy efficiency is a critical concern across all sectors. Research and strategies intended to reduce energy consumption in residential buildings are crucial for sustainable development. This paper investigates the use of simulation techniques for energy management in residential buildings. The data indicate that energy consumption in residential buildings has reached substantial levels on an urban scale. It is anticipated that energy simulations based on the approach outlined in the study will contribute to reducing energy consumption in residential buildings, underscoring the paper's significance.

The Industrial Revolution has created a significant energy demand and environmental threats [1]. Since then, various concepts have emerged, and awareness of these issues has increased. Consequently, sustainability has become a part of national and international policies [2]. Globalization accelerated as the Industrial Revolution spread geographically and socially. The growth of the population has also increased societal needs [3]. Improved standards, a growing population, and an increasing number of dwellings have raised demands for energy [4]. All these developments have led to a rise in the urban population worldwide. The urbanization movement has impacted energy consumption, industrial processes, and waste management in cities [5–7]. Cities are essential for global sustainability [8,9]. Worldwide, cities are energy-intensive regions. Buildings currently account for 50% of total energy consumption, which is expected to increase to 60% in the near future [10,11]. Further, the building sector accounts for 19% of total greenhouse gas emissions [12,13]. Analyzing the morphology of cities reveals that residential buildings are the most critical and common building types [14].

The increase in the rate of urbanization worldwide and the advancement of technology have affected energy consumption behaviors in housing. Under changing circumstances, the occupancy phase generates the most carbon emissions in the building sector [15]. During the use phase, indoor environmental quality and user comfort have become prominent factors affecting energy consumption. As the comfort needs of users increase, maintaining the energy balance in residential buildings becomes more complex [16]. This comfort is provided through various equipment. The most energy-consuming installations are primarily HVAC equipment [17]. Therefore, heating and cooling are the most energy- and carbon-intensive operations during the use phase [18].

With the increasing number of housing units and urban populations, it is crucial to develop new approaches for sustainable development [19]. Energy-related decisions are key to the approach to be developed. The transition to renewable energy is inevitable [20]. Dealing with large-scale issues requires holistic approaches. Global energy challenges have promoted interdisciplinary studies [21]. Balocco et al. [22] indicated that the construction sector is critical in achieving sustainable, low-carbon energy in Europe [23]. Considering developing countries, this statement may also be applicable on a global scale.

Energy management in buildings is accomplished through a range of design strategies. These strategies can be validated through energy simulations. Energy simulations dynamically calculate the energy consumption of buildings [24]. From this perspective, energy simulations in residential buildings have been investigated. A common framework needs to be identified among the simulation studies reviewed. These differences in approach are explained further in the discussion section. In studies employing simulation in housing design, several discrepancies were observed based on parameters such as building status, zoning regulations, study objectives, and the type of simulation. This situation highlights the existing research gap. At the outset of the research, the rationale is determined: “The lack of systematic use of energy simulations in housing design.” The research question was then defined:

RQ: “What is the range of applications for energy simulations in residential design?”

This study aims to define the scope of energy simulations in residential design to improve energy efficiency. In this context, the study targets identification of the role and application of energy simulations in architectural design. The hypothesis of this study is as follows:

Defining the scope of energy simulations in residential design will contribute to optimizing architectural design. Consequently, this can lead to a reduction in energy consumption in residential buildings.

This study applied a systematic literature review (SLR) method. SLRs are based on researching, collecting, evaluating, and processing current literature information [25]. The PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analysis) protocol was employed for data collection. Following the screening process, 97 studies were analyzed using Bibliometrix and VOSviewer for bibliometric data. Subsequently, a qualitative analysis was conducted on the keywords, and the studies were interpreted. Recommendations were made based on the identified deficiencies.

A roadmap for researchers in the field was provided based on bibliometric data and insights from the qualitative analysis. The fundamental concepts and emerging trends in the field are presented herein. The methodological deficiencies in the existing literature were examined using qualitative analysis. No comparable study on using simulation tools in residential buildings was identified. Thus, the original value of the study is demonstrated. The approach developed in this study stands out as a novel contribution to the field.

The introduction outlines the significance of the study, formulates the research question and hypothesis, and presents the aim, objective, contributions, and overall research flow. The methodology section of the study describes the methods and tools employed. In the findings section, the quantitative bibliometric data are presented. In the discussion section, the contents of the clusters obtained from the keyword co-occurrence analysis are analyzed, and two themes are formed. These themes are examined, and the deficiencies are identified. The results are provided in the conclusion section.

As a result of the study, an approach has been developed to determine the simulation parameters based on the building and the purpose of the research. This approach also provides a framework for data sharing within simulation methodology. Also, a suggestion has been developed regarding the methodology of the studies and the keywords used to increase their accessibility.

2. Materials and Methods

The method of this research is a systematic literature review (SLR). SLRs are based on researching, collecting, evaluating, and processing current literature information [25,26]. A research question was first determined at the beginning of the systematic literature review. Then, articles, papers, and book chapters written on the subject were collected within specific frameworks. Sources compiled from selected databases were analyzed in depth. Inferences drawn from the analyses were interpreted, and the results reported. As a result, existing knowledge is revealed, deficiencies are identified, and suggestions are provided for future research. The PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analysis) protocol was used for data selection in this paper (Figure 1). PRISMA ensures data uniformity and decreases bias in SLRs and meta-analysis studies [27]. This study, with ID number 586782, is registered in the PROSPERO (International Prospective Register of Systematic Reviews) database.

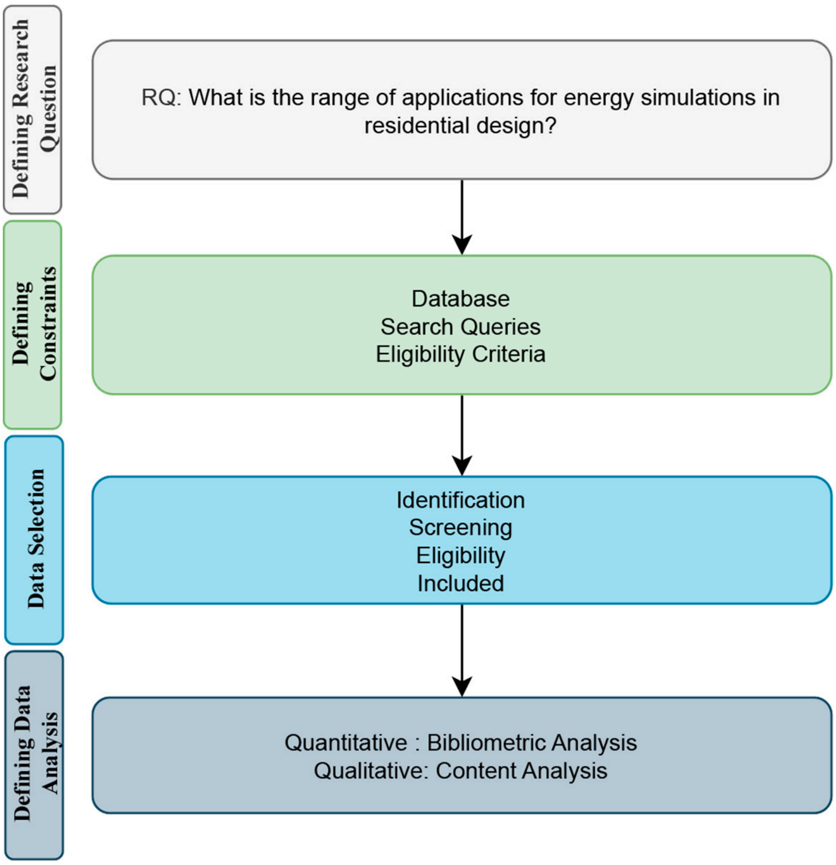

Figure 1. Study Workflow.

The study covers only the Web of Science database. As a consequence of the searches, it was observed that the database contains a sufficient number of studies in the field of architecture in terms of quantity and quality. Two separate search queries were conducted for data collection. These searches are as follows: In the first search, the terms "energy analysis" and "hous*" were used in the topic parameter. The second search was performed on the topic parameter and with the keywords "energy simulation" and "hous*". The queries employed broad keywords. Two extensive searches were conducted to compile all simulation-related studies. All results are limited to the "Architecture" field from the" Web of Science Categories", and no further limiting parameters were applied (Table 1).

Table 1. Literature Search Criteria.

Database	Web of Science (April 2024)
Search	-energy analysis (Topic) AND hous* (Topic) AND Architecture (Web of Science Categories) -energy simulation (Topic) AND hous* (Topic) AND Architecture (Web of Science Categories)
Time Period	No Restriction
Search Categories	Architecture
Document Type	Proceeding Paper, Article, Book Chapters, Review Article
Language	English

In the search for 'energy analysis', 168 proceeding papers, 158 articles, and seven book chapters were identified. For the 'energy simulation' search query, 145 proceeding papers, 105 articles, and two book chapters were retrieved. After eliminating duplicate entries, 492 studies were listed. Then, the abstracts, titles, and keywords of the studies were reviewed for eligibility based on the following criteria:

- Studies conducted in the field of architectural design;
- Studies on residential buildings;
- Studies that used computer simulation in energy analysis;
- Studies published in the Web of Science database and written in English.

After eliminating 395 entries, 97 studies were listed for review (Figure 2).

The issue addressed in the study is that energy simulations of residential buildings are not systematically employed. The Biblioshiny interface of the Bibliometrix application (R-tool 4.3.3) and VOSviewer 1.6.20 were utilized for quantitative analysis and visualization [28–30]. Bibliometrix (4.3.0) is an open-source software package designed for bibliometric analysis. It functions as a free plugin for R, a statistical programming language. VOSviewer is a free software tool for analyzing and visualizing bibliometric data. Bibliometric analyses were included in the quantitative findings section of the study. In the discussion section, clusters obtained from the co-occurrence keyword analysis were utilized. VOSviewer was used for the 'co-occurrence of keyword analysis', while the 'most used simulation software' and 'annual scientific production' were conducted manually. Bibliometrix was employed for the remaining bibliometric analyses. Figure 3 addresses the workflow of data analysis.

