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Status Quo of Multi-Objective Design Optimization of Kinetic Facades: A Quantitative Review

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Highlights

• Improved energy efficiency and comfort by kinetic facades.
• Computational heuristics application in multi-objective optimization.
• Promising machine learning techniques to enhance the performance.

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Energy efficiency,
Human comfort

Abstract

Kinetic facades provide numerous advantages, such as improving the energy efficiency in buildings, effective control of daylight and natural ventilation, and the assurance of human comfort within indoor spaces. Either in the process of designing or programming the active control systems for kinetic facades, addressing the complicated nature of indoor climate necessitates advanced models that aid in determining optimal operations. However, the status quo of multi-objective (MOO) optimization in kinetic facade performance remains largely unexplored. This study delves into the trends in MOO methods and their broad applications through a scientific mapping and quantitative review process. The goal is to investigate the kinetic facade designers' contributions to expanding the application of computational MOOs. The findings indicate that researchers focused on kinetic facades have played a limited role in extending the MOO applications. This review paper is significant as it explores a less-explored facet of knowledge related to building design optimization, aiming to inspire researchers to stay well-informed of evolving trends and integrate recent computational innovations into their kinetic facade designs.

1. INTRODUCTION

Human comfort and the indoor environment are complex issues encompassing various aspects such as lighting, temperature, and air quality [1]. Moreover, elements like privacy level, visual exposure, and optical status are integral components of overall comfort [2]. Building envelope designers have developed alternative adaptive and kinetic facades to efficiently use daylight and solar radiation and enhance visual and thermal comfort in alignment with energy- and cost-saving principles [3-15]. These approaches involve virtualizing the facade operation through advanced modelling techniques to understand and explore the solutions to enhance and optimize their performance. However, the optimization objectives do not always correlate, such as achieving maximum daylight while maintaining maximum indoor privacy dyad. Moreover, the problem of many-objective performance optimization, such as comfort and energy consumption, integrating thermal efficiency, visual, and thermo-optical comfort, has been addressed so far by kinetic facade researchers [16], emphasizing the complexity and importance of the topic.

The aforementioned issue prompts the search for optimal tradeoffs among objectives using multi-objective optimization (MOO) methods. MOO techniques are mathematical or computational problem-solving approaches that involve exploring the tradeoff surface among the given objectives and iteratively refining the solutions until a satisfactory Pareto front is obtained [17]. “The Pareto front is defined as the set of non-

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dominated solutions, where each objective is considered as equally good" [18]. MOO is utilized across diverse domains, including engineering design and resource allocation [17, 19, 20]. The important optimization methods are computational heuristics and machine learning techniques which are the familiar tools in building design optimization [21-23], such as Evolutionary algorithm (EA) and Genetic algorithm (GA). For instance, the heuristic EAs is used for minimizing cooling and heating load while reducing thermal and visual discomfort by interchanging fabric material properties of the building envelope [24]. Also, in the realm of material engineering, [25] evaluated the potential of adaptive insulation material with controllable thermal transmittance employing a combined method of building performance simulation and multi-objective optimization. Material attributes like density, thermal properties, and the window-to-wall ratio are considered significant geometric factors in MOO using GA [26].

Furthermore, the MOO application extends to post-occupancy stages, e.g., automated active control systems of kinetic facades, to achieve real-time performance optimization and effectively coordinate the dynamic operation of the adaptive envelopes [2]; these active control systems are programmable and may even feature learnability. Kinetic facade performance optimization has been addressed in a few studies; see Table 1 for research highlights in this realm, which hint at the optimization techniques employed.

The operation of a dynamic photovoltaic system for adaptive shading is enhanced by employing an exhaustive search space method, which improves its performance in energy-saving aspects and solar-related factors such as cooling, heating, and lighting. [14]. Aiming at comfort and optimum energy generation, [27] adopted a multi-domain model-based control for double skin facades to balance comfort and reduce energy usage. The visual comfort and optimal openness configurations are also the key factors participating in a MOO of a dynamic envelope performance aiming at efficient cooling load and daylighting in [28] research. Another example is applying MOO to an adaptive shading system operation in fully glazed buildings to enhance visual comfort and operational energy efficiency [29]. [30] developed a decentralized kinetic facade control that enhances visual comfort by integrating fuzzy logic and GA in a personalized adaptive façade system and improves occupant satisfaction while outperforming conventional controls. EA is adapted for real-time control of adaptive building-integrated photovoltaic systems [31]. Also, with energy consumption concerns, parametric design and EA optimize hospital room shading for daylight balance [32].

