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Original Research Article

A Systematic Bibliometric Analysis of Energy Optimization Methods in Buildings*

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Abstract

Problem statement: With increasing environmental concerns and the need to reduce energy consumption, the use of optimization methods for improving building performance has expanded. Since buildings are among the largest energy consumers and greenhouse gas emitters, enhancing their energy efficiency can significantly reduce pollutants and costs. This study examines various optimization methods, including Genetic Algorithms and Particle Swarm Optimization, to analyze trends and identify effective techniques for improving building energy performance. Which optimization methods play a more effective role in building energy simulation, and how are these methods distributed and utilized in Bibliometric research?

Research objective: This study aims to identify and analyze widely used and effective optimization methods for improving building energy performance. The present study examines the distribution and frequency of these methods in Bibliometric articles and seeks to identify existing trends and the contribution of each approach to optimizing energy consumption and other aspects of building performance.

Research method: Within the framework of a systematic review and to accurately identify optimization methods in building energy, a targeted search was conducted in reputable national and international databases using relevant keywords. After an initial screening and selection of related sources, data analysis was performed using VOS Viewer and bibliometric techniques to extract connections among Bibliometric texts. A conceptual model of effective optimization methods for improving building performance was developed, leading to a comprehensive understanding of their application and impact.

Conclusion: Optimization methods, particularly Genetic Algorithms and Swarm Intelligence, are crucial in enhancing building energy performance. A comprehensive analysis of current trends underscores the necessity of integrating real-world data and intelligent techniques to develop more efficient solutions.

Keywords: *Energy Optimization, Genetic Algorithms, Bibliometric Analysis, Energy Efficiency, Building Energy Consumption.*

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under the supervision of Dr. "Niloufar Nikghadam" and Dr. "Alireza Karimpour", with the consultation of Dr. "Zhaleh Sabernezhad", in 2025, at the Department of Architecture, Tehran South Branch, Azad University.

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Introduction

With the growing global concerns about climate change and the energy crisis, optimizing energy consumption in buildings has become one of the main priorities in engineering and energy management (Mathebula et al., 2024). As one of the largest energy consumers worldwide, buildings play a significant role in producing greenhouse gases, and optimizing energy consumption can help reduce costs and environmental impacts (da Silva et al., 2024). Various optimization methods, including genetic algorithms (Ogar et al., 2023), particle swarm optimization (da Silva et al., 2024), and hybrid methods (Gonidakis et al., 2024), have been widely used to improve building performance across different domains, from design to operation (Najafi et al., 2023). These methods allow researchers and designers to manage energy and enhance efficiency in buildings more effectively. On the other hand, the diversity of optimization methods and the complexities related to their application in various climatic and operational conditions have increased the need for a thorough review and examination of these methods (Yue et al., 2023). A systematic review using scientometrics can help researchers and specialists select appropriate and effective optimization strategies by analyzing existing trends in bibliometric research and identifying more efficient methods. In the current context, where environmental and energy crises have become one of the world's most significant challenges, optimizing energy consumption in buildings is particularly important (Hong & Le, 2023). As one of the largest energy consumers globally, buildings significantly contribute to greenhouse gas production and environmental pollution (Sharma & Kumar, 2022). Therefore, reducing energy consumption and increasing efficiency in this sector can substantially reduce costs and adverse environmental effects. With the development of novel optimization methods, new opportunities have arisen to improve building energy performance (Shivaprasad More et al., 2023). However, the diversity of these methods and the complexities related to each of them in different conditions and situations necessitate a systematic and comprehensive review of their effectiveness and application in the building sector. The

importance of this study lies in its ability to provide a thorough insight to researchers and experts in the field through Bibliometric evaluation and analysis of research trends. A scientometric systematic review of optimization methods in buildings enables the identification of the most efficient methods, analysis of their strengths and weaknesses, and the selection of more suitable approaches for specific climatic and usage conditions. From this perspective, the results of this research can assist policymakers, designers, and researchers in formulating effective strategies for optimizing energy consumption in buildings and play a key role in moving toward sustainable development and addressing the energy crisis. Regarding the present research topic, no comprehensive study has been conducted that systematically and integratively examines the scientometrics of energy optimization methods in buildings. Without a coherent and specific analytical framework for evaluating optimization solutions and their impacts on reducing energy consumption and improving overall building performance, this research seeks to clarify and identify trends and standard practices in using these methods through a comprehensive analysis of the existing literature. This study aims to highlight the most effective energy optimization methods and the level of bibliometric contribution from various researchers and academic institutions and identify emerging patterns and research gaps in this area. Through a systematic review of articles, this research seeks to identify and categorize energy optimization methods in buildings, determining the contribution of each method to reducing energy consumption and illustrating their potential and effectiveness in improving building energy efficiency. Given the importance of energy optimization in reducing energy costs and environmental impacts, this study aims to present a comprehensive conceptual model and a reliable framework for evaluating, monitoring, and comparing energy optimization methods in buildings so that precise criteria can be defined within this model for measuring and assessing the success and effectiveness of various interventions in achieving sustainable optimization goals. Table 1 analyzes and reviews multiple studies using different algorithms and methods for energy optimization

Table 1. Research background on optimization in the energy sector. Source: Authors.

