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Review

A Systematic Review of Applications of Generative Design Methods for Energy Efficiency in Buildings

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Abstract: Energy efficiency is a principle of architectural design that reduces environmental impact. Generative design can offer alternative options to improve energy efficiency in buildings, but significant gaps exist in the application due to accessing complex knowledge. This study aimed to explore publications on generative design and energy efficiency in buildings and identify generative methods for energy efficiency topics. This study conducted a systematic review using the PRISMA methodology in December 2023 by searching publications from databases including Scopus, Google Scholar, and Thai Journals Online. Descriptive analysis examined 34 articles, showing the publication year, source, and citations. Comparative qualitative and descriptive analysis identified generative methods. Publications are increasing over time, and further growth is expected related to the accessibility of computational design and practical applications. Tools and frameworks demonstrated reduced energy usage compared to prototypes or traditional design approaches. The most studied is thermal performance, which was reduced by 28%. Energy performance achieved up to a 23.30% reduction, followed by others and daylighting. In addition to single-topic studies, there are also studies with multiple topics. Evolutionary algorithms are standard. Parametric search strategies have increased. Exploration reveals rule-based and mixed methods. Machine learning and AI garner attention.

Keywords: generative design; generative method; energy efficient; buildings

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1. Introduction

Currently, we are confronted with an escalating energy crisis and the intensifying impacts of climate change, both of which pose increasingly severe repercussions on a global scale with each passing day [1,2]. Buildings are a primary contributor, accounting for approximately one-third of global greenhouse gas emissions [3,4]. The building sector is also a significant source of carbon dioxide (CO_2) emissions, releasing a substantial quantity into the environment [5]. The energy consumption attributed to buildings comprises one-third of the world's total energy consumption [6]. The most significant portion of building energy consumption is allocated to Heating, Ventilation, and Air Conditioning (HVAC) systems, accounting for 40% of total building energy usage [7–9]. Consequently, architectural design should prioritize enhancing energy efficiency within buildings [2,4,7,10,11] to make energy usage more cost-effective and reduce carbon emissions, a crucial aspect of mitigating the environmental impact.

Many studies have indicated that early design stages are crucial for achieving energy efficiency in buildings [12–14]. Multiple objectives influence the overall performance of a design [15]. Therefore, energy assessment is of paramount importance [16,17]. Generative design has been developed to enhance efficiency by facilitating evaluation from the earlier stages of the design process [18–20]. Generative design is an iterative process that automatically generates all design options based on specified conditions [21,22]. Generative design enhances efficiency through existing processes by employing computational methods, which are techniques for solving problems using computers that drive design exploration [23] with a rules-driven iterative design process [24]. This approach is rooted in algorithmic and parametric modeling, facilitating automatic exploration, iteration, and optimization of design possibilities [25]. With many choices available, designers can select the optimal solution or other intriguing alternatives for further development [26].

Generative design diverges from traditional design approaches, where architects primarily rely on their experience but may not fully explore the potential design solutions available [27]. Energy efficiency is typically evaluated after the design phase [18] through quantitative analysis using mathematical algorithms [20] or building energy simulation programs [28]. Therefore, determining the most suitable design for specific conditions may not be immediately apparent [11]. Thus, generative design has the potential to enhance building efficiency by generating design alternatives and aiding decision making processes through decision support.

Generative design for enhancing energy efficiency in buildings is actively employed in practical applications. For example, a study conducted by Wang T.K. and Duan W. [18] utilized generative design techniques in the design of residential floor plans. The analysis revealed significant improvements, with consumer satisfaction increasing by up to 38.78% and energy performance enhancing by up to 11.18%. Likewise, Si et al. [29] demonstrated a practical application of generative design in optimizing the building envelope of a tourist center. By employing algorithmic optimization techniques, they successfully decreased the building load by 11% and reduced the average predicted percentage dissatisfied (PPD) by 8.3%. Additionally, various other research endeavors in the realm of generative design address a multitude of topics, including but not limited to facade optimization [30,31], building shape [32], photovoltaics integration [33], cooling and heating energy consumption [34], daylight performance [35], thermal efficiency [36], and life cycle carbon analysis [37]. The research provides compelling evidence that generative design holds significant promise for enhancing building energy efficiency. It addresses a diverse range of topics related to energy efficiency. The primary concern revolves around buildings' total energy consumption, significantly influencing energy usage and environmental impact. However, it is worth noting that other intriguing topics of building design also impact energy efficiency. Hence, generative design can effectively enhance energy efficiency across various topics.

Generative design is accepted among architects and design researchers [38]. Access to knowledge in this field is limited due to its status as an advanced computational technique [39], which is inherently complex and challenging to comprehend [40]. Generative design is knowledge typically taught at the master's level or higher [23]. This is aligned with the current reality where humans still lack knowledge about energy-efficient automation systems [41]. Moreover, few studies aim to apply generative design to building performance design [42,43]. Therefore, it is necessary to review the quantity of research related to generative design in the field of energy-efficient buildings to assess quantity, trends and identify sources for referencing in future data studies. Although generative design has become more popular, it still receives scattered attention. Only a few research studies have been conducted in the context of architectural design [44]. Additionally, there is a lack of studies on generative design techniques or methods [39,43]. Hence, considering the knowledge gap and the potential of generative design to enhance energy efficiency in buildings beyond traditional approaches, a significant opportunity exists to mitigate environmental impacts. Therefore, this article aims to review the application of generative design in energy efficiency and explore the utilization of generative design methods. This endeavor seeks to enhance accessibility to generative design knowledge and facilitate its practical application in energy efficiency.

In a review of research closely related to the research gap of applications of generative design for enhancing energy efficiency, Jiang et al.'s [45] 2023 systematic review identified and classified generative methods into three groups: rule-based generative methods, evolutionary algorithms, and deep generative methods, specifically in urban design. The study indicated that deep generative methods are poised to play a significant role in the future. However, this research primarily focuses on urban design and does not directly address the application of generative design for enhancing energy efficiency in buildings. Jaisawal et al.'s [46] literature review categorized generative design into five types: parametric search strategy, evolutionary algorithm, iterated local search, shape grammar, and topology optimization tool. It presented the advantages and limitations of each type in its application. However, a systematic review has not yet been conducted, and the study primarily utilizes generative design within a product design context. Therefore, based on the review of the past research literature, the application of generative design to enhance energy efficiency in buildings remains unsolved, and most other research is experimental.