The content, methodology, and results of all of the studies were examined in the entire record, and clusters were analyzed. The clusters obtained with Vosviewer were validated by referencing the reviewed studies. Studies with common purposes, objectives, and results were classified under two themes at synthesis. The occurrence of clusters and the outcomes of studies within the same cluster were examined. Then, the studies were evaluated under two categories based on their shared and contrasting aspects in terms of content. In the content analysis, the current status and deficiencies of the themes were examined. The results are included in the discussion and conclusion sections to guide future research. The themes in the discussion section were built with clusters validated by references from the reviewed studies. The keywords of the 97 studies align with their themes and clusters. However, the contents of some studies are similar to each other. Some keywords refer to the same concept, leading to heterogeneity in keyword analysis. This challenge is analyzed in the following sections of the study, and solutions are presented in the conclusion.

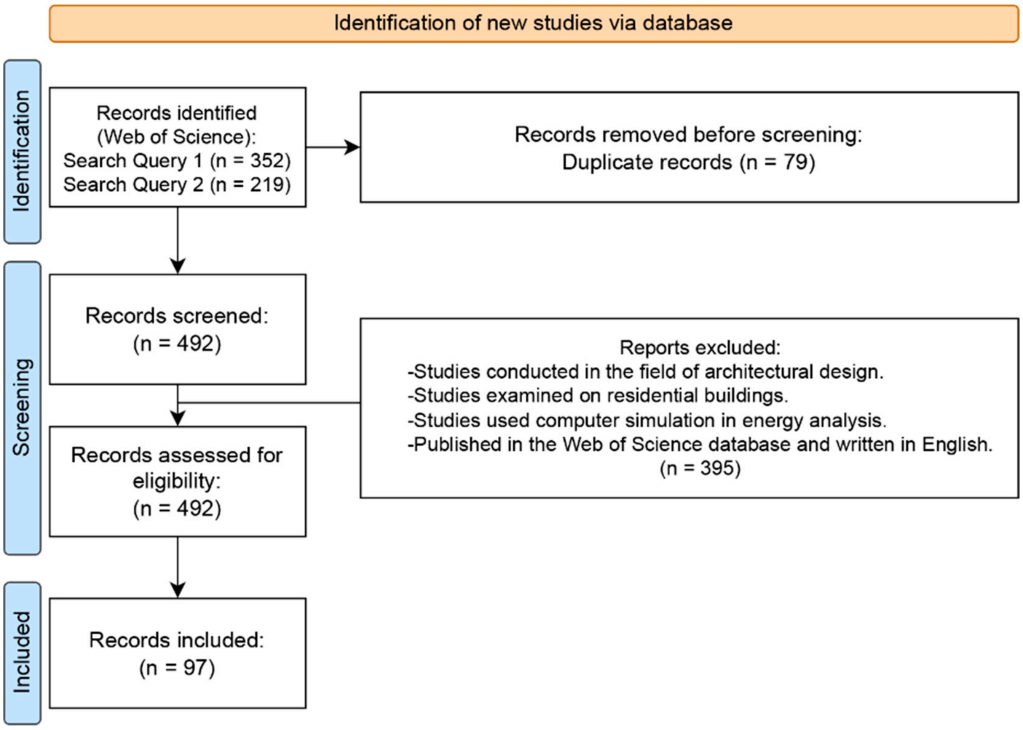

Figure 2. Data Selection Workflow (PRISMA).

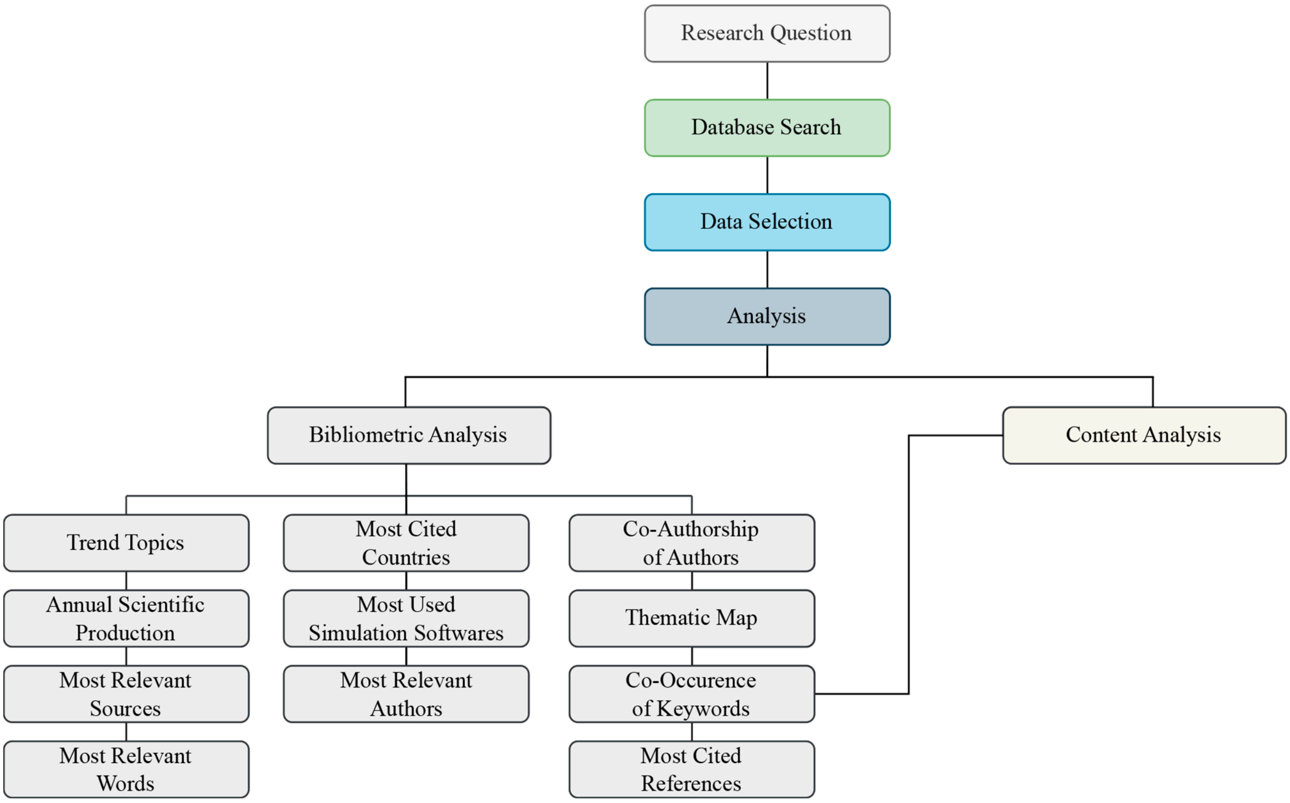

Figure 3. Data Analysis Workflow.

A further risk of SLR is the crossover between themes. The results of a study on one theme can become a research topic for another. While this may seem like a risk for bibliometrics, it does not pose a problem for energy simulations. While one study may focus solely on energy performance, another study may analyze the planning decisions that led to it in the same building. Simulation tools in architectural design are used in both directions.

All the studies examined in this SLR conducted quantitative measurements with simulation tools. The results were calculated using publicly available software packages. Researchers interpreted the results of these calculations. However, the simulation results do not introduce bias or uncertainty. This paper investigates the use of energy simulation tools. The contents and interpretation of the results are not included in the SLR. The themes, clusters, and types of energy analysis in all of the studies are combined and presented in a table.

The studies included in the review had no restrictions for the regions selected for field research. The authors in the studies detail the parameters such as climate data, local conditions, floor plans, and the software used. The information provided by the authors can be used to develop 3D models of buildings, execute simulations, and validate results when necessary. However, there is a lack of unity in data sharing regarding the energy consumption period and the unit of energy. Shared data have a unit conversion problem.

3. Findings

The bibliometric data collected in the study are presented in this section. The first study on the use of energy simulations in residential design was published in 2002. Then, 12 studies were conducted until the end of 2013, and the number increased in 2014 and thereafter. Between the beginning of 2014 and the end of 2020, 69 studies were published, and then interest began to decline. Although the number of studies conducted has decreased, the subject remains relevant. Studies on this subject can be divided into three phases. The first phase is 2002–2013, the second is 2014–2020, and the third is 2021 and later. The most productive period in these studies is the second phase (Figure 4).