No.	Source	Title	Optimization goal	Issue	Energy domain	Algorithm
1	(Al-Saadi & Al-Jabri, 2020)	Optimization of housing facade design in hot climates using a genetic algorithm (GA) computational approach	Multi-objective	Facade	Energy consumption reduction	Genetic
2	(Bui et al., 2020)	Enhancing building energy efficiency using adaptive facades: A computational optimization approach	Multi-objective	Facade	Energy efficiency improvement	Genetic
3	(Li et al., 2020)	A review of operational energy consumption calculation methods for urban buildings	Multi-objective	Form	Energy consumption	Cluster analysis
4	(Feng et al., 2021)	Particle swarm optimization algorithm for building two-level energy transaction	Bi-objective	Energy	Energy consumption	Particle swarm
5	(Ikeda & Nagai, 2021)	Novel metaheuristic optimization method for daily operation in energy and storage systems of buildings	Multi-objective	Energy systems	Reducing energy demands	Metaheuristic
6	(Rabani et al., 2021)	Zero-energy building performance with improved thermal and visual comfort through window, cover, shading device, and energy optimization	Multi-objective	Visual comfort	Zero-energy building	Genetic
7	(She et al., 2021)	Life cycle cost and energy in zero-energy buildings through multi-objective optimization	Multi-objective	Life cycle	Zero-energy	Real data
8	(Omrany et al., 2022)	A review of the energy rating system concept for buildings in Australia: A path to zero-energy building design in the life cycle	Single-objective	Thermal systems	Energy consumption	
9	(Mousavi et al., 2023)	Optimization of low-energy residential buildings for improved energy and thermal comfort in semi-arid climates	Multi-objective	Form	Machine learning algorithms	9
10	(Noorollahi et al., 2024)	Multi-objective optimization of energy demand and net-zero energy building design based on climatic conditions (Case study: Iran)	Multi-objective	Thermal comfort	Genetic	10
11	(Wang et al., 2024a)	Multi-objective optimization of building energy consumption and thermal comfort based on NSGA-II	Multi-objective	Envelope	Genetic	11
12	(Wang et al., 2024b)	Evaluation of evolutionary algorithms combined with a conventional neural network for determining energy consumption in residential buildings	Multi-objective	Form	Evolutionary	12
13	(Zhang et al., 2024a)	Optimization and prediction of shading devices for office buildings for energy, daylight, and views using genetic algorithms	Multi-objective	Shading	Genetic	13
14	(Zhan et al., 2025)	Multi-objective optimization method for building renovation with economic costs and semi-life cycle	Multi-objective	Construction	Genetic	14
15	(Zhu et al., 2025)	Application of a hybrid machine learning algorithm for multi-objective optimization of energy efficiency in green buildings	Multi-objective	-	Genetic	15
16	(Wang et al., 2025)	Robust energy management in a multi-energy building under district heating: A deep reinforcement learning approach	Multi-objective	-	Machine learning	16

in buildings. These studies illustrate the growth and development of various tools to address complex building design and performance challenges. In recent decades, optimizing energy consumption and enhancing occupant comfort have become key priorities in architectural design and building engineering.

Theoretical Foundations

The term “optimization” in building energy efficiency does not necessarily imply achieving the absolute best solution to a given problem, as the complexity of the issue or the limitations of simulation tools may prevent attaining this ideal outcome (Mathebula et al., 2024). Many researchers consider optimization an iterative process to improve performance (Mohan et al., 2023) rather than strictly reaching a globally optimal solution (Rachmawati et al., 2024). This process is often conducted using computer simulations, resulting in optimal or suboptimal solutions (Yang et al., 2024). Instead of relying on complex mathematical optimization techniques, some scholars have employed methods such as sensitivity analysis or experiment design as effective strategies for enhancing building energy performance. Additionally, approaches like “compensatory search” (Zhang et al., 2024c) and “expert-based optimization” (Wen et al., 2024) have been explored. In simulation-based optimization (Rahnamayiezekavat et al., 2024), the term is a fully automated process that integrates numerical simulation with mathematical optimization (Quang & Phuong, 2024). This process is typically carried out by linking a building energy simulation program to an “optimization engine” composed of one or more algorithms. Simulation-based optimization has emerged as a powerful tool for designing high-performance buildings that meet the growing demands for low-energy buildings (Saffari et al., 2023), green buildings, and net-zero carbon structures. Research conducted by scholars such as Wang, Fasanghari (Ogar et al., 2023), Bambrook (Shivaprasad More et al., 2023), and Castro-Lacouture (Khodadadi, 2023) has demonstrated that employing optimization techniques in the design of energy-efficient buildings can have positive impacts on energy consumption reduction and sustainable

building performance. This is particularly significant given the additional benefits these features provide in green building rating systems (such as LEED credits) (Hong & Nguyen, 2023).