Given the existing knowledge gap, it is imperative to study generative design methods for energy efficiency in buildings. Therefore, a systematic literature review with a replicable process is essential, wherein researchers systematically search a body of literature to document the state of knowledge on this specific subject. The primary objective of our research is to conduct systematic reviews using the PRISMA methodology. This involves selecting publications from scientific databases to fill the knowledge gap in research. This systematic literature review analyzes existing publications on generative design and energy efficiency in buildings. By examining previous research publications to identify generative design applications in the energy field, the review seeks to gather foundational and reliable information. This information can serve as a basis for studies, ensuring efficient and quality in research endeavors. In addition to specifying energy topics that utilize generative design, this review aims to elucidate the methods employed in identifying these methods specifically for energy efficiency topics. This will be advantageous for both designers and users, as it will provide them with greater access to knowledge about how to use generative design to enhance energy efficiency in buildings. This review aims to address the following questions:

Q1: What are the trends and quantity of research on generative design in the field of energy-efficient buildings?
Q2: What are the various applications of generative methods for energy efficiency topics?

2. Methodology

We accomplish this by employing transparent, systematic reviews and the meta-analysis (PRISMA) technique, ensuring results' reliability and reproducibility while mitigating bias to address the research gap [47,48]. In early December 2023, one architectural researcher, two architectural professors, and two architects were invited to review selected articles and offer recommendations to confirm that the selected research addresses the research questions and is comprehensive within the database.

2.1. Database

The primary databases utilized for this study included Scopus, Google Scholar, and Thai Journals Online. The largest database, Scopus, aggregates abstracts, references, and works from renowned authors worldwide [49]. Google Scholar is essential for mitigating publication bias because it encompasses both the scholarly and gray literature and is the preferred search engine for many researchers [50]. Finally, unlike other studies, Thai Journals Online was chosen as the central electronic journal database system, encompassing all disciplines in Thailand.

2.2. Data Collection

The research process follows the PRISMA guidelines, which recommend four crucial steps for reporting publications in systematic literature review procedures aligned with our established research questions (Figure 1).

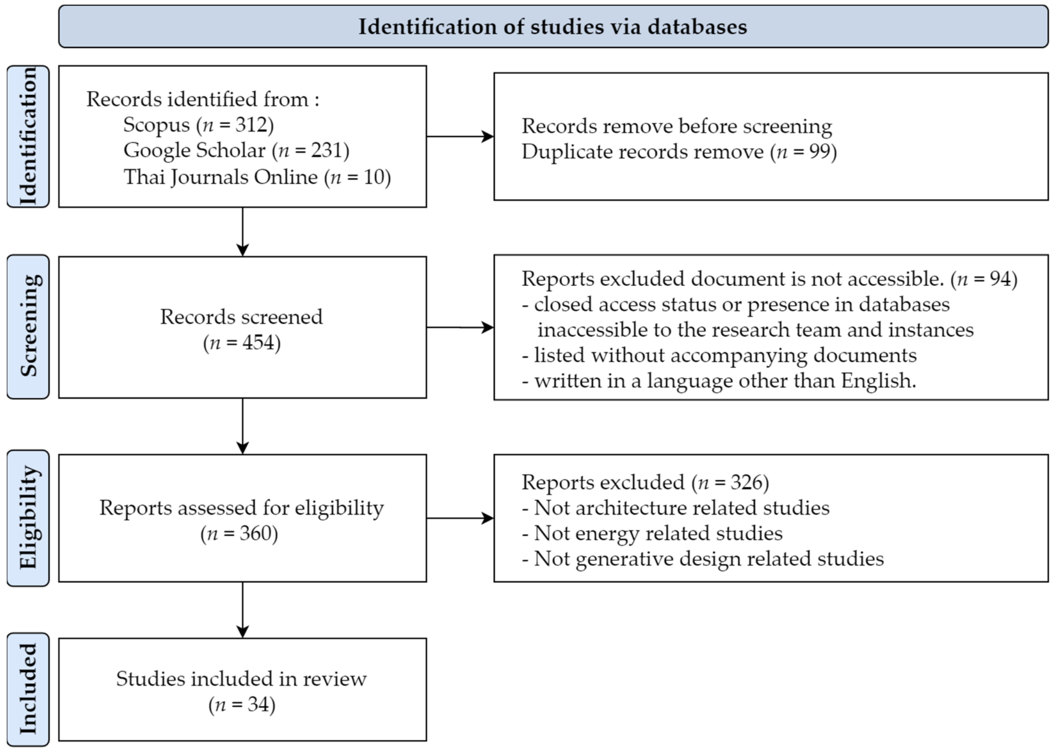

Figure 1. Flow diagram for systematic literature review based on PRISMA.

(1) Identification phase:

Scopus was used for searching documents with title + abstract + keywords (title + abstract + keywords) using keyword search words (generative design) AND (design AND building) AND (energy) along with another keyword search for (generative design) AND (architecture) AND (energy). This database provided a total of 312 documents between 1985 and 2023.

In Google Scholar, a search for "secondary source" or the gray literature was conducted to include limited published documents such as reports, theses, academic conference papers, and others that might not be formally published; the search aimed to ensure comprehensiveness. The search criteria involved the terms "(generative design) AND (design AND building) AND (energy)" within the title–abstract field. We obtained 231 publications from 2021 to 2023.

Thai Journals Online (ThaiJO) is a national research database in Thailand. Energy efficiency in buildings has been important since the implementation of the Building Energy Code in 2020. We will confirm the utilization of generative design in the country for future research. The search was conducted using the criteria of title + abstract, using the keyword search "generative design". We obtained 10 publications from 2017 to 2021.

A total of 553 publications were identified from 1985 to 2023. The remaining publications proceeded to the screening process after 99 documents were excluded due to duplication in the Scopus and Google Scholar databases.

(2) Screening phase:

The document results comprise 454 publications spanning from 1995 to 2023, obtained during the identification process, which is considered in the screening phase. A quick scan was conducted to ensure the documents' readiness for use. Following the screening, 94 publications were excluded due to their inaccessibility or unavailability. This was primarily attributed to their closed access status or presence in databases inaccessible to the research team and instances where they were listed without accompanying documents or written in a language other than English.

(3) Eligibility phase:

From the screening phase, 360 publications remained for further assessment to confirm this review's validity and objectivity. The research team screened publications for relevance to the research questions. They eliminated research unrelated to generative design, architecture, and energy. Subsequently, 326 publications were excluded from the review as they were found to be outside the scope of the research. Most of these unrelated publications were from medicine, computer science, etc.

(4) Including phase:

Finally, after meticulous consideration and thorough discussion among all authors, a total of 34 publications were included in this systematic review.

2.3. Data Analysis

Descriptive analysis was used to answer the first question (Q1): what are the trends and quantity of research on generative design in the field of energy-efficient buildings? All 34 selected publications underwent descriptive analysis. A deductive approach was employed to categorize the articles based on their publication year, source, and number of citations.