Table 1. *MOO in kinetic facade research*

Reference	Source	MOO technique	Facade system	Optimization objectives
[14]	Applied Energy	Exhaustive search	Dynamic photovoltaic and adaptive shading system	Energy consumption, heating/cooling, and natural light
[27]	Energy and Buildings	Multi-domain model-based control (MBC) algorithm	Double skin Adaptive facades	Comfort and energy consumption
[28]	Building and Environment	Large search space parametric non-linear method	Climate-adaptive building envelope with dynamic operation	cooling load and daylight
[29]	Open House International	Integrated parametric design and evolutionary algorithms	adaptive shading system in fully glazed buildings	Comfort, outdoor landscape, visual comfort, and operational energy efficiency
[30]	Journal of Building Engineering	İntegrated Fuzzy logic and genetic algorithms	Decentralized control of personalized kinetic facade modules	Glare, daylight, and outdoor landscape

[31]	Frontiers in Built Environment	Evolutionary algorithm	Photovoltaic systems with real-time control	Comfort and energy consumption
[32]	Sustainability	Integrated parametric design and evolutionary algorithms	Modular kinetic shading system	Daylight and energy consumption

The highlighted studies underscore the importance of implementing innovative strategies in building envelope design and control. These strategies aim to enhance occupant comfort, energy efficiency, and sustainability across various contexts. Research has demonstrated that employing MOO techniques and simulation-based approaches is more effective than conventional controls. Despite the limited focus on MOO application in the kinetic facade design field, the potential for adaptive building facades and climate-responsive envelopes to significantly improve both occupant well-being and environmental performance highlights the need to understand recent advancements in MOO techniques. Additionally, gaining insight into the current status of MOO integration within kinetic facade research is crucial.

Moreover, as presented in Table 1, the EA and GA are dominant MOO techniques integrated into active control systems performance improvement. On the grounds that the objectives are vast and the scope of studies varies, there is a need to discover other potential MOO techniques and foresee their future role in kinetic facade developments. This study aims to provide insights into emerging MOO techniques and their potential influence on building facade research. The aim is achieved via three main research objectives: 1) investigating trending MOO techniques and their applications, 2) identifying the popular objectives in façade design optimization, and 3) revealing the status quo of kinetic façade MOO in emerging MOO trends.

In this study, two datasets are collected and quantitatively mapped. The first dataset includes 2000 highly cited journal articles published in recent years (2018-2023), which feature MOO applications. The second dataset contains the bibliographic data from all journal papers on building facade design with MOO focus. The insights obtained from the two datasets are compared and discussed in the following sections. This study is original in employing the quantitative science plotting method to reveal the kinetic façade status quo in the broader realm of MOO applications.

2. REVIEW METHOD

The research method consists of four main steps: selecting an appropriate scientometric analysis tool, extracting datasets, creating knowledge maps, and analyzing the maps. Selecting an appropriate quantitative review tool and a relevant database is essential for executing the analysis. Considering the primary objective of this paper, which is to explore MOO applications, a potential database covers a vast scientific spectrum. Scopus is the primary database used in this paper since it provides a vast array of high-quality articles and is not limited to a specific scientific domain. VOSviewer software is used in this study due to its user-friendly interface and suitability for quantitative exploration of the large bibliographic datasets [33, 34]. The tools embedded within this software, such as those for visualizing co-occurring keywords and analyzing text, facilitate the achievement of this study's objectives.

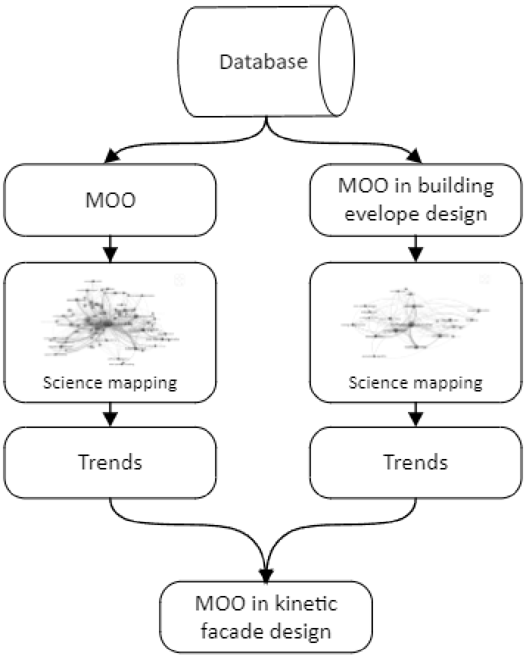

Figure 1. *Flowchart of research method*

As depicted in Figure 1, the datasets containing bibliographic data of articles focused on MOO and its application in building envelope/façade design were obtained in the first step. In the initial data collection phase, the keyword "multi-objective optimization" is used to browse the abstracts, keywords, and titles of articles indexed in Scopus. Subsequent filtering is applied to refine the results. The dataset analyzed in this paper is limited to the 2000 most-cited articles published between 2018 and 2023, referred to as "MOO articles." Next, a keyword co-occurrence network is generated using VOSviewer. The top-ranked terms were then identified and discussed for a more comprehensive understanding of these networks. In the second phase, the search is narrowed down by employing the keywords "MOO" in conjunction with "building envelope" or "building façade" to focus on the specific domain of interest. Due to the specification, the search result is not vast and includes 241 journal papers. The dataset, titled "MOO in building facade design articles," underwent scientometric analysis.