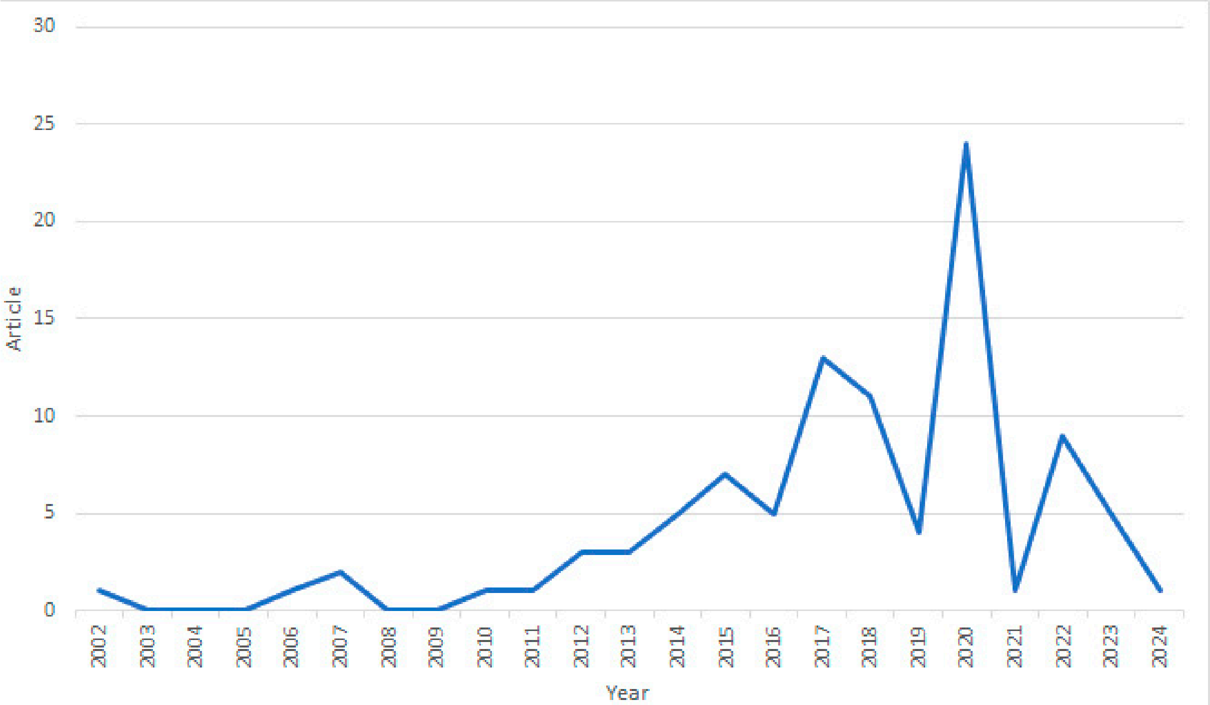

Figure 4. Annual Scientific Production Analysis.

Among the conferences containing the most studies, NSB 2017 (Nordic Symposium on Building Physics), 2020, and PLEA 2018 (Passive and Low Energy Architecture, Smart and Healthy Within the Two-Degree Limit vol1 and vol3) come first. *Architectural Science Review*, *Open House International*, *Journal of Green Building*, and *Frontiers of Architectural Research* are the journals where most of the articles were published (Figure 5).

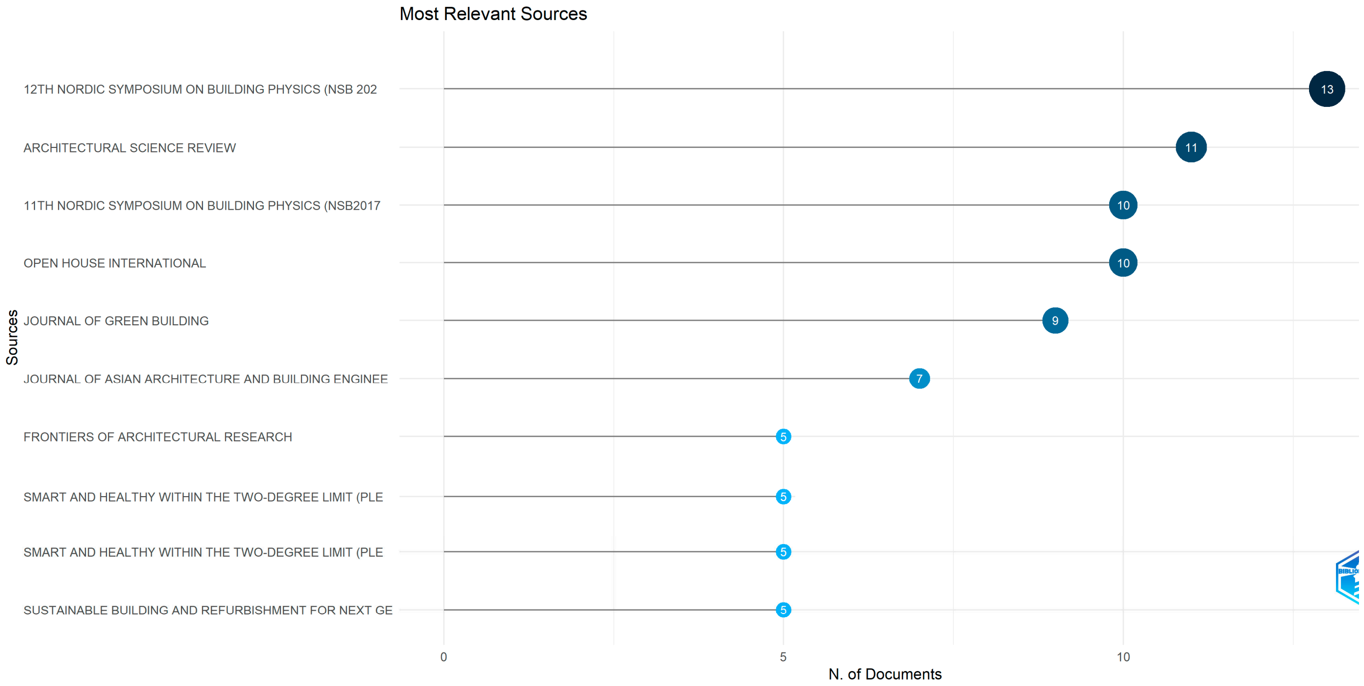

Figure 5. Most Relevant Sources of the Literature Review.

The authors focused on three main keywords: thermal comfort, energy efficiency, and thermal mass. These keywords were followed by words such as thermal performance and building energy. There is no severe decoupling between these keywords (Figure 6).

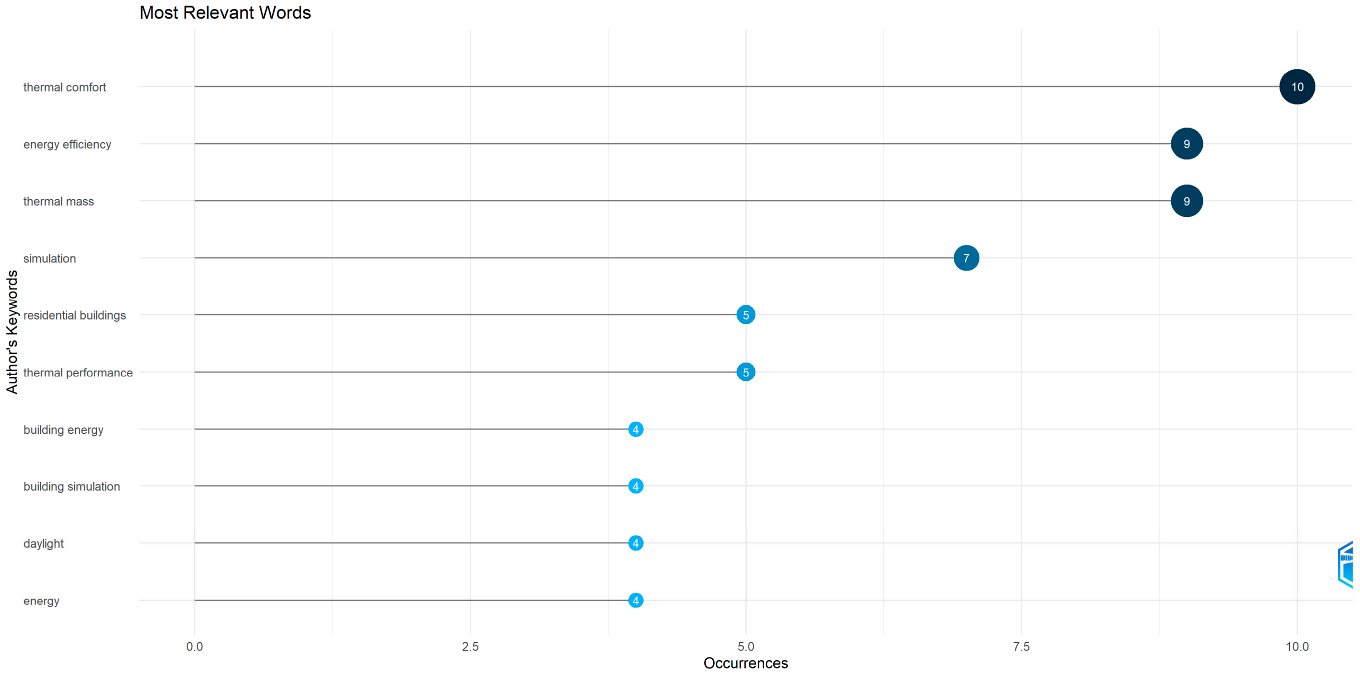

Figure 6. Most Relevant Words of the Literature Review.

For studies published in 2022 and later, the trending words are "CFD, data analysis, courtyard, and orientation". Beginning in the 2010s, "energy" has become one of the most widely used words over the long term. Trending terms such as "thermal performance" and "energy efficiency" have been replaced by keywords like "sustainability," "simulation," and "consumption." The analysis included the three most frequently used words for each year (Figure 7). "Energy," "sustainability," and "consumption" are three keywords that remained on the list for an extended period.