• Optimization across various bibliometric disciplines

Optimization is defined differently across Bibliometric disciplines, with varying approaches depending on the field of study. Fig. 1 presents a review of several definitions of optimization from different perspectives. Optimization encompasses various methods derived from diverse fields, including operations research, artificial intelligence (Bragadin et al., 2022), computer science, and machine learning. These techniques are increasingly being leveraged to enhance architectural processes and improve building energy efficiency. Fig. 1 illustrates the role of optimization across different Bibliometric domains.

• Energy simulation with optimization

Optimization challenges (Duhirwe et al., 2023) arise in various architectural design and sustainability aspects. For instance, in architectural energy design (Güney, 2023), an architect designing a residential or office building must select materials that are not only cost-effective (Olave, 2022) but also possess suitable thermal properties to reduce energy consumption and enhance thermal efficiency. Similarly, in energy simulation (Ghasemi Nasab et al., 2021), engineers must determine the optimal placement and size of windows, type of glazing, insulation levels, and building orientation to maximize natural daylighting and solar heat gains. In

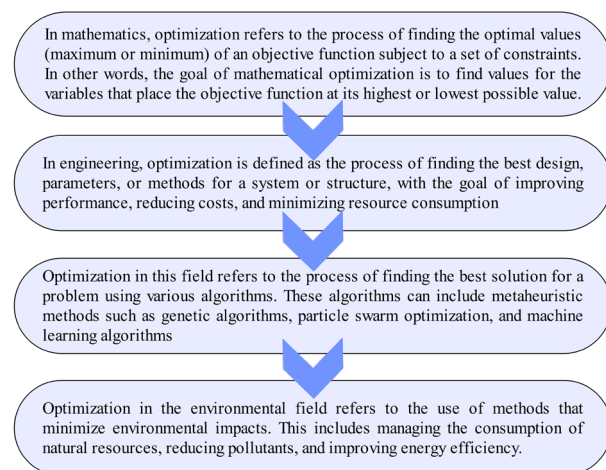


Fig. 1. Definition of optimization in various sciences. Source: Bragadin et al., 2022.

this process, optimization algorithms assist architects in exploring multiple design scenarios through simulations, enabling them to identify the most practical combination of materials, energy systems, and environmental design strategies.

For example, evolutionary algorithms, such as thermal simulation-based optimization, which focuses on thermal modeling (Xu et al., 2024) and thermal behavior analysis (Yu et al., 2024), can help architects develop energy-efficient designs. These methods enhance the balance between aesthetic design, energy efficiency, and construction costs (Zhang et al., 2024b), resulting in buildings that exhibit architectural beauty, consume less energy, and utilize resources more efficiently.

Many energy simulation tools with user-friendly interfaces and extensive educational resources are available today. These tools enable design teams to explore novel design alternatives that would have been inaccessible through traditional methods (Yang et al., 2024). For instance, recent legislative changes in Europe have led to revisions in national energy codes, incorporating more advanced computational approaches (Wang et al., 2024c). Consequently, compliance with these codes is often a driving force behind adopting such tools (Tajik et al., 2024), though it does not necessarily guarantee building energy optimization (Su & Zhao, 2024).

Until now, studies analyzing the impact of various parameters on building design have relied on parametric analyses based on detailed building simulations. However, these simulations are computationally expensive, making brute-force evaluations of all possible solutions infeasible. Thus, the need for a more efficient and faster solution for space exploration has led to the adoption of optimization techniques. It is important to note that translating a real-world design problem into a mathematical domain introduces limitations, and standard optimization algorithms used in building design problems do not guarantee to find the absolute optimal solution (Quang & Phuong, 2024). Nevertheless, buildings designed using optimization methods may perform better than conventional approaches that do not integrate optimization (Nouri et al., 2023).

Thus, understanding the strengths and limitations of

optimization techniques is essential for their practical application in relevant design problems. While building performance simulation tools have been widely utilized in research, their integration into architectural design practice has only gained momentum in the past decade. Several factors have contributed to this delay, including the complexity of these tools, the need for specialized skills, associated costs, uncertainties in simulation results, and the perception that the limitations of these tools constrain designers. Fig. 2 illustrates the classification of optimization problems.

• Performance and selection of optimization algorithms

The demand for a search method that efficiently addresses a specific optimization problem has led to the development of various optimization algorithms. Therefore, selecting an appropriate optimization algorithm for a given situation is crucial to achieving the maximum reduction in the objective function (Ismail, 2024). However, choosing an optimization method for a building optimization problem is not straightforward and typically involves several considerations, including: The nature of design variables: Continuous, discrete, or a combination of both, The presence of constraints on the objective function and The characteristics of objective functions: Whether they are linear or nonlinear, convex or non-convex, continuous or discrete, and the number of local minima, among other factors (Hong & Pham, 2024).