Descriptive and comparative qualitative analysis was used to answer the second question (Q2): what are the various applications of generative methods for energy efficiency topics? We organized data on generative design methods, focusing on energy efficiency topics across 34 publications. This systematic approach allowed us to identify the commonly used types of generative design methods for enhancing energy efficiency in buildings and explore their potential applications in achieving specific energy efficiency topics.

3. Results

This section presents the results of the systematic literature review, divided into two parts. Part 1: descriptive analysis to address Q1: publications related to generative design and energy efficiency in buildings, identifying articles by year, source, and number of citations. Part 2: descriptive analysis to address Q2: what are the various applications of generative methods for energy efficiency topics? This section identifies generative methods related to energy efficiency topics.

3.1. Published Related to Generative Design and Energy Efficiency in Buildings

(1) Year of publication

A total of 34 articles were selected spanning 2003–2023 (Table 1). The earliest work identified dates to 2003, but there was a hiatus of 9 years until 2012 before the idea was revisited. From 2012 to 2019, an average of one to two articles were published per year. There were five additional research papers in 2021 and six papers in 2022. There were 11 published articles in the latest year, 2023 (Figure 2). The increase in articles underscores the ongoing interest in this content, notably the recent surge.

Table 1. A list of publications in the systematic literature review.

Article Title	Authors	Year	Publishing Source	Citation
"Generative Design of Floor Plans of Multi-Unit Residential Buildings Based on Consumer Satisfaction and Energy Performance"	Wang T. K. and Duan W. [18]	2023	Developments in the Built Environment	1
"Performative Driven Form Finding in the Early Design Stage	Elgohary et al. [51]	2023	Journal of Engineering and Applied Science	0

Table 1. *Cont.*

Article Title	Authors	Year	Publishing Source	Citation
Pushing the Boundaries of Modular-Integrated Construction: A Symmetric Skeleton Grammar-Based Multi-Objective Optimization of Passive Design for Energy Savings and Daylight Autonomy”	Zhou Q. and Xue F. [35]	2023	Energy and Buildings	3
“Climate Change and Ideal Thermal Transmittance of Residential Buildings in Iran”	Rodrigues et al. [36]	2023	Journal of Building Engineering	9
“Investigation of the Height Distribution Effect of Residential Complex Blocks on Optimization of Cooling and Heating Loads (Tehran, District 9)”	Ghasemi Sangi et al. [34]	2023	Journal of Renewable Energy and Environment	0
“Maximizing Energy Efficiency and Daylight Performance in Office Buildings in BIM through RBFOpt Model-Based Optimization: The GENIUS Project”	Ratajczak et al. [52]	2023	Buildings	1
“Performance-Based Generative Shape Grammar Method: Energy Efficient Facade Design for Fully Glazed Multi-Storied Office Building—Hot and Humid Climate, Chennai, India”	Chockalingam et al. [32]	2023	International Journal of Sustainable Construction Engineering and Technology	0
“Using BIM to Facilitate Generative Target Value Design for Energy-Efficient Buildings”	Saurav et al. [53]	2023	ISARC Proceedings of the International Symposium on Automation and Robotics in Construction	0
“Building for Tomorrow: Analyzing Ideal Thermal Transmittances in the Face of Climate Change in Brazil”	Rodrigues et al. [54]	2023	Energy and Buildings	1
Data-Driven Modelling of Building Retrofitting with Incomplete Physics: A Generative Design and Machine Learning Approach”	Yu et al. [55]	2023	Automation in construction	0
“Generative Design for a Sustainable Urban Morphology”	Turki et al. [56]	2023	Energy and Buildings	0
“Toward a National Life Cycle Assessment Tool: Generative Design for Early Decision Support”	Hassan et al. [37]	2022	Developments in the Built Environment	28
“Generative Design to Reduce Embodied GHG Emissions of High-Rise Buildings”	Zaraza et al. [22]	2022	Journal of Engineering and Applied Science	9
“Optimization of PV Modules Layout on High-Rise Building Skins Using a BIM-Based Generative Design Approach”	Vahdatikhaki et al. [33]	2022	Energy and Buildings	21
“An Optimization Framework and Tool for Context-Sensitive Solar-Driven Design Using Cellular Automata (SDCA)”	Luitjohan et al. [57]	2022	Annual Modeling and Simulation Conference	1
“Reevaluation of the Egyptian Code of Housing and Energy Consumption with Emphasis on Shading Devices Rotation Angles”	Kamel T. [58]	2022	Journal of Engineering Research	1
“Modelling Platform for Schools (MPS): The Development of an Automated One-by-One Framework for the Generation of Dynamic Thermal Simulation Models of Schools”	Schwartz et al. [59]	2022	Energy and Buildings	6

Table 1. *Cont.*

Article Title	Authors	Year	Publishing Source	Citation
"BIMPO: A Generative Parametric Technique for Building Envelope Design"	Fathy et al. [60]	2021	WIT Transactions on The Built Environment	2
"A Benchmark Model for Predicting Building Energy and Daylight Performance in the Early Phase of Design Utilizing Parametric Design Exploration"	Khidmat et al. [61]	2021	IOP Conference Series: Earth and Environmental Science	4
"A Decision Support Tool for Building Design: An Integrated Generative Design, Optimisation and Life Cycle Performance Approach"	Schwartz et al. [39]	2021	International Journal of Architectural Computing	25
"Generative Design and Performance Optimization of Residential Buildings Based on Parametric Algorithm"	Zhang et al. [14]	2021	Energy and Buildings	57
"Simplified Evaluation Metrics for Generative Energy-Driven Urban Design: A Morphological Study of Residential Blocks in Tel Aviv"	Natanian J. and Wortmann T. [62]	2021	Energy and Buildings	29
"Thermal Transmittance Effect on Energy Consumption of Mediterranean Buildings with Different Thermal Mass"	Rodrigues et al. [63]	2019	Applied Energy	68
"Multivariate Relationships Between Campus Design Parameters and Energy Performance Using Reinforcement Learning and Parametric Modeling"	Chang et al. [64]	2019	Applied energy	51
"Automation of CAD Models to BEM Models for Performance Based Goal-Oriented Design Methods"	Santos et al. [65]	2017	Building and Environment	45
Energy Performance Optimization as a Generative Design Tool for Nearly Zero Energy Buildings"	Touloupaki E. and Theodosiou T. [66]	2017	Procedia engineering	60
"An Approach to Urban Quarter Design Using Building Generative Design and Thermal Performance Optimization"	Rodrigues et al. [67]	2015	Energy Procedia	25
"How Reliable are Geometry-Based Building Indices as Thermal Performance Indicators?"	Rodrigues et al. [68]	2015	Energy Conversion and Management	37
"Climate-Sensitive Urban Growth: Outdoor Thermal Comfort as an Indicator for the Design of Urban Spaces"	Tapias E. and Schmitt G. [69]	2014	WIT Transactions on Ecology and the Environment	21
"Adaptive Façade Design for the Daylighting Performance in an Office Building: The Investigation of an Opening Design Strategy with Cellular Automata"	Kim J. [30]	2013	International Journal of Low-Carbon Technologies	21
"Building Envelope Shape Design in Early Stages of the Design Process: Integrating Architectural Design Systems and Energy Simulation"	Granadeiro et al. [70]	2013	Automation in construction	240
"A Visualization System for the Comfort Analysis of Modular Architecture: A case Study"	Kim et al. [71]	2012	Visualization, and Engineering: 9th International Conference	3