Scientometrics is defined as the "quantitative study of research on the development of science" [35]. It is known as the study of scientific communications and networks by processing the bibliographic data [36] and modeling the knowledge exchanges [37]. Some software, like VOSviewer, aids in this process. This paper utilizes version 1.6.18 of VOSviewer, a Java application featuring advanced scientific plotting tools to generate bibliometric maps via distance-based networks, showcasing connections between concepts.

Furthermore, it's feasible to merge various expressions of a single concept within a network. This process entails a preliminary examination of the keywords and consolidating synonymous or closely related terms to create unified entities. The subsequent step involves the creation and integration of a thesaurus text file to enhance coherence and comprehensiveness in the final network mapping. In this work, the preliminary analysis of the author keywords and terminologies in the dataset is conducted. A thesaurus file is created to standardize various wordings of a specific concept, such as "optimization" and "optimisation", or "air conditioning" and "air conditioning systems". Additionally, close concepts like "near-zero energy building" and "energy efficiency" are consolidated into a single entity, "energy efficiency".

In the network visualization preview of the VOSviewer software, distance-based networks contain nodes and linkages. Each node represents a concept or entity (e.g., if the network describes the co-occurrences, then the nodes represent keywords). The size of each node corresponds to the frequency of that concept occurring within the keywords of articles in the dataset. The link among the nodes indicates their interrelatedness. For instance, if there is a link between nodes A and B, these two concepts co-occur in at least one article. The thickness of the link also represents how frequently these two concepts coincide. The distance, represented by the length of the links, provides a comprehensive overview of the mapped knowledge, showcasing the relative positions of nodes.

Moreover, VOSviewer categorize network entities based on their connections, what are shown in distinct colors, providing a clearer understanding of bibliometric networks [33, 34]. Based on the network types, the clusters can represent thematic areas, research trends, or communities of researchers working on similar topics. For example, in a bibliometric analysis of scientific articles, VOSviewer might identify clusters of keywords that frequently appear together in the titles or abstracts of papers. Each cluster is assigned a unique color, and the keywords within each cluster is connected by lines indicating their co-occurrence. In this work, distinguishing the relationships within the dataset directs the results section and facilitates the identification of the correlated subjects and techniques of MOO.

3. RESULTS

3.1. Trends in MOO Articles

The terms repeated more than ten times in the titles or abstracts of MOO articles were mapped to gain insight into current debates, as shown in Figure 2. Utilizing the textual analysis tool in the VOSviewer, an extensive search is conducted within the dataset to identify the top-ranked terms and words found in either the abstracts or titles. This analysis resulted in the formation of six clusters from a total of 781 items within the network. The predominant concept of each cluster is given in Table 2.