• Classification of building optimization methods and algorithms

Classifying optimization problems and algorithms is a fundamental basis for developing new optimization strategies and selecting the appropriate algorithm for a specific situation (Deng et al., 2024). Fig. 2 presents a general classification of optimization problems. Certain classifications used in other fields, such as fuzzy optimization, do not apply to building performance optimization and are therefore excluded from this study. Fig. 3 outlines the research process.

Research Method

This study employed a systematic review approach, focusing on optimization methods for energy

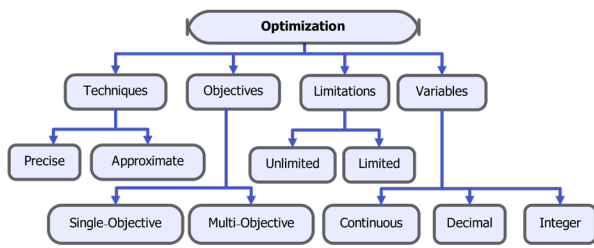


Fig. 2. Classification of optimization problems. Source: Hong & Pham, 2024.

efficiency in buildings. This methodology was used to identify, evaluate, select, and synthesize Bibliometric evidence related to energy optimization in the building sector. The research pyramid illustrates the hierarchy of research designs, highlighting that studies based on quantitative analysis and rigorous Bibliometric methods are positioned at the top due to their higher internal validity.

This study followed the systematic assessment method proposed by Wolfswinkel et al. (Ghaderi Dehkordi & Nedaei Toosi, 2024), which consisted of four key phases: definition, search, selection, analysis, and synthesis. Each phase is described below:

Definition: In this initial phase, the scope and boundaries of the research were established through iterative discussions among the authors. This process involved identifying suitable databases, formulating search strategies, and selecting relevant keywords.

Search: A comprehensive search was conducted in major Bibliometric databases, including Web of Science, Scopus, ProQuest, and Google Scholar, as well as Iranian databases such as Irandoc, SID, and Magiran. The search spanned the period from 1995 to 2024, using keywords such as “energy optimization in buildings,” “building optimization methods,” and “sustainable energy optimization.” Relevant sources—including journal articles, dissertations, and books—were recorded in EndNote for further analysis, and duplicate entries were removed.

Selection: All retrieved sources’ titles, abstracts, and keywords were screened to identify relevant studies. Articles addressing energy optimization in buildings and related principles were selected, and their full texts were reviewed for a more detailed examination.

Analysis: The selected studies focused on standard and

advanced optimization techniques for building energy optimization and the methodologies applied in each study. **Synthesis:** In this phase, findings from various studies were integrated to provide a comprehensive overview of the current state of building energy optimization methods and their effectiveness. The results indicate this field’s widespread application of optimization methods, including genetic algorithms, parametric design, machine learning, and multi-objective optimization. This systematic review offers a holistic perspective on emerging trends and technologies in building energy optimization, serving as a valuable resource for researchers and engineers.

Thematic network analysis: Using VOSviewer software to identify key concepts and themes related to building energy optimization, a network analysis of keywords was conducted. In this phase, keyword relationships were examined through open coding, and frequently occurring keywords with strong connections were extracted. The findings reveal that optimization, generative design, genetic algorithms, machine learning, and parametric optimization are among the key concepts in this domain, reflecting their significance and broad application in enhancing building performance and energy efficiency. A thematic analysis approach was employed to integrate and consolidate findings. This method enables the identification and analysis of patterns within qualitative data. The extracted concepts were categorized into structured thematic clusters. The results show that the key topics fall into two main categories:

Traditional optimization methods, such as genetic algorithms and parametric design.

Emerging techniques such as machine learning and generative design are gaining increasing attention due to their flexibility and ability to optimize multiple criteria simultaneously.

This classification highlights the shift towards advanced data-driven and AI-based optimization techniques, progressively shaping the future of building energy efficiency research and practice.

Findings

The initial search across various fields resulted in 1,940 articles on energy optimization in buildings. After rigorous

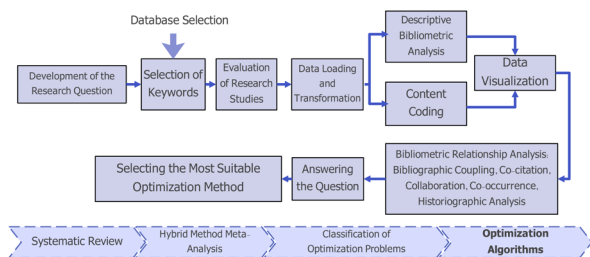


Fig. 3. Research process. Source: Authors.

screening and refinement, this number was reduced to 290 articles selected for final analysis. These articles were categorized and analyzed to identify key objectives, trends, and standard optimization techniques used in the field. Among the most frequently applied approaches were multi-objective optimization, evolutionary algorithms, and machine learning techniques.