Table 1. *Cont.*

Article Title	Authors	Year	Publishing Source	Citation
"A Methodology for Daylight Optimisation of Facades: An Investigation of the Opening Design Strategy with Cellular Automata for an Office Building"	Kim J. [31]	2012	9th international conference & expo on emerging technologies for a smarter world (CEWIT)	5
"An Evolutionary Model for Sustainable Design"	Caldas et al. [72]	2003	Management of Environmental Quality: An International Journal	37

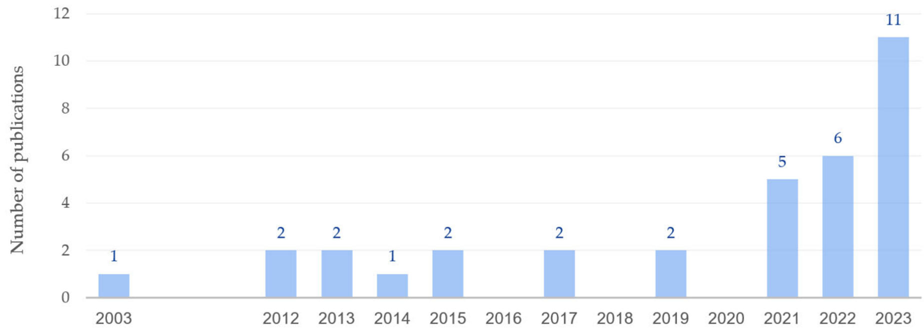

Figure 2. Distribution of number of publications per year.

(2) Publishing source

The publications' sources can serve as a reference point for future studies. The highest number of publications (Figure 3), totaling five articles in this study, were published in the journal *Energy and Buildings*. The journal is directly relevant to the study of energy use in buildings. Following closely, the journal *Applied Energy* features three articles related to energy conservation. Number 3, *Automation in Construction*, contributed two articles relevant to computer-aided design and building. Of the remaining 26 publications, one article was chosen, covering the interdisciplinary fields of engineering, applied science, technology, architectural computing, and the environment. The publications highlight the pivotal role of generative design and energy efficiency in buildings within the research field.

(3) Number of citations

The number of citations indicates the research's significance. This aligns with the growing interest in the field, evidenced by the rise in research papers. Furthermore, high citation counts highlight specific studies as valuable sources of information for exploring generative design and energy efficiency in buildings, affirming this systematic review's reliability (Figure 4).

The provided data indicate that the top 10 most referenced publications out of the 34 considered are Granadeiro et al. [70], 240 citations; Rodrigues et al. [63], 68 citations; Touloupaki E. and Theodosiou T. [66], 60 citations; Zhang et al. [14], 57 citations; Chang et al. [64], 51 citations; Santos et al. [65], 45 citations; Caldas et al. [72], 37 citations; Hassan et al. [37], 28 citations; Rodrigues et al. [67], 25 citations; and Schwartz et al. [39], 25 citations.

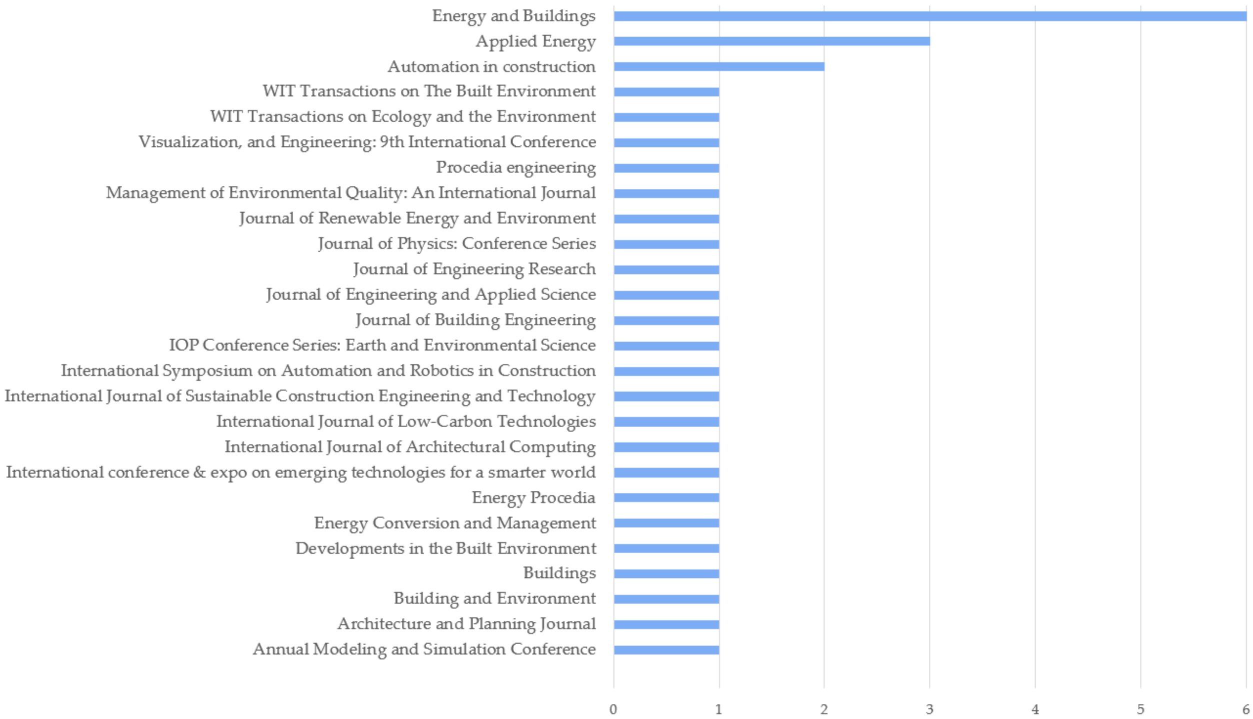

Figure 3. Publishing sources of the articles.