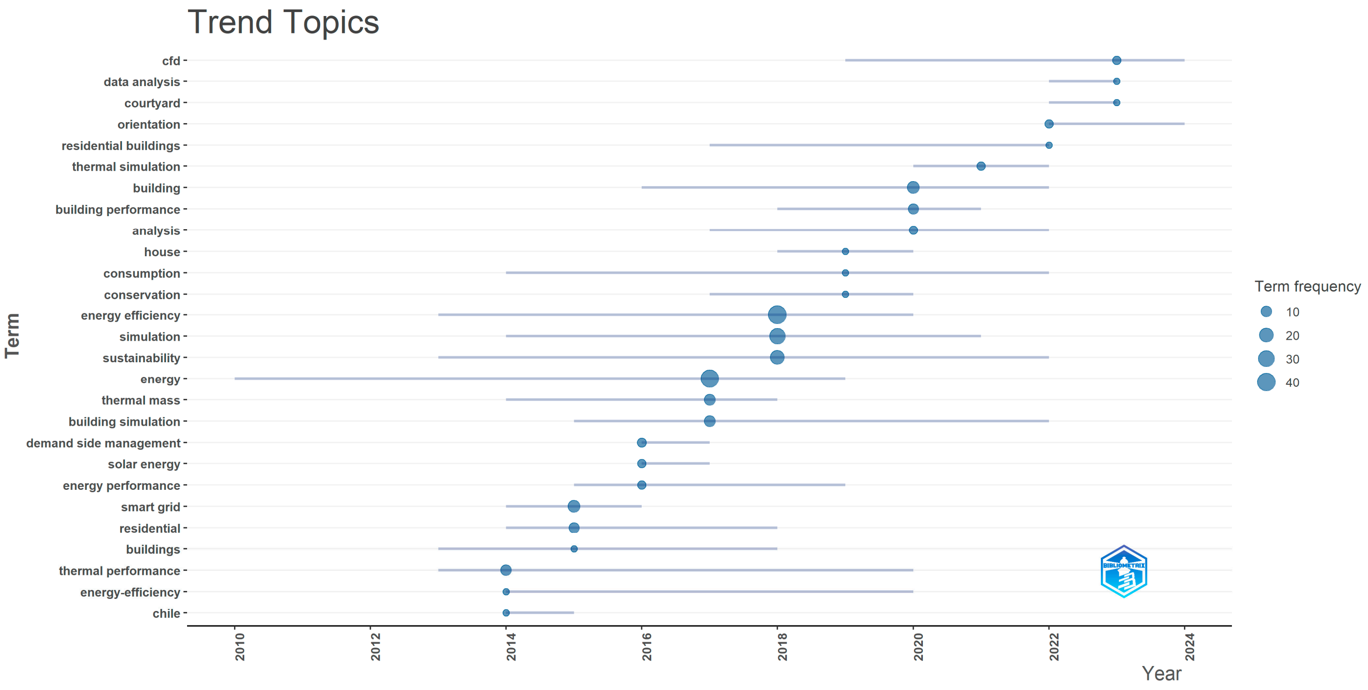

Figure 7. Trend Topic Analysis.

The figure highlights the countries with the highest number of studies. The image's bolded symbols represent countries with many scientific studies (Figure 8). The USA, China, the UK, Australia, and India are the leading five countries, respectively.

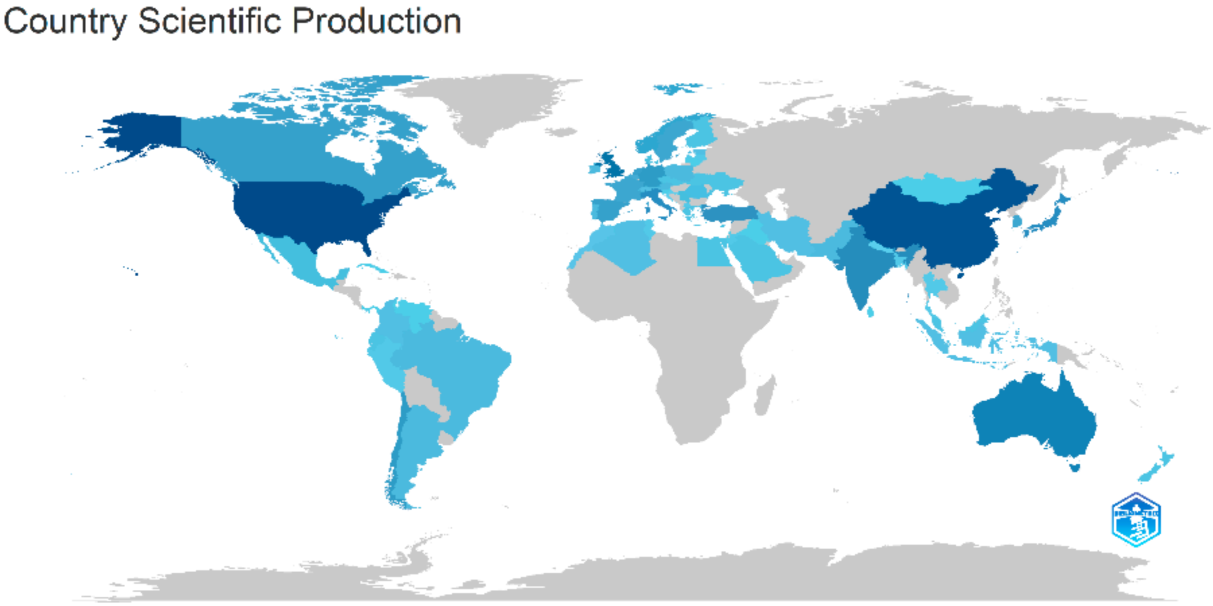

Figure 8. Scientific Production by Country in the Literature Review.

Table 2 lists the countries that received the most total citations among the studies analyzed in full record in the searches. Germany comes first with 592 citations. Four of the ten countries identified are located in Europe. Citations exhibit a global distribution pattern through their presence across various continents.

Table 2. Most Total Citations by Country.

	Country	**Citation**
1	Germany	592
2	USA	525
3	Peoples R. China	355
4	U. Arab Emirates	250
5	Australia	164
6	England	117
7	Canada	112
8	Switzerland	96
9	Japan	82
10	Turkiye	65

The simulation software that the authors used most is shown in Figure 9. Among the studies examined, the most used simulation software in architectural design is DesignBuilder. DesignBuilder serves as an interface to the EnergyPlus simulation engine. EnergyPlus is an open-source simulation tool capable of collaborating with other programs. They can perform simulations such as HVAC, lighting, and carbon calculations. DesignBuilder and EnergyPlus are followed by Ida-Ice (11), Ies Ve (8), Trnsys (5), Grasshopper (5), and various other programs.

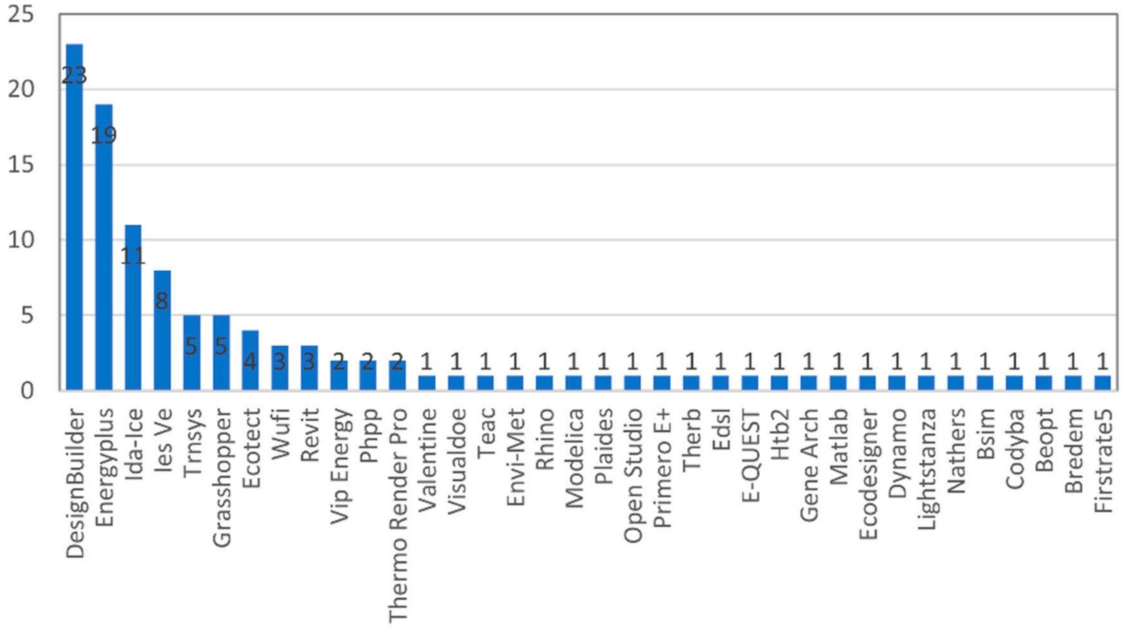

Figure 9. Most Used Simulation Software.

Among the 97 studies, the authors with the most publications were Kurnitski, J. (4) and Thalfeldt, M. (3). These authors are followed by people who have two works each (Figure 10).

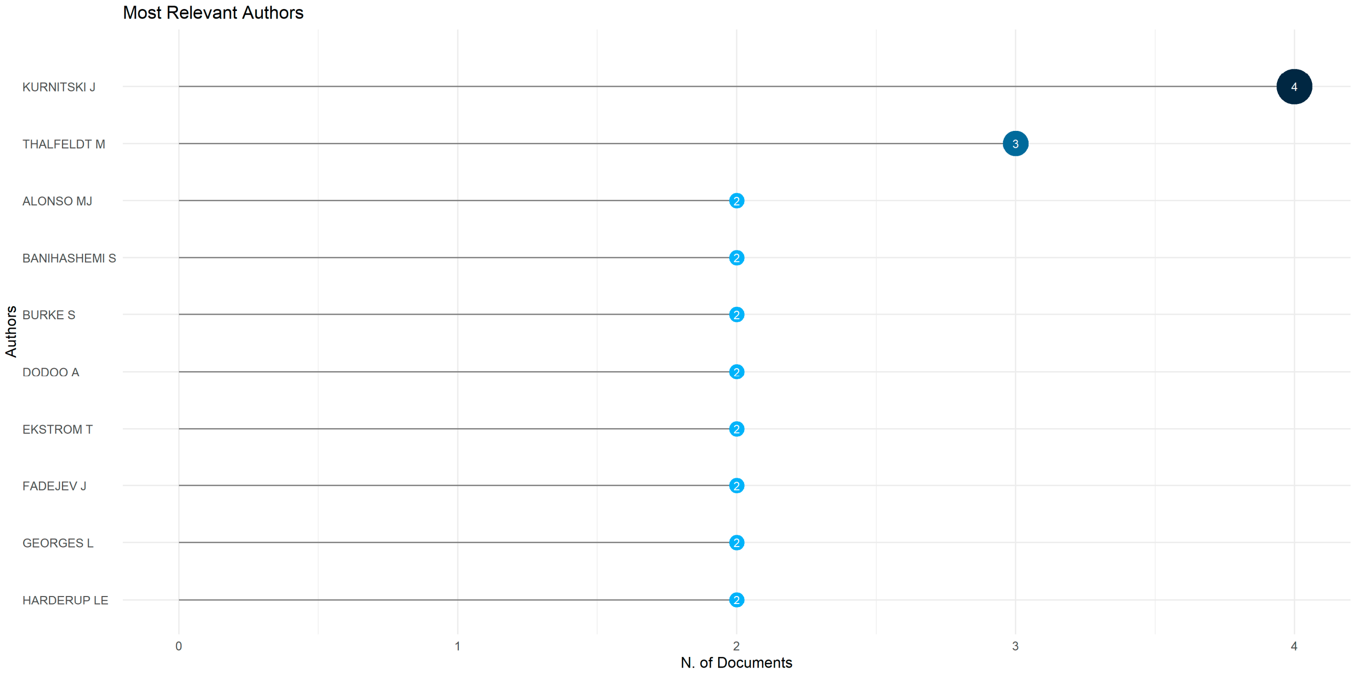

Figure 10. Most Relevant Author Analysis.