• **Temporal Analysis**

A time-based analysis was conducted based on this domain’s publication years and growth trends. The findings indicate a significant increase in optimization methods for building energy efficiency from 2003 to 2024, particularly in evolutionary algorithms and machine learning (Fig. 4). Fig. 5 illustrates this upward trend, highlighting the growing importance of these techniques in enhancing energy efficiency and reducing energy consumption in buildings.

Spatial analysis: Bibliometric research on building energy optimization has been predominantly conducted in developed countries such as the United States, China, Germany, and Singapore. These nations lead in advancing research in this field due to their well-established research infrastructure, access to high-impact Bibliometric resources, and active participation in international collaborations.

Network data analysis indicates that publications from these countries receive frequent citations, forming a cohesive network of authoritative Bibliometric sources. Fig. 6 illustrates this Bibliometric network, demonstrating the influential role of researchers from these nations in shaping global research trends in building energy optimization.

Citation network analysis: Following the data collection in the content analysis phase and the refinement of findings

in Vosviewer, keyword extraction related to optimization methods was conducted through a three-stage coding process. These keywords were then categorized under thematic organizing indices, providing a structured classification of optimization techniques (Table 2). A qualitative synthesis method and thematic analysis were used to combine the results. This method is particularly effective in analyzing qualitative data, transforming scattered data into a cohesive and conceptual form. Thematic analysis helps identify and report the main and recurring patterns within the data. Accordingly, a set of main themes, such as “optimization,” “parametric design,”

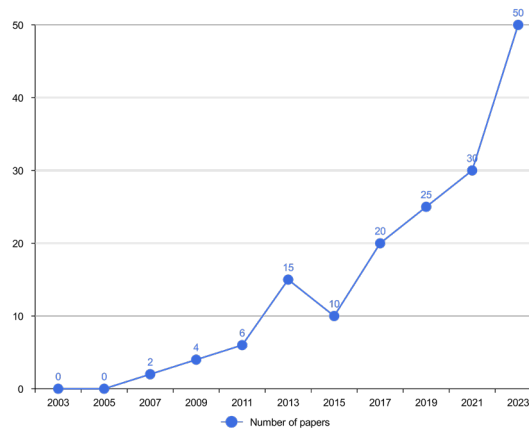


Fig. 4. Resource selection method. Source: Authors.



Fig. 5. Distribution of studies based on temporal data analysis. Source: Authors.

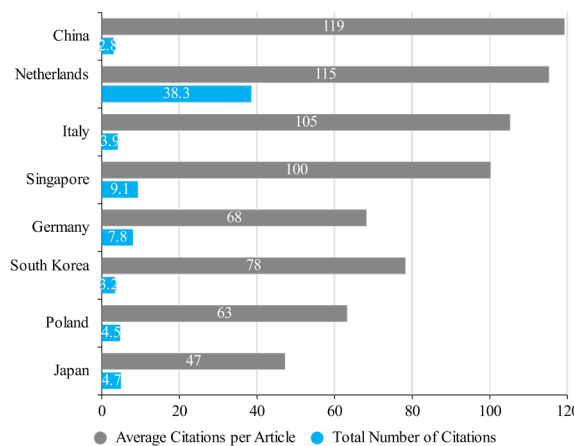


Fig. 6. Average citations per country. Source: Authors.

Table 2. Conversion of main and sub-themes to organizing themes. Source: Authors.

Total link power	Organizing themes	Frequency of use	Method/Algorithm
8	Algorithm-based methods	1	Combinatorial optimization
12	Optimization methods	2	Numerical optimization
1	Optimization methods	1	Geometric optimization
1	Optimization methods	1	Diversified search
10	Local search	4	Guided local search
6	Local search	1	Local search
35	Simulation methods	13	Simulation with real data
5	Simulation methods	1	Simulation with experimental data
8	Behavior analysis	2	User behavior simulation
9	Simulation methods	3	Local simulation
27	Intelligent algorithms	9	Swarm intelligence
40	Evolutionary algorithms	15	Evolutionary algorithms
66	Genetic algorithms	35	Genetic algorithm
11	Swarm intelligence	2	Ant colony optimization
34	Swarm intelligence	13	Particle swarm optimization
7	Simulation methods	1	Simulated

“genetic algorithms,” and “evolutionary algorithms,” were identified as core concepts repeatedly mentioned in optimizing building energy.

These themes reveal key concepts and assist researchers in better understanding existing studies and guiding future research. To analyze the Bibliometric network and identify key keywords in various studies, bibliometric software such as VOSviewer is used. These software tools identify keywords that have the most significance in the Bibliometric network in terms of frequency of occurrence and total link strength.