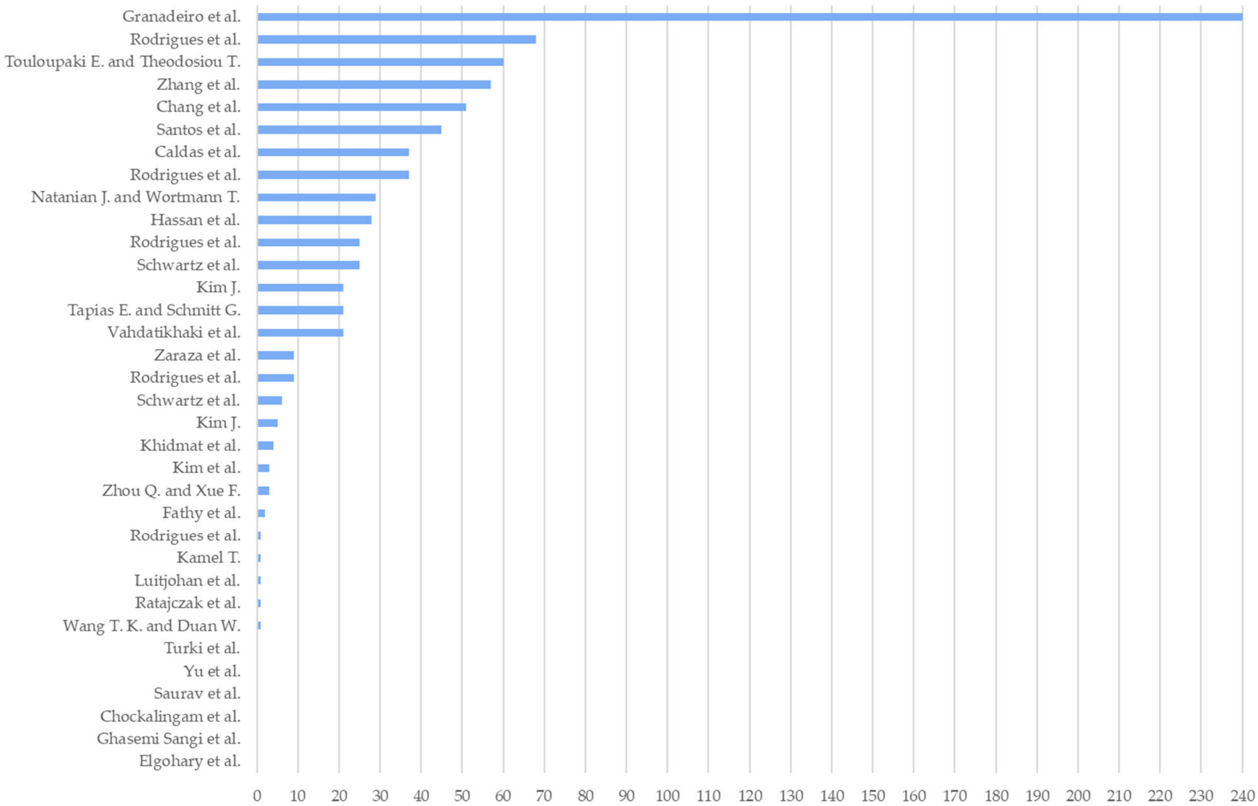

Figure 4. Number of citations for the articles.

3.2. Generative Design Methods for Energy Efficiency in Building

To address the research gap, it is imperative to investigate generative design methods for energy efficiency in buildings. This will help identify emerging findings within energy efficiency topics and the use of generative methods in research on generative design.

Consequently, this will enable better access to generative design knowledge and facilitate its application in practice.

This literature review reveals that generative design methods manifest in diverse forms and operate at various levels of sophistication. The parametric search strategy falls under the umbrella of parametric design, which constitutes a subset of computer-aided design (CAD) systems that facilitate the creation of novel design solutions [73]. Parametric design allows designers to focus on formative and generative design using advanced parametric applications [74], such as Rhino and Grasshopper or Revit and Dynamo. Rule-based generative design is based on a set of rules governing a process of manipulation of original ideas or requirements to satisfy a set of goals, and the algorithms used for the generation are often astonishingly simple [75]. Evolutionary design is an approach that utilizes different evolutionary computation techniques in various stages [76]. Evolutionary algorithms can handle the complexities of generative design problems, which often involve many design variables and multiple potential solutions [11]. Machine learning and artificial intelligence can glean insights from existing design data and possess enhanced decision making capabilities, thereby instructing algorithms to discern optimal solutions [77]. Notable methodologies include generative adversarial networks (GAN), variational autoencoders (VAE) [78], and artificial neural networks (ANN) [79]. The review of generative design is categorized into four primary methods and subdivided into sub-methods, as delineated in Table 2: generative design methods for energy efficient in building.

Table 2. List of abbreviations.

Abbreviation	Meaning
AI	Artificial Intelligence
ANN	Artificial Neural Networks
ASE	Annual Solar Exposure
CAD	Computer-Aided Design
EPSAP	Evolutionary Program for the Space Allocation Problem
EUI	Energy Use Intensity
GAN	Generative Adversarial Networks
NSGA-II	Non-Dominated Sorting Genetic Algorithm II
PV	Photovoltaic
sDA	Spatial Daylight Autonomy
SRI	Annual Solar Radiation Incident
VAE	Variational Autoencoders

3.2.1. Overview of Generative Design for Enhancing Energy Efficiency in Buildings

A systematic review of 34 research publications from 2003 to 2023 reveals the following findings regarding the challenges associated with employing generative design: thermal performance is identified as the most prevalent issue, followed by energy performance as the second most frequently studied. Daylighting is less often discussed than energy and thermal performance. Other topics include life cycle assessment, embodied emissions, solar access, life cycle carbon footprint, and life cycle costs. The review encompasses studies that analyze single and multiple topics, including daylight and energy performance. The highest number of studies was found in a joint analysis of more than one topic, such as daylight and thermal performance and daylight, thermal, and energy performance (Figure 5).