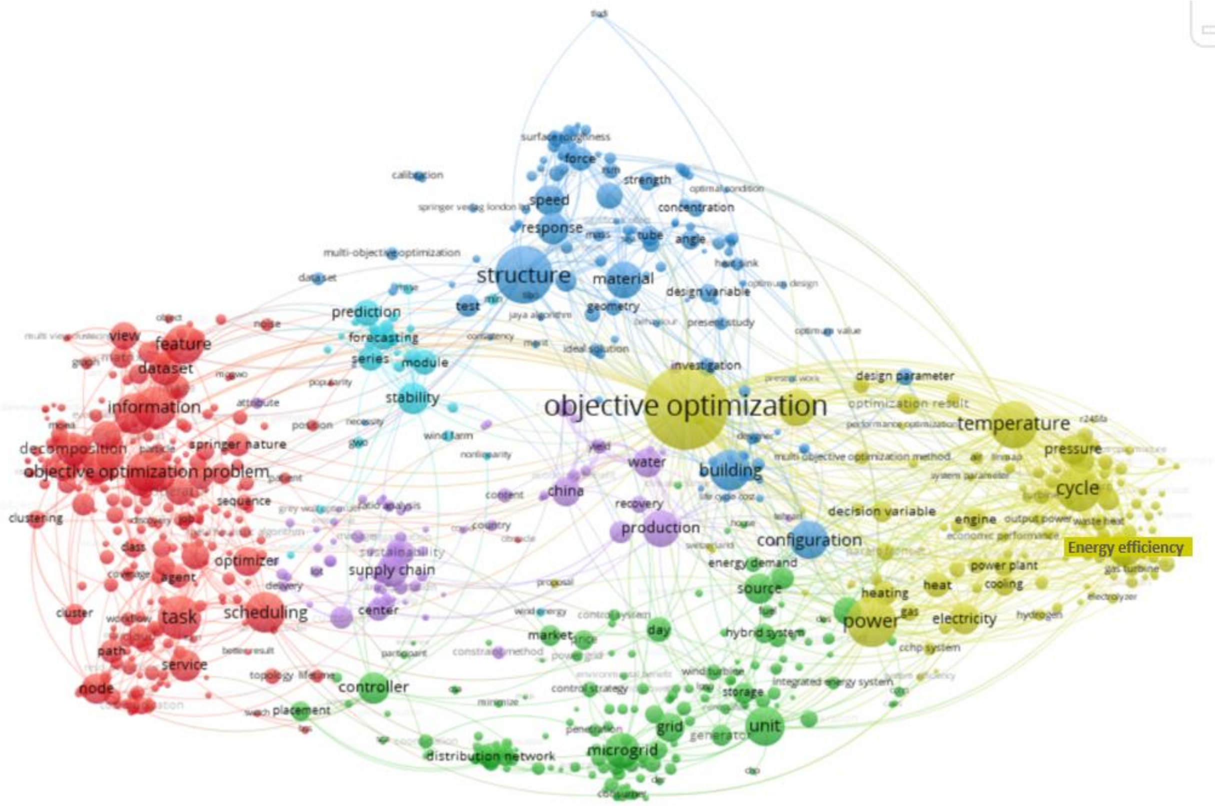

Figure 2. *Textual analysis of MOO articles: term network visualization*

Table 2 demonstrates the ID of the clusters and their colors in the network in the first and second columns. The “main subject” column reflects the dominant concept for each cluster, while the “representative items” column includes some selective terms within the clusters that encapsulate their themes. The “sub-cluster main subject” results from manually browsing each cluster to determine whether any sub-cluster exists. The representative items in each sub-cluster are introduced in the last column. It is important to note that sub-clusters were defined through manual scrutiny of the clusters to find more relevant concepts and links, enhancing our understanding and providing in-depth insights into each cluster.

Table 2. *Clusters of trending terms in MOO articles' textual analysis*

Cluster ID (items)	Assigned color	Main subject	Representative items	Sub-cluster main subjects	Sub-cluster representative items
#1	red	MOO techniques and technical terms	Evolutionary algorithms; whale optimization algorithm; ant colony optimization; artificial bee colony algorithms; pareto optimal front; support vector machine; moea/d (multi-objective evolutionary optimization based on decomposition); genetic algorithm (nsga-ii, nsga-iii); deep reinforcement learning; np hard problem; feature (and feature selection); classification; computational efficiency (and computational cost); search space; objective space; cuckoo search; memetic algorithm; hybrid algorithm; clustering; fitness function; matrix; topology optimization	Smart city	Mobile device; sensor network;
				Algorithms and optimization techniques	Evolutionary algorithm; genetic algorithm; ant colony; bee colony;
				Machine learning techniques	Classification; clustering;
#2	green	Carbon emission	Environmental performance; control strategy; renewable energy source; energy management; peak load; cost; electric vehicle; microgrid; wind power	Home/City	Appliance; smart home; microgrid;
				Vehicle	Hybrid electric vehicle;
#3	dark blue	Building	Structure; force; depth; material; surface roughness; machining; beam; mass; thickness	Structure variables	Heat transfer; pressure drop; Crashworthiness
				Optimization and modelling techniques	Artificial neural network; numerical simulation; java algorithm; grey relational analysis; Taguchi method; response surface methodology;

#4	yellow	Energy efficiency	Temperature; thermal efficiency; economic performance; power generation system; exergy efficiency; iste; zeotropic mixture; heating; power; electricity; Pareto frontier; exergoeconomic optimization; fuel cell; iste heat recovery; organic Rankine cycle; Brayton cycle	power	organic Rankine cycle; exergoeconomic optimization; zeotropic mixture; Brayton cycle; natural gas; electricity; power plant; biomass
				economy	exergoeconomic optimization; levelized cost;
#5	light blue	Customer services	Supply chain; productivity; manufacturer; resilience; disaster; supply chain management; costumer; disaster; sustainable development; inventory; transportation; delivery;	-	-
#6	purple	forecasting	Prediction; forecasting; benchmarking; evaluation model; Extreme learning machine	-	-

The following network visualization unveils the trends associated with the keywords provided by the authors. This network aids in comprehending the actual points of focus and objectives within the papers. Figure 3 shows the author keywords of the 2000 dataset articles, which occurred more than ten times. The most robust connections within the network are among “multi-objective optimization” and “genetic algorithm (strength=60)”, “evolutionary algorithm (strength=25)”, “particle swarm (strength=22)”, “feature selection (strength=22)”, “artificial neural network (strength=14)”, and “energy efficiency (strength=10)”. Table 3 includes the information on the top keywords.