Based on the data and chart provided, frequently used keywords with strong connections can be extracted, representing the main topics in this research field. A qualitative synthesis and thematic analysis approach was used to combine the results. This method is particularly effective in analyzing qualitative data, transforming scattered data into an integrated and conceptual form. Thematic analysis helps identify and report the main and recurring patterns in the data. Based on this, a set of main themes, such as optimization, parametric design, genetic algorithms, and evolutionary algorithms, were identified as recurring key concepts in building energy optimization. These themes highlight key concepts and assist researchers in better understanding existing studies and guiding future

research. Scientometric software such as VOSviewer analyzes the Bibliometric network and identifies key keywords in various studies. These software tools identify keywords most important in the Bibliometric network based on their frequency and overall link strength. Based on the provided data and chart, frequently used and strongly connected keywords can be extracted, which reflect the main topics in this research field. Fig. 7 shows the Bibliometric network of sources in research methods.

Discussion

The thematic and citation network analysis in this study revealed that optimization methods based on evolutionary algorithms and machine learning play a crucial role in improving the energy performance of buildings. Additionally, due to its flexibility and high accuracy, generative and parametric design has become one of the hot research areas in recent years, as shown in Table 1. The analysis of methods and algorithms used in research indicates that some of these approaches have played a more significant role in solving complex problems and achieving research objectives. The genetic algorithm, used 35 times, is recognized as the most frequently applied method, widely used in many research projects due to its high power in solving complex optimization and design

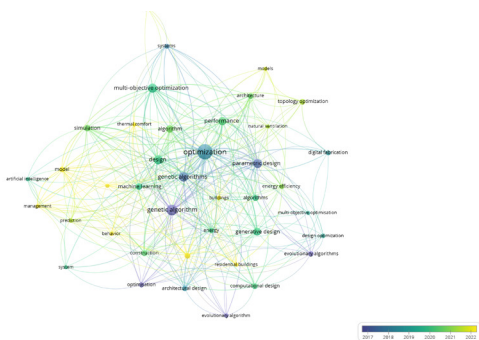


Fig. 7. Bibliometric network of sources in the field of optimization methods. Source: Authors.

problems. In second place, with 15 uses, evolutionary algorithms have been extensively employed in multi-objective optimizations and solving complex issues. Other popular methods include simulation using accurate data and particle swarm optimization, each used 13 times, which are practical tools for data analysis and modeling dynamic processes.

Furthermore, swarm intelligence, used 9 times, has gained a special place in research related to uncertain and complex problems. On the contrary, methods such as numerical optimization, simulation with experimental data, and user behavior simulation have had limited applications and have only been used in specific cases. Interestingly, some methods, such as combinatorial optimization, geometric optimization, and differential evolution, showed no application in the analyzed data, which may be due to the limitations of these methods in specific research fields. Overall, the obtained data indicate that methods based on evolutionary algorithms and accurate data simulation have demonstrated the most significant effectiveness and popularity in research. These results can serve as a valuable foundation for designing future research and selecting more effective methods.

The essential keywords: The genetic algorithm, used 35 times with an overall link strength of 62, is one of the most widely used optimization tools in complex problems. Evolutionary algorithms, used 15 times, are recognized as effective for solving multi-objective optimization problems. Accurate data simulation, with 13 occurrences, is one of the key tools in performance evaluation due to its high accuracy in predicting system behaviors. Particle swarm optimization, used 13 times, is widely applied in solving

engineering problems and optimization tasks. With nine occurrences, swarm intelligence emphasizes using novel approaches to solve nonlinear problems. Guided local search, used 4 times, is a focused method for solving optimization problems. Local simulation and ant colony optimization, each used 2 times, are applied to specific optimization problems. Methods such as combinatorial optimization and differential evolution, which were not used in the existing data, likely have lower effectiveness in the relevant field or have been less considered.

These keywords represent the main topics and are the most commonly used tools in optimization and simulation. They can also be used graphically to display the Bibliometric network. This analysis shows that the primary research focuses on evolutionary algorithms, accurate simulations, and innovative optimization methods.

Comparative results: There is an increasing trend in using evolutionary algorithms and real-data-based simulations, especially in complex optimization and engineering fields. This indicates the growth and development of novel methods in this area, which can help improve efficiency and accuracy in solving complex problems. Fig. 8 illustrates the number of themes in optimization methods, and Table 3 briefly summarizes the advantages, disadvantages, and implementation approaches.

Genetic algorithms are highly effective for complex and nonlinear problems, but due to their high computational time, they may pose challenges in large projects with extensive data. While real data-based simulations require reliable and up-to-date data for accurate predictions, artificial intelligence and machine learning can perform much better in dynamic projects and large datasets. Technique analysis: In the field of energy optimization in buildings, selecting the right tool for simulation and optimization is heavily dependent on the specific characteristics and complexities of the project.