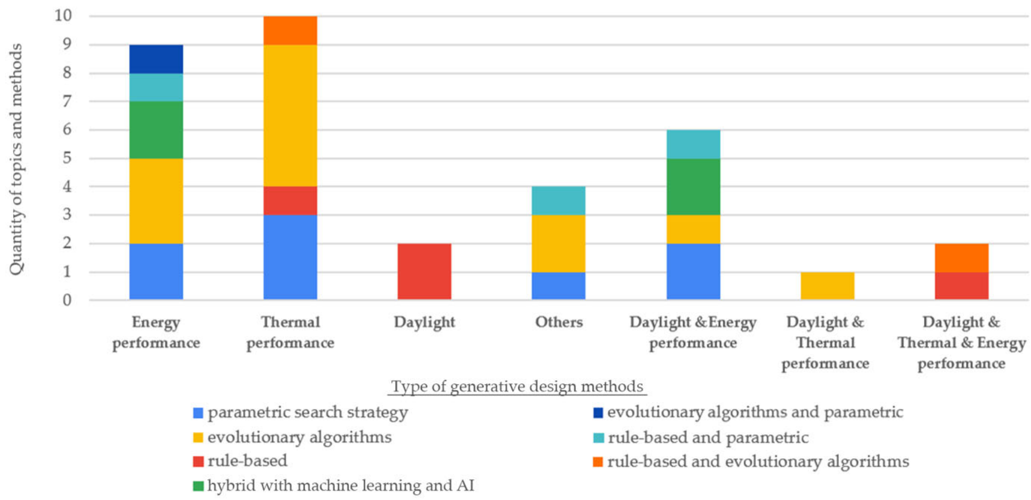

Figure 5. Stacked column chart of quantity and type of generative design methods in energy efficiency topics.

The generative design methods identified in the literature can be categorized into four main categories. The most common category is evolutionary algorithms, which have been consistently utilized from the past to the present. In recent years, there has been an increasing trend in the use of parametric search strategies, particularly from 2021 onwards. The third category is rule-based methods. Finally, machine learning and artificial intelligence methods, often combined with other techniques, are classified as hybrid with machine learning and AI. This approach has become increasingly prevalent in recent years, particularly in 2023. In addition to single forms, mixed forms combining multiple methods have been identified in specific years. These mixed forms include combinations of three methods: rule-based and evolutionary algorithms, rule-based and parametric, and evolutionary algorithms and parametric methods (Table 3).

Table 3. Energy efficient of buildings achieved through generative design in energy efficient topics.

Energy Efficient Topics	Energy Efficiency of Buildings Achieved through Generative Design
Energy Performance	Compared with the initial scheme, the energy performance improved by 11.18% (Wang T. K. and Duan W., 2023) [18].
	Energy consumption was reduced by 360 kWh/m^2/year compared to the traditional design (Saurav et al., 2023) [53].
	The proposed approach can model the building's performance with more than 90% confidence and shows variation in results (Yu et al., 2023) [55].
	PV module layout design framework can offer more favorable solutions than baseline scenarios (Vahdatikhaki et al., 2022) [33].
	The optimal scheme's total load is 15.8% lower than the worst scheme and 4.2% lower than original scheme (Zhang et al., 2021) [14].
	The urban energy optimization workflow method focuses on more harmonized energy supply and demand-driven approaches (Natanian J. and Wortmann T., 2021) [62].
	Energy simulations revealed efficient passive building designs achieving up to 70% improvement (Santos et al., 2017) [65].
	User-friendly generative design can transform how architects design (Touloupaki E. and Theodosiou T., 2017) [66].
	Research demonstrates an ability to create diverse shapes with varying energy demands (Granadeiro et al., 2013) [70].

Table 3. *Cont.*

Energy Efficient Topics	Energy Efficiency of Buildings Achieved through Generative Design
Thermal Performance	The results can evaluate the energy efficiency of buildings affected by climate change (Rodrigues et al., 2023) [36].
	Optimal case proper layout reduces the annual cooling and heating energy consumption by 28% and 13% (Ghasemi Sangi et al., 2023) [34].
	Research found that maintaining the present-day ideal U-values also significantly impacts the thermal loads in the timeframes (Rodrigues et al., 2023) [54].
	Research developed energy use prediction equations based on shading device angle and material (Kamel T., 2022) [58].
	Research developed tools for building energy modeling, which achieve 70% geometric accuracy compared to real structures (Schwartz et al., 2022) [59].
	Research explores the influence of thermal transmittance on building energy efficiency and finds that the ideal amount of thermal mass depends on the building's insulation (Rodrigues et al., 2019) [63].
	Research optimizes buildings' thermal performance algorithms developed as prototype tools (Rodrigues et al., 2015) [67].
	Results show building shape metrics predict thermal performance when considering climate and building type (Rodrigues et al., 2015) [68].
	Research presents methods for designing urban areas that prioritize human comfort and potentially contribute to energy efficiency (Tapias E. and Schmitt G., 2014) [69].
	Research implements processes to allow for generative design, visualization of analysis, and optimization of alternative targeting factory manufacturing buildings with BIM-based design (Kim et al., 2012) [71].
Daylight	Research achieved a balance between creating aesthetically pleasing facades and ensuring good daylight performance (Kim J., 2013) [30].
	Research demonstrates that the design of building facades optimizes daylight quality while maintaining aesthetic appeal (Kim J., 2012) [31].
Others	Research framework for life cycle assessment tool that analyzes the environmental impact of buildings during the design phase (Hassan et al., 2022) [37].
	Research achieved a 7% reduction in embodied emissions compared to a sub-optimal solution (Zaraza et al., 2022) [22].
	Optimal building's automatic design tools show significant reductions in life cycle carbon footprint and life cycle cost (Schwartz et al., 2021) [39].
	Specially designed building shapes can increase solar energy capture by up to 24% for renewable energy generation (Luitjohan et al., 2022) [57].
Daylight and Energy Performance	Achieves up to 0.42% energy savings and 9.71% spatial daylight autonomy improvement compared to baseline design (Zhou Q. and Xue F., 2023) [35].
	Project results equip architects to find design solutions that match their goals (Ratajczak et al., 2023) [52].
	The proposed research approach guarantees better use of solar resources in building envelopes (Turki et al., 2023) [56].
	Tools prove the ability to efficiently achieve numerous origamic solar device alternatives for improved energy efficiency (Fathy et al., 2021) [60].
	Study examines building factors (direction, windows) to design a model ideal for year-round energy efficiency (winter and summer) (Khidmat et al., 2021) [61].
	The research analyzes building layout's impact on energy, sunlight, and openness to guide urban planning efficiently and visually (Chang et al., 2019) [64].

Table 3. *Cont.*

Energy Efficient Topics	Energy Efficiency of Buildings Achieved through Generative Design
Daylight and Thermal Performance	Generative design system that architects can use in the early to intermediate stages of design to help improve buildings' environmental performance (Caldas et al., 2003) [72].
Daylight and Thermal and Energy Performance	The resultant generated form was 42% more energy-efficient than the existing design (Chockalingam et al., 2023) [32].
	Research framework optimizing daylight and managing heating/cooling for architects to choose energy-saving building shapes (Elgohary et al., 2023) [51].