Kurnitski, Thalfeldt, Burke, Ekstrom, Fadejev, Harderup, and Simson collaborated the most. Figure 11 shows a network analysis of the authors.

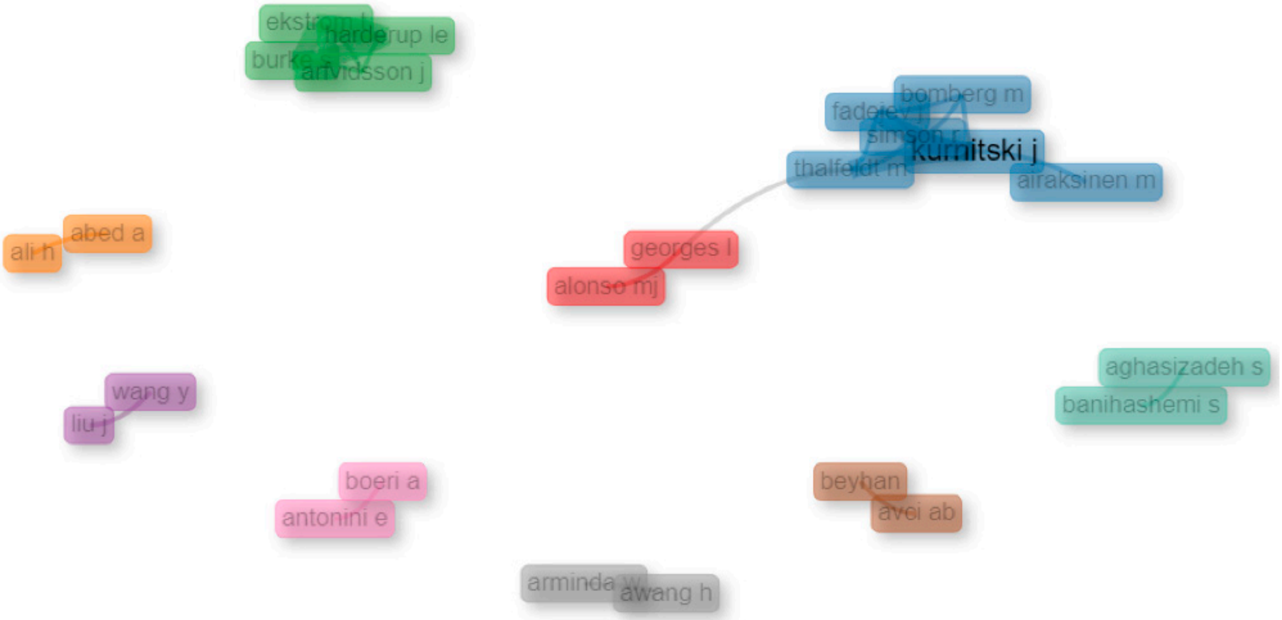

Figure 11. Author Collaboration Analysis.

Table 3 shows the most cited studies based on a complete record analysis of the listed sources. Nguyen [31] comes first with ten citations (Table 3).

The thematic map created from the analysis of the searches is provided in Figure 12. This analysis, conducted using Bibliometrix, examines studies by keywords and years and identifies the frequently used concepts. Concepts that show an emerging or declining trend appear as “monitoring” and “energy consumption”. The vertical development axis indicates popularity in the lower left area, where the keyword “monitoring” appears to rise, while "energy consumption" shows a downward trend. The concepts of "sustainability", "simulation" and "thermal performance" are the main study areas of this topic. All studies are theoretically grounded in these concepts. Motor concepts are the driving forces behind contemporary research. The current literature focuses on "Orientation" and "energy efficiency". Niche work areas include the "passive house", "natural ventilation", and "smart grid" keywords. Researchers conducting new research on this subject should focus on niche themes and know the basic themes.

Table 3. Most Local Cited Authors.

	Cited Reference	Number of Citations
1	Nguyen At, 2014 [31]	10
2	Crawley Db, 2008 [32]	8
3	De Wılde P, 2014 [33]	8
4	Pérez-Lombard L, 2008 [34]	8
5	Anna-Marıa V, 2009 [35]	7
6	Grıego D, 2012 [36]	7
7	Roudsarı Ms, 2013 [37]	7
8	Bustamante W., 2009 [38]	6
9	Caetano I, 2020 [39]	6
10	Coakley D, 2014 [40]	6

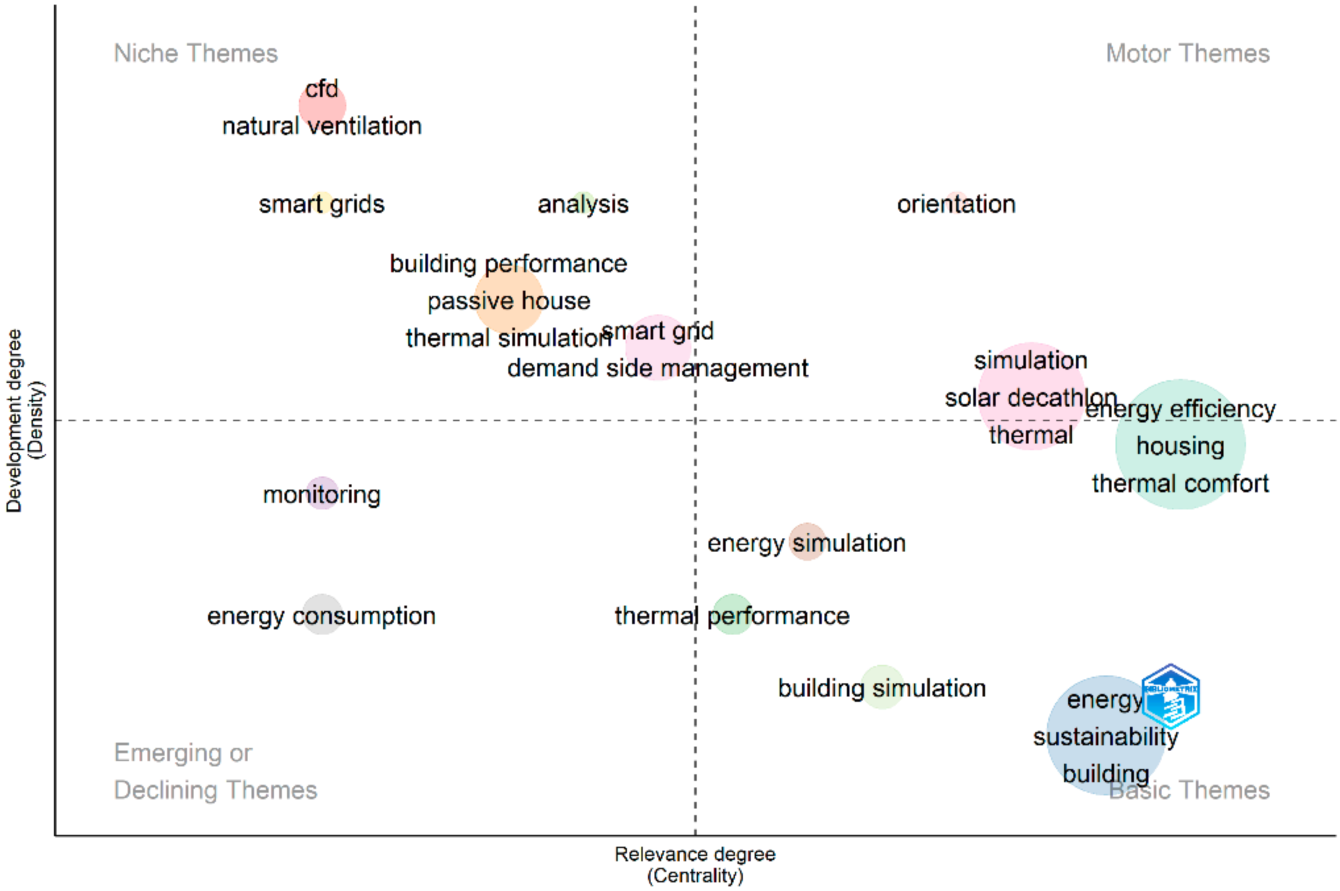

Figure 12. Thematic Map Analysis.

Figure 13 shows the co-occurrence analysis of the keywords used in the studies. This analysis shows which sub-areas of energy simulation the studies are concentrated on. The clusters formed from the analysis reveal which research methods were used in the studies.