Accurate data-based simulation is one of the key tools in energy optimization, helping to improve the accuracy and better alignment of simulation models with real-world conditions. This method is particularly effective in projects that require high precision and accurate energy consumption predictions. In projects with historical data and extensive empirical information, such simulations can

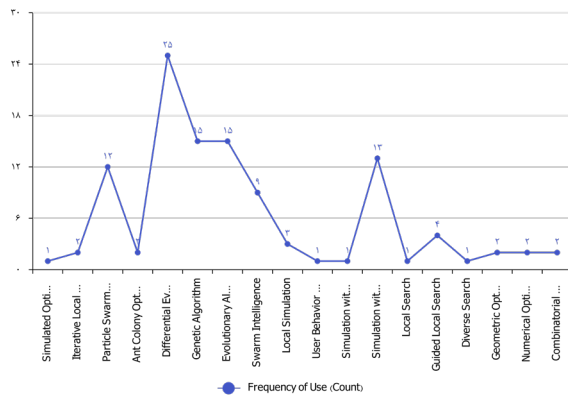


Fig. 8. Organizing themes in optimization methods. Source: Authors.

provide more precise results and assist designers in aligning their models with actual conditions. Ultimately, selecting the appropriate optimization tool should be based on the specific characteristics of each project. Projects with more complex features like nonlinear systems, numerous variables, and complex interactions between factors will benefit from genetic algorithms and Particle Swarm Optimization. At the same time, guided local search techniques may be more suitable for projects with lower complexity.

In recent years, machine learning and generative design have emerged as two innovative methods in energy optimization for buildings, significantly impacting efficiency improvements and energy consumption reductions. These techniques have revolutionized design and optimization processes, especially in complex and large projects. Each method, either separately or in combination, offers capabilities that help designers and engineers provide more optimized and accurate solutions for energy consumption in buildings.

Machine learning, particularly in supervised learning and deep learning, is increasingly used to optimize energy consumption. By utilizing empirical and historical data, these methods can predict energy consumption patterns and simulate the behavior of energy systems in buildings. Since machine learning continuously benefits from new data, it provides more accurate predictions of future energy needs and automatically optimizes settings for energy systems like heating, cooling, and ventilation. This tool is especially useful in projects that require accurate energy consumption forecasting over time. Additionally, machine learning can

dynamically optimize energy consumption in real time, helping systems operate optimally with minimal energy use.

On the other hand, generative design, as an advanced method in building design processes, enables optimization algorithms and complex simulations to find the best design solutions. This method is typically implemented using parametric software such as Rhino and the Grasshopper plugin, which allow designers to dynamically and quickly adjust various design parameters and observe their impact on energy consumption and building performance. Generative design enables designers to provide optimal solutions for energy-efficient buildings more effectively and faster than traditional design methods. This approach helps to achieve the best combination for optimizing energy consumption by altering parameters such as building form, window placement, and selection of building materials. Combining machine learning and generative design can yield significantly stronger results in energy optimization. Ultimately, integrating machine learning and generative design in real-world projects can lead to the design of buildings that are effective in aesthetics and functionality and minimize energy consumption.

The collected data represents the widespread distribution of various techniques and their impact on Bibliometric articles in this field (Fig. 9). This categorization is based on the algorithm type, the techniques' characteristics, and their influence in applied areas. As shown in the provided tables, optimization techniques such as genetic algorithms, evolutionary algorithms, and swarm intelligence have the highest frequency of use and popularity in Bibliometric research. Fig. 10 illustrates the optimization methods based on keyword co-occurrence and their frequency in the study. One of the notable points in these findings is the importance of data-driven simulation, which has been widely used in the Bibliometric literature due to its role in improving accuracy and making analyses more practical. Particle swarm optimization algorithms, a form of swarm intelligence, also play a key role in solving complex simulation-related problems. Inspired by natural behaviors and social interactions, these algorithms have proven practical tools for searching for optimal solutions. Additionally, local search techniques, such as guided local search, with less frequent

Table 3. Comparative results of algorithms. Source: Authors.

Algorithm	Advantages	Disadvantages	Implementation method
Genetic algorithm	Ability to search large and complex parameter spaces. Suitable for nonlinear and multi-objective problems.	High computation time, especially in complex problems. Requires precise parameter settings.	Highly effective in complex projects with a large number of variables, particularly in nonlinear and multi-objective problems.
Swarm intelligence	Ability to solve nonlinear problems. Fast search in large parameter spaces.	May reach local optima. Requires fine-tuning of the algorithm for optimal performance.	Suitable for large-scale problems and nonlinear issues that require optimal searching in the solution space.
Real Data simulation	High accuracy in predicting system behavior. Suitable for precise modeling and system performance evaluation.	Requires accurate and up-to-date data; limited in projects with no reliable data.	Applied in projects with accurate data and precise energy modeling, especially for energy consumption prediction in buildings.
Local search techniques	Fast and efficient for simpler problems. Can be implemented in a short time.	Risk of getting stuck in local optima, not suitable for complex problems.	Suitable for small problems and those with fewer dimensions that don't require precise searching.
Generative and parametric design	Optimizes complex and parametric designs. High flexibility in variable designs.	Requires complex computation steps. High computation time in complex designs.	Highly effective in projects requiring flexible design and complex simulations.
Ant colony optimization	Efficient and extensive search in large spaces. Suitable for optimization problems with many variables.	Limited in high-dimensional problems with high complexity. May be restricted to local solutions.	Suitable for large-scale optimization problems and projects requiring extensive searches in the solution space.
Artificial intelligence & machine learning	Ability to learn from data and make accurate predictions. Can improve performance over time.	Requires valid training data. Complexity in implementation and needs high expertise.	Very suitable for dynamic projects and large datasets that require accurate prediction.
Combined and differential evolution optimization methods	Ability to solve complex problems. Optimizes search in large spaces.	High computational complexity. May have lower efficiency in certain conditions.	Effective for projects that require solving complex problems and extensive searches in large spaces.