The energy efficiency of buildings achieved through generative design was explored in 34 research publications from 2003 to 2023 (Table 3). These topics encompass energy performance, thermal performance, daylighting, others, and multiple topics within a single study. The development of tools and frameworks has demonstrated a reduction in energy usage compared to prototypes or traditional design approaches. The development of the framework includes achieving energy efficiency in buildings through generative design. The specific unit of reduced energy cannot be specified, as the criteria for each project are different and cannot be compared using statistical methods. However, the success of generative design can be highlighted based on the results obtained. In the optimal generative design scheme compared to the original scheme (Figure 6), the best energy performance achieves an energy saving of up to 23.30% (Saurav et al., 2023) [53] and worst achieves an energy saving of up to 4.2% (Zhang et al., 2021) [14]. The cooling and heating load can be reduced by 28% and 13% (Ghasemi Sangi et al., 2023) [34]. Embodied emissions can be reduced by 7% (Zaraza et al., 2022) [22]. Solar energy captures up to 24% (Luitjohan et al., 2022) [57]. Daylight and energy performance achieved up to 9.71% spatial daylight and 0.42% energy savings (Zhou Q. and Xue F., 2023) [35]. Daylight–thermal energy performance achieved up to 8%, and spatial daylight achieved a 45% reduction in peak heat gain from the envelope and 42% energy savings (Chockalingam et al., 2023) [32].

3.2.2. Generative Design Methods for Energy Efficiency Topics

To expand on the details regarding generative design methods for energy efficiency topics, generative design methods encompass a variety of techniques aimed at optimizing building performance in terms of energy efficiency (Table 4 and Figure 7).

Thermal performance is associated with heat transfer and envelope efficiency. The main focus is on factors such as transmittance (U-value) and envelope design [36,68]. Research endeavors often integrate various methodologies, including exploring novel concepts utilizing building information modeling (BIM) through the RBFOpt Model [52]. This approach is thus categorized as employing rule-based and evolutionary algorithms. Additionally, some studies use the EPSAP algorithm and rule-based algorithms [68].

The second most prevalent concern of energy performance is a crucial concern, one of the most pervasive issues [18]. To achieve energy savings [14,18,53], the aggregate cooling and heating loads are considered [14,18]. Various research initiatives delve into hybrid approaches, encompassing the training of AI and machine learning algorithms [53,64]. Additionally, some studies integrate methods exploring the concept of shape grammar-based parametric design systems to attain flexible designs while ensuring adherence to architectural compositional principles [70]. Furthermore, a blend of evolutionary algorithms and parametric methods has been identified [66].

Figure 6. Energy efficiency of buildings achieved through generative design separated by topic [36,38,39,56,59,63,64,69].

Table 4. Generative design methods in energy efficient topics found in publications.

Energy Efficient Topics	Generative Design Methods						
	Parametric Search Strategy	**Rule-Based**	**Evolutionary Algorithms**	**Hybrid with Machine Learning and AI**	**Rule-Based and Evolutionary Algorithms**	**Rule-Based and Parametric**	**Evolutionary Algorithms and Parametric**
Energy Performance	Parametric [14,62]	-	NSGA-II [18,33], genetic algorithm [65]	Machine learning and AI with parametric and rule-based [53], ANNs use BRBNN with parametric [55]	-	Shape grammars and parametric [70]	Evolutionary algorithms and parametric [66]
Thermal Performance	Parametric [34,58,71]	Rule-based [59]	EPSAP algorithm [36,54,63], Evolutionary algorithms [67,69]	-	EPSAP algorithm and rule-based [68]	-	-
Daylight	-	Cellular automata [30,31]	-	-	-	-	-
Others	Parametric [37]	-	NSGA-II [22,39]	-	-	Cellular automata and parametric [57]	-
Daylight and Energy Performance	Parametric [56,61]	-	NSGA-II [35]	AI with rule-base and genetic algorithms and RBFOpt [52], Reinforcement learning and AI and parametric [64]	-	Parametric and rule-based [60]	-
Daylight and Thermal Performance	-	-	Evolutionary algorithms [72]	-	-	-	-
Daylight and Thermal and Energy Performance	-	Shape grammar [32]	-	-	Shape grammars and genetic algorithm [51]	-	-

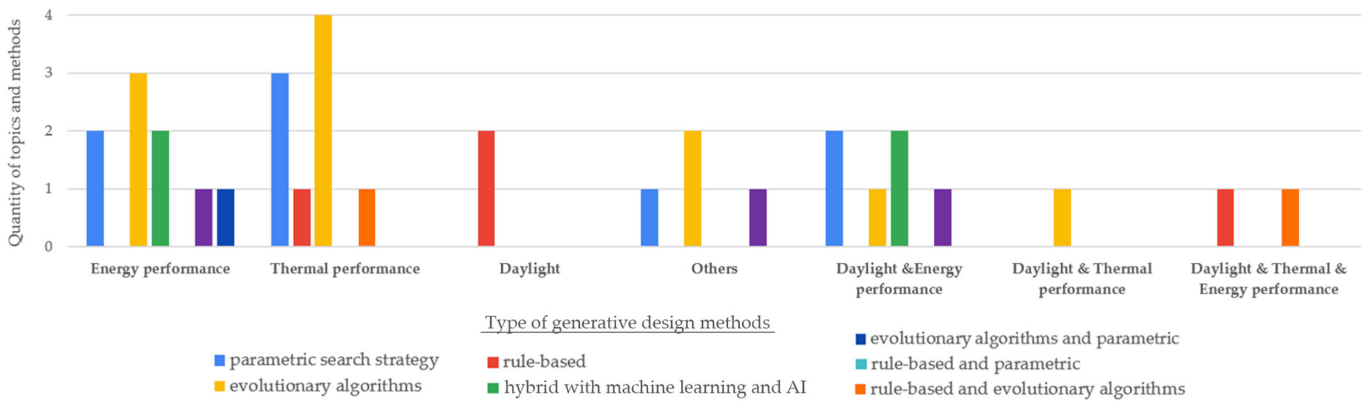

Figure 7. Clustered column chart of quantity and type of generative design methods in energy efficiency topics.

Energy and thermal performance frequently employ generative design methods, with evolutionary algorithms commonly utilized. Notably, algorithms such as NSGA-II, EPSAP algorithm, and the genetic algorithm, among others, are prevalent in these applications. Additionally, parametric search strategy methods are frequently encountered, with popular tools including the Rhino and Grasshopper plugins [34,58,61] and Autodesk Revit and Dynamo [53,56]. Architects widely favor these programs, and they are readily accessible for implementing parametric design strategies.