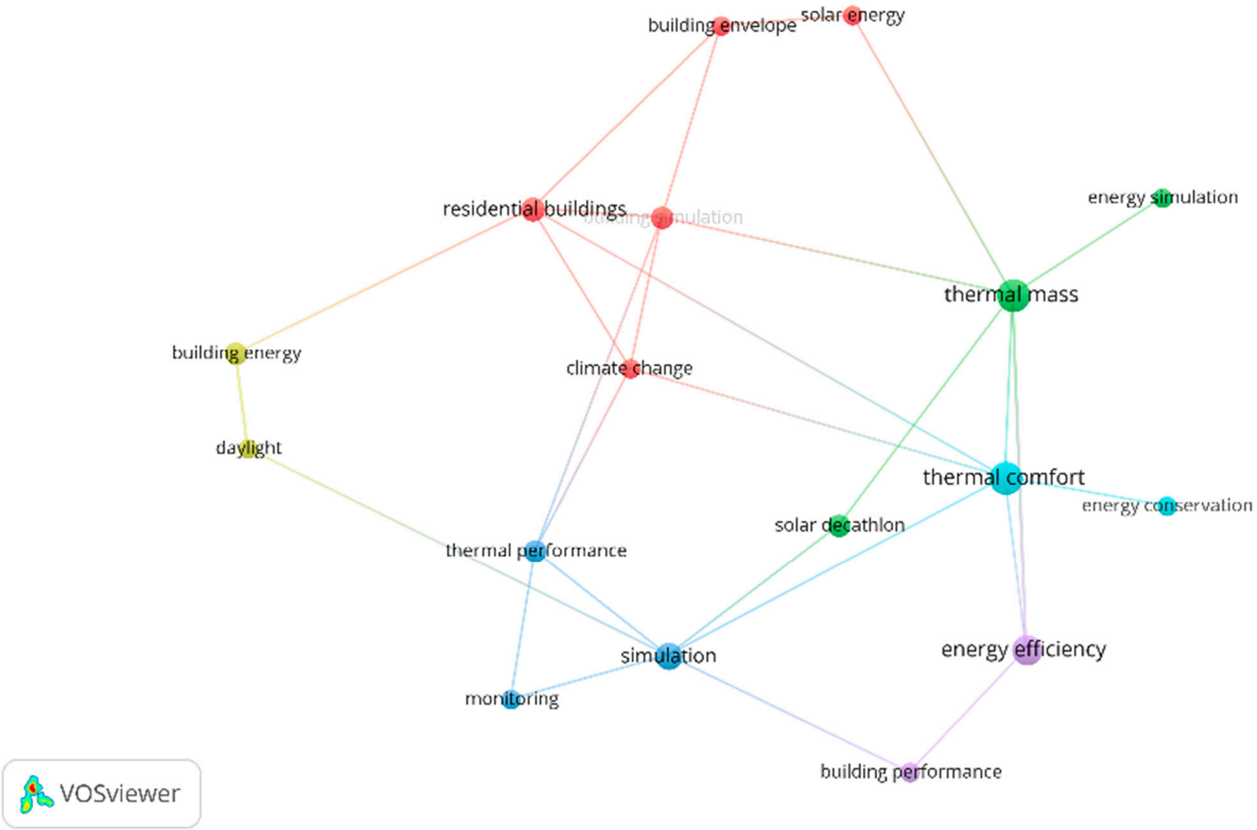

Figure 13. Co-Occurrence of Keyword Analysis.

Table 4 indicates clusters formed by keywords used together. The minimum occurrence threshold of a keyword was set to three.

Table 4. Cluster from Keyword Analysis.

Cluster	Keywords
1	Building Envelope Building Simulation Climate Change Residential Buildings Solar Energy
2	Energy Simulation Solar Decathlon Thermal Mass
3	Monitoring Simulation Thermal Performance
4	Building Energy Daylight
5	Building Performance Energy Efficiency
6	Energy Conservation Thermal Comfort

4. Discussion

The quantitative data of the research are interpreted in this section. Clusters and sub-themes from the keywords in Table 4 were defined. Studies conducted within these thematic frameworks are examined below.

4.1. Cluster I

The keywords in the first cluster are “building envelope”, “building simulation”, “climate change”, “residential buildings”, and “solar energy”. Studies focused on building envelopes are interpreted as studies on materials science in architecture. These studies investigate the impact of construction material selection on energy efficiency. Different materials and different detail design phases are compared with computer simulations. These comparisons may include renovation or usage phases of existing residences, as well as newly designed residences [41–45].

The building simulation keyword primarily focuses on the functions of buildings and their overall energy consumption. Climate change studies make predictions based on best- and worst-case scenarios. The significance of these studies is to make designs according to the predictions of climate conditions. Forecasted climate conditions are determined with climate data on previous years and mathematical equations [46,47].

The solar energy keyword represents the utilization of renewable energy in architecture. Renewable energy sources that impact the designs of residential buildings are defined as solar and wind energy. These studies aim to assess the effects of parameters such as daylight, sunshine duration, shading elements, prevailing wind, and natural ventilation on the design. The optimal utilization of these variables is intended to increase energy efficiency [48].

4.2. Cluster II

Studies with the “Energy simulation” and “thermal mass” keywords concentrate on the heat transfer between indoor and outdoor environments. In this context, “Energy simulation” includes calculating heat transfer. While the concept of “thermal mass” seems closely related to building material science. The primary studies in this cluster concentrate on the energy difference between indoor and outdoor spaces. The definition of energy simulation includes all simulation types, such as heating, cooling, ventilation, and lighting. The concept of thermal mass explains the relationship between all the energy in the building and its surrounding outdoor space. These studies are generally the subject of building physics. The objective of simulations is to compare design alternatives and provide optimization. While the selection of building materials remains a parameter in these simulations, factors such as form design, courtyards, and atriums are among the basic parameters in the design process [49–52].

The Solar Decathlon is an annual student design competition focused on clean energy. Teams participating in competitions turn their research into scientific studies and publish them in various journals. The works submitted to the competition appear to focus on “energy simulation” and “thermal mass” [52,53].

4.3. Cluster III

The keywords in this cluster are used in studies primarily focused on measurements and calculations. These studies are categorized into two groups. Simulation measurements are sufficient in cases where all the building materials are known [54,55]. The thermal conductivity coefficients of materials are defined using software, and the measurements are then verified. Simulation measurements must be verified in the field in cases such as those of historical buildings. Temperature measurements are employed in cases where building materials cannot be precisely determined. These measurements are conducted periodically, and the results are compared [56]. Studies in this cluster focus on the use of information technologies in architecture. As a result of these measurements, the thermal performance of the buildings can be evaluated. Studies in this field are usually based on thermal performance comparisons [57–61].

4.4. Cluster IV

Daylight is one of the critical parameters affecting architectural design [62]. A holistic approach is necessary for "building energy" and "daylight" in the design process. Space and façade orientations, façade width, window-to-wall ratios, lighting design, heating and cooling energy, and shading elements are design inputs affected by daylight. Daylight impacts building energy in various ways [63,64]. The sun is a renewable energy source, and using natural light enhances the energy efficiency of buildings. Lighting design influences both visual comfort and electrical energy usage [65–67]. "Building energy" refers to all the energy usage of buildings. The building energy model is used to analyze energy consumption in buildings. Studies in this cluster concentrate on building energy consumption and daylight analysis [68].

4.5. Cluster V

The terms 'building performance' and 'energy efficiency' have been employed in studies comparing the energy usage of buildings or design alternatives. In this context, the keyword "building performance" refers to energy performance. A building's energy usage is intended to be reduced according to sustainability targets. To assess whether these targets have been met, specific indicators are necessary, and design criteria are required to make comparisons with these indicators [69–71]. The most common comparison method involves sustainability assessment systems utilizing the LCA model (BREEAM, LEED, DGNB, etc.). In these comparisons, indicators of certain sub-criteria can be accessed with simulation tools. For example, if annual heating data in a residence is considered an indicator, the simulations provide a quantitative comparison for two design scenarios [72]. Building performance and energy efficiency comparisons can be made through simulations and indicators such as daylight, heating, cooling, lighting, carbon emissions, and zero-energy targets. However, while carrying out these studies, it is essential to define targets, criteria, and indicators [73–75].

4.6. Cluster VI

The studies with the keywords "Energy conservation" and "thermal comfort" focus on protecting energy in indoor spaces. These studies involve comparative strategies on energy in architectural design. These comparisons focus on energy losses and gains [76]. Loss and gain data are calculated through simulations. Additionally, simulations can provide data on perceived temperature, relative humidity, and airflow as inputs for thermal comfort analysis. Energy costs directly affect thermal comfort [77,78]. High energy costs can reduce indoor environmental quality. Therefore, comfort achieved at less cost is essential for users. Improving the quality of indoor environments is also beneficial for users' health. However, user habits are a crucial parameter for thermal comfort [79]. Various methods are used to collect user data. These methods include analyzing invoiced energy consumption or collecting user data through questionnaires. Defining the variables to be compared is crucial for the validity of the studies [80].

Table 5 summarizes all the reviewed studies. The themes and clusters shown in Table 5 are explained in the discussion section. Theme 1 refers to "energy efficiency", and Theme 2 refers to "architectural design strategies".

Studies included in the SLR are only from the Web of Science database. Upon analyzing the clusters and themes, it was observed that the database contains sufficient studies for meaningful results. The study focuses only on residential buildings. Therefore, the conclusions and recommendations apply only to housing structures. The findings presented in this paper are solely based on the study of architecture. The results are primarily related to architectural design but apply to interdisciplinary studies. The clusters and themes of the review are shown in Figure 14.

Table 5. Summary Information from Included Studies.