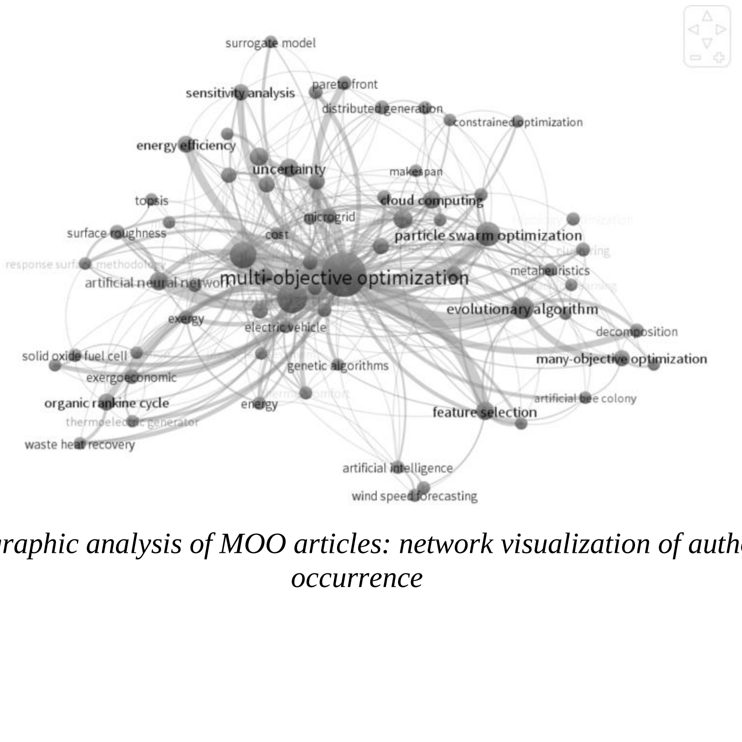

Figure 3. *Bibliographic analysis of MOO articles: network visualization of author keyword co-occurrence*

Table 3. *MOO articles bibliographic analysis: top author keywords*

Keyword	Occurrences
multi-objective optimization	607
optimization	162
genetic algorithm	118
particle swarm optimization	83
evolutionary algorithm	68
feature selection	41
artificial neural network	36
multi-objective	36
sustainability	36
cloud computing	33
uncertainty	30
renewable energy	27
organic rankine cycle	25
energy consumption	24
energy efficiency	24
machine learning	23
robust optimization	22
differential evolution	21
energy management	20
multi-objective programming	20
energy storage	19
many-objective optimization	19
reliability	19
renewable energy sources	19
distributed generation	18
clustering	17
deep learning	17
demand response	17
electric vehicles	17
microgrid	17
sensitivity analysis	17
decomposition	16
exergoeconomic	16
meta-heuristics	16
surface roughness	16
artificial intelligence	15
metaheuristics	15

3.2. Emerging Trends in MOO in Building Facade Design Articles

To find prevailing trends in articles focused on the main objective optimization for building facade design, a textual analysis using the VOSviewer tool is employed. The network shown in Figure 4 is based on terms found within the abstracts and titles of 241 papers. Terms appearing fewer than ten times were excluded from this network. Table 4 provides information about the colored clusters.

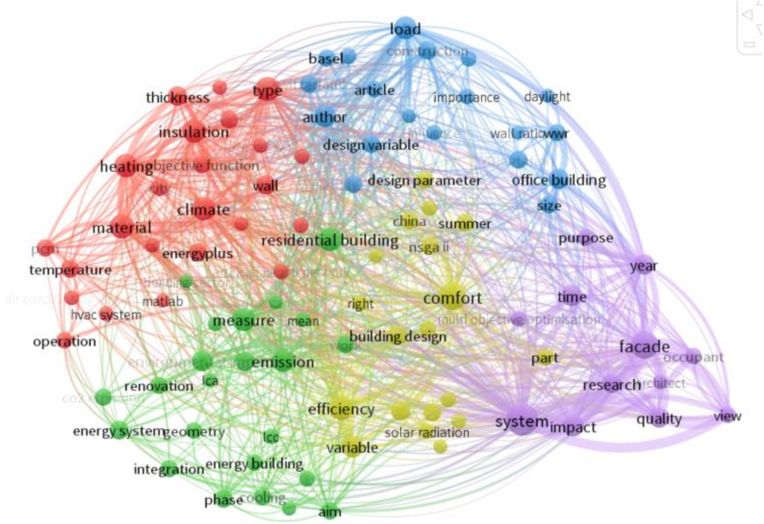

Figure 4. *Textual analysis of MOO in building facade design articles: trending term network visualization*

In Table 4, the first and second columns refer to the cluster IDs and assigned colors in Figure 4's network. The primary focus of each cluster is identified in column 3, with representative terms for each cluster given in the last column. The insights derived from this textual analysis highlight that "energy efficiency" stands as the predominant subject in the context of applying MOO to building facade design. Also, other clusters with "carbon emission", "daylight", "thermal comfort", and "visual comfort" reveal the factors that have thus far been optimized and involved in the processes of MOO in building facade design.