Daylighting plays a crucial role due to its impact on energy consumption within buildings [30]. A related study by the same author continues this line of inquiry, focusing on developing facade design alternatives using the cellular automata method. This methodology entails arranging cells on a grid according to predefined rules, with iterative adjustments based on time steps [30].

Based on other research findings, in addition to considering supplementary issues, these employ life cycle assessment [37] methodologies during the preliminary design phase, utilizing a parametric approach that leverages generative design techniques to propose diverse options for residential exterior walls with minimized environmental embodied impacts. Research of embodied emissions [22] and environmental repercussions stemming from their accumulation in the atmosphere employs evolutionary algorithms, specifically NSGA-II, to address these challenges. Furthermore, solar access assessment [57], alongside energy performance evaluation utilizing cellular automata characterized by rule-based and parametric functionalities, is also explored in the development of building forms. Finally, the study integrates life cycle carbon footprint and life cycle cost analyses [39], employing evolutionary algorithms (NSGA-II) to evaluate both embodied carbon and operational carbon aspects of buildings.

Nine research publications examined various combinations of two or three topics. Six publications focused on the integration of daylighting and energy performance. Two studies employed parametric search strategies, while one utilized the evolutionary algorithm, specifically the non-dominated sorting genetic algorithm (NSGA-II), to address the problem involving optimizing multiple objectives (energy efficient and daylight autonomy) simultaneously [35]. Additionally, hybrid approaches incorporating machine learning and artificial intelligence (AI) [52] were explored. These hybrids combined rule-based methods with genetic algorithms and RBFOpt, an AI technique. Furthermore, parametric search strategies were integrated with machine learning, specifically reinforcement learning and AI [64]. Moreover, the research combines rule-based and parametric search strategies, drawing on parametric design tools commonly used by architects to generate optimized alternatives tailored to specific targets [60].

One publication that addresses both daylighting and thermal performance considerations was identified. This research delves into the implementation of evolutionary algorithms, marking the earliest work in this review, dating back to 2003. The study examines the benefits of integrating rapid prototyping technology during the early to intermediate stages of architectural design. Specifically, the variables investigated encompass fenestration design, shading systems, and building shape, including roof geometry [72].

Two publications have been identified that integrate daylighting considerations, thermal performance, and energy efficiency. One study employs a performance-based shape grammar (PBSG) approach for form finding, facilitating the creation of rule-based options for building facades [32]. Another research effort utilizes a mixed methodology, combining shape grammars with evolutionary genetic algorithms to establish a framework for generating building forms [51].

4. Discussion

Generative design is indeed gaining acceptance for practical use [38]. However, this review indicates a significant gap in its application to enhance building energy efficiency [39,43,44]. This systematic review reveals, through data gathered from three databases, that the quantity of publications is not extensive. However, the research remains consistent and ongoing. Following the period after 2021, there has been a significant growth in publications, which has continued to the present day. If this trajectory aligns with previous patterns, there is a likelihood of further increased growth in the future. Growth in research publications is increasingly aligning with the evolving design landscape, departing from traditional design methods. The growth and accessibility of computational design [80], coupled with advancements in architecture design BIM software [81], have facilitated this shift. Generative design is now being utilized in practical applications, with globally renowned architectural firms leveraging technology and innovative design techniques. Examples are Zaha Hadid Architect's Mathematics gallery, The Serpentine pavilion designed by Frida Escobedo [82] and The Autodesk Toronto office [83].

Furthermore, international trends indicate a sustained interest in computational design, environmental considerations, and artificial intelligence (AI). Consequently, future studies are poised to amplify exploration in these domains. Given the potential of generative design to inform decision making processes, shape design endeavors, and enhance energy efficiency in buildings, its integration is poised to serve as a guiding principle for sustainable architecture moving forward.

A review of generative design methods for enhancing energy efficiency in buildings highlights the ongoing challenge of determining the appropriate level of generative knowledge and its application. The focus is scrutinizing the practical applications emerging from prior and subsequent research endeavors. The method's complexity depends on the predefined conditions. More intricate scenarios necessitate the utilization of sophisticated methodologies. Remarkably, parametric design has become more accessible to designers, facilitated by software platforms like Revit and Rhino, which have become fundamental tools for contemporary architects. Consequently, the potential for utilizing generative design through parametric means presents an accessible avenue for enhancing its usability. Moreover, there is a growing trend towards integrating machine learning and AI alongside other methodologies, aligning with broader research trends and the imminent advent of the AI Era.

5. Conclusions

Descriptive analysis was used to answer Q1. In total, 34 selected articles were categorized by year, source, and number of citations. The earliest work identified dates to 2003. From 2012 to 2019, an average of one to two articles were published per year. There were five additional papers in 2021, six papers in 2022 and eleven published articles in the latest year, 2023 (Figure 2). The publications' sources can serve as a reference point for future studies. The highest number of publications came from the journal "Energy and Buildings". Articles found in journals were related to energy usage and conservation, computer-aided design, and interdisciplinary. A high number of citations highlights a valuable resource. The most-cited publication in this study is that of Granadeiro V. et al., with 240 citations. Publications ranked 2–5 have over 50 citations each, and those ranked 6–10 have more than 25 citations.

Comparative qualitative and descriptive analysis was used to answer Q2. We arranged the topics from the highest to lowest according to the number of studies in which they were studied: The most extensively studied topic was thermal performance, which was reduced by 28%. Energy performance achieved up to a 23.30% reduction. Other topics followed these (life cycle assessment, embodied emissions, solar access, life cycle carbon footprint and life cycle costs), and the least is daylighting. In addition to single-topic studies, there were also studies of multiple topics including daylight energy performance, which achieved up to 9.71% spatial daylight and 0.42% energy savings, followed by daylight thermal performance, and daylight thermal–energy performance, which achieved up to 8% spatial daylight, with a 45% reduction in the peak heat gain from the envelope and a 42% energy saving. There are multiple applications of generative methods for energy efficiency topics: Evolutionary algorithms are standard as the most frequently used in generative design methods. In recent years, parametric search strategies have been rising. Exploration reveals rule-based and mixed methods, including parametric with evolutionary algorithms, rule-based with evolutionary algorithms, and rule-based with parametric algorithms. Machine learning and AI garner attention.

The study is limited to three databases: Scopus, Google Scholar, and Thai Journals Online. However, articles on this topic in other databases should not be included. Parametric search strategies in conjunction with other methodologies could be lacking because some research focuses on presenting algorithmic methods and may not mention parametric approaches. Future research could expand the current knowledge by delving into the processes and variables involved in applying generative design methods to enhance energy efficiency in buildings. Currently, researchers are developing a framework for applying generative design, which has not been studied in Thailand's national research databases, to enhance energy efficiency with building energy codes.

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