Reference	Cluster						Theme		Simulation Tool	Analysis
	1	2	3	4	5	6	1	2		
[81]						●		●	Designbuilder	Heating, Cooling, CO_2
[82]				●				●	Designbuilder	Daylight
[72]					●		●		Ecodesigner, Firstrate5	Thermal Load
[83]		●		●				●	Designbuilder	-
[75]					●		●		Energy+	Heating, Cooling
[66]				●				●	Beopt	Heating, Cooling
[84]					●		●		Ies Ve	CO_2
[67]					●			●	Revit	Daylight
[85]						●		●	Designbuilder	Thermal Comfort
[69]					●		●		Designbuilder	Thermal Load
[43]	●						●		Valentine	Heating, Cooling
[53]		●						●	Pleiades	Thermal Load
[44]	●						●		Ida-Ice	CO_2
[86]	●						●		Designbuilder	Heating, Cooling
[50]		●						●	Gene Arch	Heating, Cooling, Lighting
[87]		●						●	Grasshopper, Dynamo	Daylight, Thermal Load
[88]	●						●		Trnsys	Thermal Load
[58]			●		●		●		Energy+, Heliodon, Analysis Bio	Thermal Comfort
[59]			●				●		Codyba	Thermal Comfort
[89]	●						●		Nathers	Thermal Comfort
[51]		●				●		●	Rhino, Envi-met	Thermal Comfort
[90]						●		●	Energy+	Heating
[70]	●				●		●		Ida-Ice	Thermal Load
[74]	●				●		●		Ida-Ice	Heating, Cooling
[60]			●		●		●		Ida-Ice	Heating, Cooling
[91]					●		●		Designbuilder	Thermal Load
[92]			●				●		Ecotect	Heating
[56]			●				●		Designbuilder, Energy+, Revit	Thermal Load
[93]			●				●		Ida-Ice	Thermal Comfort
[42]	●						●		Designbuilder	CO_2
[49]					●		●		Ies Ve	Thermal Load
[65]				●				●	Vip Energy	Daylight
[62]				●				●	Revit	Thermal Comfort
[94]	●		●				●		Energy+	Thermal Load
[63]		●		●				●	Trnsys, Energy+	Heating, Cooling
[76]				●				●	Energy+	Thermal Load
[80]						●		●	Primero, Energy+	GHG
[95]					●		●		Phpp	Thermal Comfort
[79]						●		●	Ies Ve	Thermal Comfort
[41]	●						●		Open Studio, Energy+	Thermal Load
[96]						●		●	Htb2	Thermal Load
[97]					●		●		Energy+	Heating, CO_2
[45]	●						●		Ies Ve	Heating, Cooling, CO_2
[78]						●		●	Ecotect	Thermal Comfort

Table 5. *Cont.*

Reference	Cluster						Theme		Simulation Tool	Analysis
	1	2	3	4	5	6	1	2		
[98]					•		•		Matlab	Thermal Comfort
[99]	•				•		•		Designbuilder	Thermal Comfort
[100]		•						•	Phpp	Heating
[101]					•		•		Therb	Heating, Cooling
[102]			•				•		Thermo Render Pro	Heating, Cooling
[103]					•		•		Bredem	Thermal Load
[104]	•				•		•		Designbuilder	Thermal Load
[105]	•						•		Designbuilder	Thermal Load
[68]				•				•	Grasshopper	Heating, Cooling
[55]			•				•		Visualdoe	Heating, Cooling
[106]	•				•		•		Designbuilder	Heating
[107]	•						•		Designbuilder	Thermal Load, CO_2
[108]	•						•		Wufi	Heating, Cooling
[109]	•				•		•		Trnsys	Heating, Cooling
[110]					•		•		Ida-Ice	CO_2
[111]	•						•		Energy+	Heating, Cooling
[112]	•						•		Bsim	Thermal Comfort
[113]	•						•		Wufi	Thermal Comfort
[114]		•				•		•	Energy+	Thermal Load
[115]					•		•		Trnsys	Thermal Load
[116]	•						•		Ida-Ice	-
[64]		•		•				•	Energy+	Thermal Comfort
[61]			•		•		•		Designbuilder	Heating
[52]		•						•	Energy+	Thermal Load
[47]	•		•				•		Ecotect	Thermal Comfort
[71]					•		•		Ida-Ice	Heating
[117]	•						•		Ies Ve	Heating, Cooling
[118]	•						•		Designbuilder	Daylight
[119]				•				•	Designbuilder	Heating, Cooling
[120]				•				•	E-quest	Thermal Load
[48]	•						•		Lightstanza	Daylight
[121]						•		•	Grasshopper	Thermal Comfort
[122]					•		•		Energy+	-
[123]			•				•		Ies Ve	Cooling
[124]			•				•		Vip Energy	Heating
[54]			•				•		Ida-Ice	Heating
[125]	•						•		Designbuilder	Thermal Comfort
[126]				•				•	Designbuilder	Thermal Load
[77]						•		•	Trnsys	Thermal Comfort, Cooling
[127]					•		•		Designbuilder	-
[57]	•		•				•		Modelica	Heating, Cooling
[128]	•						•		Ies Ve	Thermal Load
[129]			•				•		Designbuilder	Thermal Comfort
[130]	•						•		Thermo Render Pro	-

Table 5. *Cont.*

Reference	Cluster						Theme		Simulation Tool	Analysis
	1	2	3	4	5	6	1	2		
[131]					•		•		Wufi	Thermal Load
[132]					•		•		Ecotect	Lighting, Ventilation
[46]	•				•		•		Ida-Ice	Heating, Cooling
[133]					•		•		Energy+	Thermal Load, Daylight
[134]	•				•		•		Grasshopper	Thermal Load
[135]					•		•		Designbuilder	Heating
[136]					•		•		Energy+	Thermal Load
[73]					•		•		Teac, Energy+	GHG

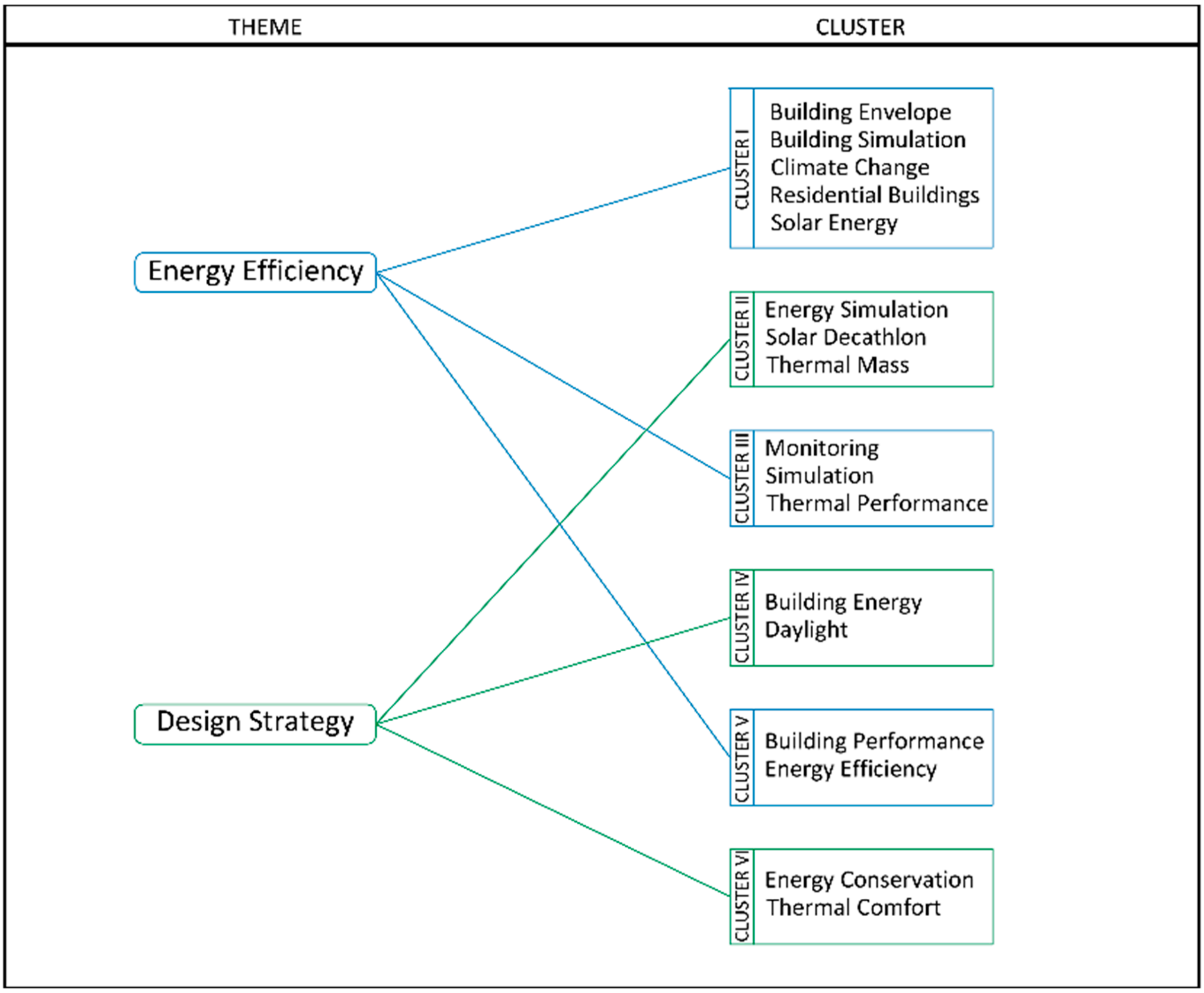

Figure 14. Themes and Clusters of SLR.

4.7. Theme 1 Energy Efficiency

Studies on this theme focus on energy performance. Keywords such as building envelope, building simulation, climate change, residential buildings, solar energy, monitoring, simulation, thermal performance, building performance, and energy efficiency constitute this theme. The studies in this theme center on comparing buildings based on specific indicators. Research questions relate to whether building energy efficiency targets are being met.

Energy efficiency is one of the critical criteria of sustainability goals in architecture. Once these goals are set, measuring the results becomes crucial. At this stage, energy analysis plays a critical role. Energy simulations allow the determined parameters to be calculated in a digital model. Calculating energy consumption data before construction provides a significant advantage for measuring targets and comparing the performances of buildings. The primary objective of studies on energy efficiency theme is to measure and compare the energy performances of buildings using simulation analyses [94,98,104]. These analyses are performed with various criteria.