Table 4. *Textual analysis of MOO in building facade design articles: trend term clusters*

Cluster ID (items)	Assigned color	Main subject	Representative items
#1	red	energy efficiency	Climate; energy plus; temperature; material; HVAC system; air conditioning system; thickness; artificial neural network; roof;
#2	green	carbon emission	Environmental impact; surrogate model;
#3	dark blue	daylight	Office building; orientation; wwr (window to wall ratio); climate zone;
#4	yellow	thermal comfort	Solar radiation; genetic algorithm;
#5	purple	visual comfort	Facade; view;

Through a bibliographic author keyword analysis, the network of keywords appearing more than five times in the dataset documents is visualized (Figure 5). Within this network, the most robust connection is shown between "multi-objective optimization" and "genetic algorithm (strength=29)". Furthermore, the links between "thermal comfort (strength=14)", "energy efficiency (strength=11)", "building envelop (strength=17)" and "Multi-objective optimization" are notably strong. Table 5 provides an overview of these network nodes, detailing their respective occurrences.

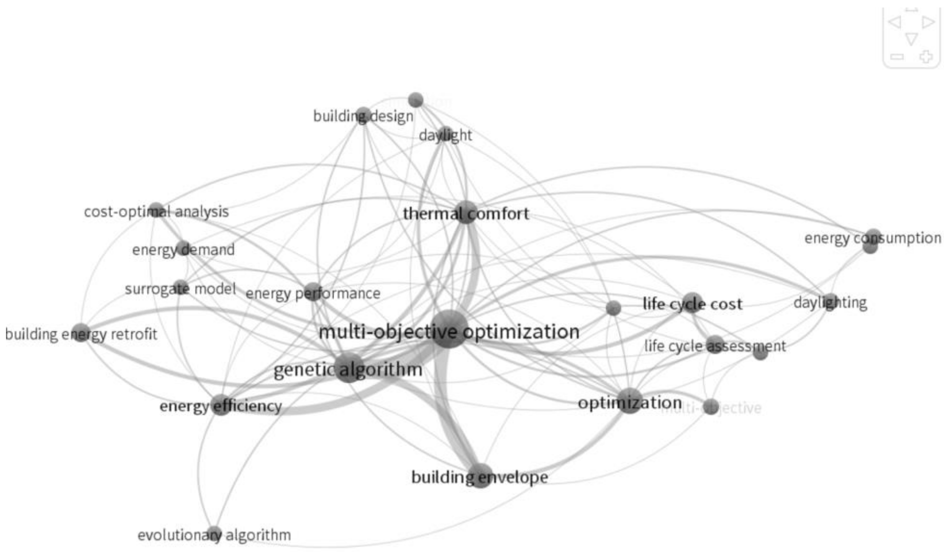

Figure 5. *Bibliographic analysis of MOO in building facade design articles: network visualization of author keyword co-occurrence*

Table 5. *MOO in building facade design articles bibliographic analysis: top author keywords*

Keyword	Occurrences
multi-objective optimization	120
genetic algorithm	48
optimization	31
building envelope	27
thermal comfort	24
energy efficiency	18
life cycle cost	14
energy consumption	12
life cycle assessment	12
building energy retrofit	9
daylighting	9
energy performance	9
visual comfort	7
building design	6
daylight	6
design optimization	6
multi-objective	6
building information modelling	5
building performance	5
building performance simulation	5
climate change	5
cost-optimal analysis	5
energy demand	5
evolutionary algorithm	5

greenhouse gas emissions	5
parametric design	5
residential building	5
sensitivity analysis	5
simulation	5
surrogate model	5

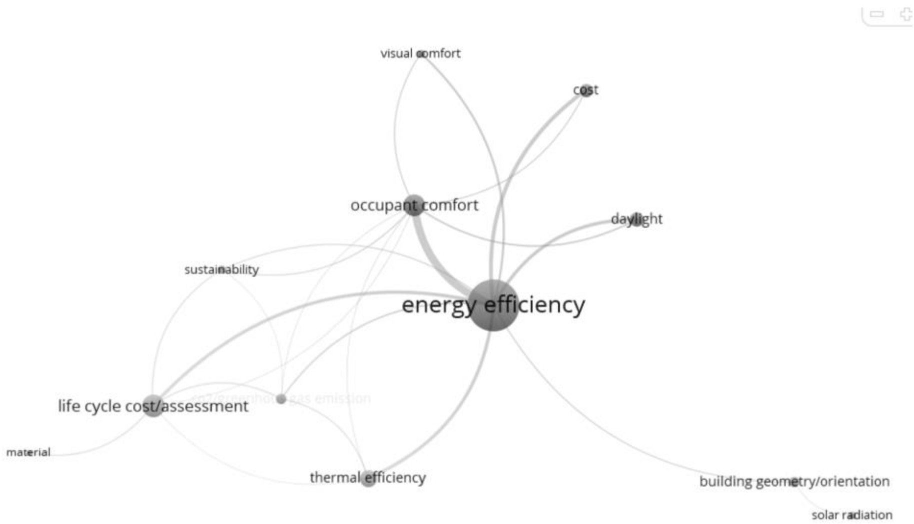

Figure 6. *Bibliographic analysis of MOO in building facade design articles: network visualization of author keyword co-occurrence with consolidated concepts*