use than evolutionary algorithms, have successfully solved localized and targeted problems. Numerical optimization techniques also remain essential tools in this field. Although methods such as geometric optimization or diverse searches have been used less in studies, this could be due to their replacement by more advanced methods or their limited applicability in complex problems.

Furthermore, the analysis of Bibliometric articles reveals that techniques based on genetic and evolutionary algorithms, due to their strong mathematical frameworks and theories that guarantee their performance, have had the most significant impact on building energy optimization. Ultimately, the findings of this study clearly show that optimization and simulation techniques in the field of

Table 4. Challenges, limitations and Igorithms. Source: Authors.

Algorithm	Limitations and challenges
Genetic algorithms	These algorithms are highly effective in large and nonlinear problems due to their extensive search in parameter spaces and their ability to solve complex issues. However, their use is time-consuming and computationally expensive.
Particle swarm optimization (PSO)	PSO algorithms are useful in solving engineering problems, especially nonlinear and complex ones. However, they may face limitations when there are many dependent variables or when the algorithm requires complex configurations.
Guided local search techniques	These methods are generally suitable for focused and simpler problems and may not perform well in more complex issues or those requiring an extensive search in the solution space.
Data-driven simulation	Data-driven simulations are highly efficient due to their accuracy in predicting system behavior, but they require precise and up-to-date data, which may pose limitations in some projects.
Ant colony optimization	This method is used in specific optimization problems and has limited performance in high-dimensional problems or those with significant complexity.
Combined optimization methods and differential evolution	These methods have not been utilized in the available data and have likely been overlooked due to computational complexity or limitations in the problem characteristics.

simulation methods, with their diverse subsets and multiple complexities, require more detailed studies and comprehensive classifications. On the other hand, offering new and efficient solutions requires integrating accurate data, advanced optimization techniques, and intelligent methods. This study recommends that future researchers consider the specific and localized aspects of optimization methods and problem-solving processes suited to the optimization problem. Attention should be given to aligning data with real-world conditions and employing interdisciplinary approaches. Combining these solutions with advanced optimization techniques can improve the quality and efficiency of research, ultimately helping to solve complex issues in various fields, including building energy optimization. This research offers a comprehensive and structured view that can inspire future studies in this area and pave the way for designing more efficient and applicable algorithms. These approaches can contribute significantly to developing more sustainable buildings, reducing energy consumption, and improving the performance of building systems in the real world. Moreover, the results of this study may lead to the design of tools that alongside high efficiency, have the scalability to solve larger and more complex issues.

Future research: Considering the challenges and limitations in using energy optimization algorithms in buildings, multiple paths for progress and improvement of these methods can be envisioned. One such path is the

development of more intelligent algorithms capable of managing energy optimization in more complex conditions and on larger scales. Using machine learning and artificial intelligence to predict energy consumption and optimize it can help improve the accuracy and efficiency of algorithms and enable the prediction of building energy system behaviors under different conditions. System integration is another important aspect that can be improved in the future. Creating integrated optimization systems that can easily coordinate with existing energy systems in buildings could reduce costs and complexities. These systems should be able to gather data from various building systems, such as ventilation, lighting, cooling, and heating, and manage them in a coordinated and optimized manner. Fig. 11 shows a conceptual model of the classification of energy optimization methods in buildings.

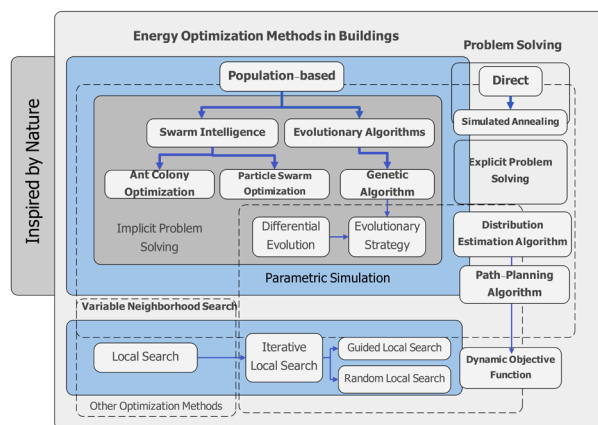


Fig. 11. Classification in optimization methods. Source: Authors.

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