Building materials and insulation details significantly impact building energy performance. Building materials can be modified without changing the design of the buildings. Monitoring the energy consumption of buildings with different materials is possible through energy simulations [111,113]. These simulations can ensure that the most suitable materials are selected before the construction process begins.

Another advantage of energy simulation is the ability to change environmental data. This enables the prediction of the energy performance of buildings under various climatic conditions [46,86,121]. Energy simulations can determine the effects of factors such as climate, daylight, and materials on building energy performance. Energy simulations are a crucial tool for setting targets and policies in the construction sector. Utilizing simulations for energy performance assessment is essential. Optimization of energy consumption should be achieved through simulations before the construction phase.

4.8. Theme 2 Architectural Design Strategies

This theme investigates the inputs affecting architectural design. It attempts to identify the elements that reduce energy consumption and shape the architectural design. Methods that provide energy efficiency in architecture are categorized into active and passive strategies. In passive strategies, natural resources are utilized without energy consumption [137]. In active strategies, energy efficiency is achieved through specific equipment. An initial investment and energy are required to install these systems. Examples of active methods include heat pumps, solar panels, and HVAC systems.

Passive methods are highly suitable for urban-scale applications. Energy simulations offer the opportunity to compare these design strategies [62,105]. This optimizes buildings for energy consumption before the design phase and increases user comfort and indoor environmental quality. This positively impacts user health and provides economic benefits. Achieving comfort with fewer resources contributes to sustainable development and economic sustainability. The widespread implementation of passive strategies, tested with energy simulations, in residential areas is crucial for the national and global economy.

The total energy within a building is directly related to the design of its components. The space syntax shapes terms such as thermal mass, thermal comfort, and energy conservation. Parameters such as atriums, courtyards, balconies, terraces, circulation areas, and building form affect energy conservation [78,109,118]. Environmental factors such as daylight and wind influence these parameters. Design inputs, including building orientation, wall-to-window ratio, space orientations, and setbacks, are directly related to energy conservation [83,121,126]. All these components should be designed with an integrated approach, in which simulation is essential.

Many countries have legal obligations or classifications regarding consumption related to energy savings targets. However, in most cases, these regulations concern the usage phases of buildings. The potential for energy savings in operational buildings has been identified in the reviewed studies [42,51,109]. Energy simulations must be integrated into the early stages of architectural design. This approach optimizes the inputs affecting energy consumption during the architectural design phase. However, specific workflows must be established to ensure this integration. These workflows are the subject of future work. Steps should be determined according to architectural design stages. To illustrate, specific limits can be set for annual energy consumption or carbon emission values. Compliance with these limits can be verified through energy simulations before construction begins.

New buildings that comply with energy policies can obtain construction permits in this way. This system could lead to a significant reduction in energy consumption, especially in developing countries.

4.9. Section Summary

The research and analysis have revealed a need for a standardized approach in studies that employ simulation software for residential design. The decision-making processes in the studies are correct and adequate; however, the decision procedures are not explained in sufficient detail, resulting in uncertainties. The authors' approaches in this regard were analyzed.

Studies [57,62,71,123,128] examine parameters such as daylight, wind, and shadow, which must be simulated at the inter-building scale. However, the authors did not identify this as a limitation or disclose their simulation models. Modeling the buildings and their immediate surroundings is essential to achieving accurate results concerning these factors. This does not imply that the studies discussed here overlooked the issue; however, not sharing this information introduces uncertainty for readers.

Gado and Games [92] measured 24 days during the hottest period of the year to verify their simulation results. They conducted an annual simulation to assess the overall energy performance in the study. This raises question of why the design day method was not used. The authors must have determined that 24 days of monitoring were sufficient. However, a specific explanation must be provided for the discrepancy between the monitoring and simulation periods. Yao and Zang [133] conducted annual simulations of energy performance, thermal load, and glare for a hot summer and cold winter climate zone. The scope of the study is also consistent with the design day method. However, the authors did not explain their choice of annual simulation.

Eikemeier et al. [90] examined the optimization parameters of heating, shading, natural ventilation, and daylighting through two scenarios. The study includes conceptual designs rather than an analysis of an existing building. However, it needs to be specified why only two scenarios were considered, or why specific scenarios were not developed for each parameter. The scope of the simulation was probably sufficient for the authors' aims and objectives; however, the adequacy of using only two scenarios for multiple factors should be demonstrated with evidence in the study.

Bustamante [86] evaluated the energy performance of retrofit proposals across nine scenarios. They proposed changes to the floor plans, provided that the main features of the houses remained intact. However, the rationale for not utilizing parametric design tools still must be explored. The likely rationale for this is that the genetic algorithm generates many scenarios, and the authors sought to limit the scope. However, the authors should provide more comprehensive details on the selection of simulation type and software.

Ibiyeye et al. [79] evaluated natural ventilation using annual simulations in their study. They simulated the periods during which the windows were left open using only two scenarios: 06:00–22:00 and continuously throughout the day. The decision process for this duration and the number of scenarios should be clearly explained. This will help address how varying weather conditions influence ventilation during the night and across different seasons.

In their study, Taki and Alabid [122] assessed energy performance during the summer months. However, details regarding the building materials utilized in the simulation were not provided. Details regarding the building envelope are crucial for assessing energy performance, and this information needs to be shared clearly with the readers. Mousa et al. [109] specified the simulation inputs in their study, but they still needed to provide the thermal conductivity coefficients of the building materials.

To address these uncertainties, structured workflows should be established. The simulation methodology, along with the aims and objectives of the studies, should be clearly explained. This approach should encompass the entire process, from selecting the study area to attaining the simulation results. The proposed process comprises nine steps, with decision stages arranged from general to specific (Table 6).

Table 6. Proposal for a Methodological Framework for Simulation-Based Research.

1	Location	Determination of the study area.
	Environmental data Climate data	The study area determines the environmental data at this stage.
2	Typology	Analyzing the typology of the building.
	Block layout Detached layout Apartment	Typology affects parameters such as the form of buildings and their relationship with each other. The variations exemplified here can be further multiplied.
3	Scale	Determining the scope in which the building will be approached.
	Housing scale Scale between housing units Neighborhood scale	The accurate determination of the analysis scale is crucial for selecting the appropriate simulation type and ensuring the reliability of the results. The simulation to be employed will be selected based on the building form, environmental data, and typology.
4	Phase	Defining the stage of intervention in the building.
	Use Early design Retrofit	Properly defining the phase to be analyzed is essential for choosing the simulation type and ensuring reliable results.
5	Materials-Equipment	Defining the systems and materials used in the building.
	Building envelope HVAC Shading Domestic hot water	The structural elements have a direct impact on the simulation outcomes. To achieve an effective result, these systems must be accurately defined. The examples provided here can be expanded.
6	Target	Determining the target of the obtained data for the result of the analysis.
	Energy savings Design optimization Comfort	Determining the study's objective is essential for selecting the type of analysis to be performed. Selecting the appropriate type of analysis and providing justification will enhance the accuracy of the results.
7	Simulation Scope	Determining the scope of the simulation.
	Existing situation analysis Generate scenarios Genetic algorithm	Determining the simulation method according to the study content will enhance the reliability of the study.
8	Analysis Period	Determining the simulation period.
	Annual/monthly Daily/hourly Design day	The determination of the analysis period narrows the scope of the results, enables clear outcomes, and also plays a role in the selection of the software to be used.
9	Software and Analysis	Determination of the software and simulation type.
	DesignBuilder EnergyPlus IES VE	Sufficient data have been collected to select the most appropriate software and analysis for the study's context and objectives. The energy unit in which the results will be presented should be clearly specified at this stage.

At the end of each stage, decisions are systematically made to ensure the selection of a simulation that aligns with the study's objectives and intended outcomes. Presenting this process transparently, along with its underlying rationale, is essential to highlight the similarities and differences with other studies in the literature. This will enhance the accuracy of the results and facilitate researchers' access to and comparison of results.

The lack of data sharing methodology in simulation studies can lead to misclassification of studies. The inappropriate use of keywords may mislead readers when previewing the work. Due to the complexity of the content, clearly distinguishing study topics can be very difficult. Keywords often have very similar definitions, and it is possible for multiple keywords to express the same concept. For this reason, it is crucial to determine and distinguish titles and keywords according to the content of the study. For instance, keywords such as daylight and solar energy, as well as thermal comfort and thermal performance, belong to different clusters and themes. But the content of the studies with these keywords is very similar. The studies can be classified under one theme in terms of content, but under another theme in terms of keywords. References [55,118,136] use the keyword "daylight," which is associated with theme 1; however, the studies themselves are related to design strategy and are categorized under theme 2. References [69,99,105,109] have selected the keyword "thermal comfort," belonging to theme 2, but the research content aligns with theme 1. The keywords and themes suggested in Figure 14 can be utilized to mitigate this confusion.

5. Conclusions

The study's findings indicate that energy simulations should be integrated into the early phases of architectural design. This will prevent the loss of energy-saving potential, as observed in buildings already in use. Incorporating this process into the building permitting procedures will enable better control to achieve regional energy targets. The establishment of this integration process will be the focus of future studies.

The absence of a common approach to the methodological knowledge of simulation studies has been identified. The decisions and limitations of simulations need to be clearly articulated. A nine-step approach has been proposed to eliminate ambiguities (Table 6). The lack of such a methodology results in the inconsistent use of keywords in studies. Keywords were categorized according to the objectives of the studies to address this issue (Figure 14).

The recommendations proposed in this study will contribute to the establishment of a methodology for using simulation for residential buildings. The spread of simulation applications will indirectly reduce energy consumption. In addition, the bibliometric data presented is expected to help the people who conduct new research on this subject.

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