Revealing the most popular parities in MOO, a keyword co-occurrence network is generated, excluding general and technical keywords. Figure 6 is a network including the keywords that occur at least twice within the literature on MOO in building facade design. The network connections in Figure 6 show the co-occurring keywords that serve as MOO criteria in the realm of building facade/envelope design. Therefore, it is assumed that the coupled terms are involved in the same MOO process. The strongest links occurred between “energy efficiency” and “occupant [thermal] comfort” (strength=14). Other important links are the connections between “energy efficiency” and “life cycle assessment” (strength=6), “energy efficiency” and “cost” (strength=7), “energy efficiency” and “thermal efficiency” (strength=6), “energy efficiency” and “daylight” (strength=6), as well as “energy efficiency” and “visual comfort” (strength=4). Figure 7 provides a visual representation of these links, with the co-occurrence and thickness of the connections between pairs indicating their involvement in a single simulation, modeling, or optimization process.

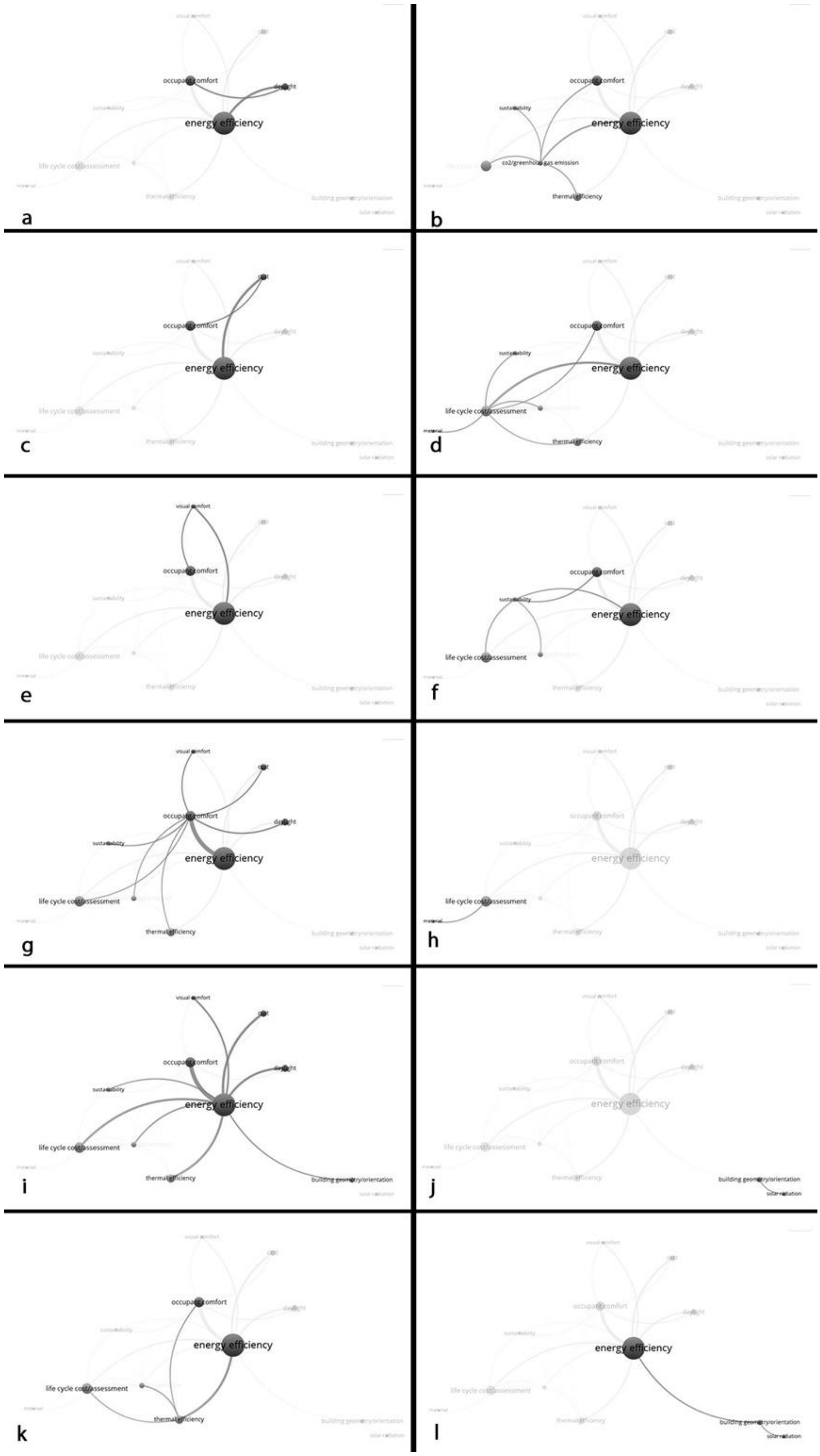

Figure 7. *Bibliographic analysis of MOO in building facade design articles: network visualization of author keyword co-occurrence with consolidated concepts: a) daylight; b) CO2 / greenhouse gas emission; c) cost; d) life cycle cost / assessment; e) visual comfort; f) sustainability; g) occupant [thermal] comfort; h) material; i) energy efficiency; j) solar radiation; k) thermal efficiency; l) building geometry/orientation*

4. DISCUSSION AND CONCLUSION

This quantitative review paper examines the scope of multi-objective optimization applications in kinetic facade design, aiming to expose the role of kinetic facade designers in extending trending MOO techniques applications. Accordingly, the preliminary objective of revealing the important MOO techniques is addressed. As detailed in Table 2, Cluster #1 is assigned to technical terms. This cluster includes leading computational meta-heuristic and biomimicry computational techniques such as evolutionary algorithms (EA), genetic algorithms (GA), as well as ant and bee colony optimization algorithms. Within the specialized domain of multi-objective optimization for kinetic facades, evolutionary algorithms play a vital role in optimizing factors participating in occupant satisfaction, such as glare, daylight, and view [30], as well as operational energy efficiency [29], known as thermos-optical optimization [16].

Cluster #1 also contains certain terminologies addressing machine learning (ML) techniques like clustering and classification. On the other hand, Cluster #3 features the ML technique and artificial neural network (ANN). This cluster predominantly revolves around terms associated with building-related concepts, with a significant portion devoted to technical terms. It clarifies that articles focusing on building optimization have used various techniques, such as ANN, Grey relational analysis, the Taguchi method, and response surface methodology. Furthermore, research related to smart cities and power and energy management stands out as the vanguard in employing MOOs to find solutions.

Exploring the second dataset, the techniques related to envelop design optimization as well as the most co-occurred parities in MOO are revealed to hit the second research objective. As shown in Table 4 and Table 5, the prominent modeling, simulation, and optimization techniques employed in articles related to building envelope design predominantly include ANN, the Surrogate model, GA, and EA. Notably, the two latter techniques are the trends across both datasets, indicating their widespread usage in this field.

On the other hand, the optimization of building design emerges as a highly significant aspect within the extensive domain of MOO applications. Large clusters in Figure 2 contain concepts related to building design optimization. It has been found that the idea of multi/many-objective optimizations of building design is popular either in enhancing “energy efficiency” or “building [structure]” design. On the other hand, the clusters in Figure 4 address the trends and factors that play a role in the optimization processes of building design. For example, air conditioning systems are the trend in the “energy efficiency” cluster.

Moreover, material thickness and environmental temperature are key factors included in such optimizations. Furthermore, a comprehensive examination of Figure 7 reveals that “energy efficiency” holds paramount significance as a criterion in building optimization, boasting the most extensive network of connections with other variables. This concept is an integral component of nine criteria within the MOO processes, as indicated by the nine endpoints connected to the “energy efficiency” node, like “energy efficiency-occupant [thermal] comfort” (14 times of co-occurrence), “energy efficiency-cost” (7 times of co-occurrence), etc. Another important node within the network, boasting a total of 8 connections, is “occupant [thermal] comfort”. It means that occupant [thermal] comfort tradeoff with eight other optimization criteria is the point of consideration in the dataset papers. For example, one can surmise that occupant [thermal] comfort-thermal efficiency, occupant [thermal] comfort-visual comfort, occupant [thermal] comfort-daylight, and some other dyads are the subjects of multi-objective optimization in building facade design. Comfort and energy is the converging point of focus in the most recent study on kinetic facade multi-objective optimization like in [31].

To achieve the third objective of this study, which is to uncover the contribution of kinetic facade designers to expanding the application of MOO techniques, the study reveals their limited role in this regard. Emerging technologies, like advanced machine learning, show the potential to enhance the performance of responsive facades [31], but remains relatively unexplored. No evidence of advanced MOO application in kinetic façade design has been found in the given datasets. ML techniques, such as classification and clustering, although popular (see Table 2), appear to be largely untouched in the context of MOO within building facade design datasets, as well as in kinetic facade control system performance optimization research. This fact hints at a substantial opportunity for future research inspired by trends observed in MOO studies.

The methodological limitations of this paper, is using a single database and employing only quantitative review approach. Kinetic facade active control systems have many potentials to be configured for improved performances. Accordingly, an integrated qualitative-quantitative review of relevant articles is necessary to provide a holistic understanding of this domain. It is also necessary to provide a framework to guide developers in selecting the most suitable MOO techniques tailored to their specific kinetic facade systems is essential.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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