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Review

A Systematic Review of the Most Recent Concepts in Kinetic Shading Systems with a Focus on Biomimetics: A Motion/Deformation Analysis

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Abstract: In the context of sustainability and ambitious goals for reducing CO_2 emissions, modifying transparency in architecture becomes a crucial tool for managing energy flow into buildings. Kinetic shading systems (KSSs) regulate light and heat entry into a room, thereby reducing energy consumption and CO_2 emissions and improving daylight comfort. Recent advancements in KSSs have led to a significant increase in published papers since early 2022. This paper systematically reviews recent technological innovations in KSSs and presents the mechanical principles utilized in these systems. Given the kinetic/mechanical nature of all case studies examined, a categorization based on 'type of motion and deformation' was used, ranging from the simplest to the most complex solutions. In the context of kinetic systems, the motion category addresses the displacement (translation, rotation, or both) of rigid façade elements, while deformation describes the transformation that changes the shape of these elements. The data are presented in tabular form, including details about building type, climate zone, research type, evaluation, and before and after values. Additionally, some reviewed systems' authors drew inspiration from nature, employing biomimetic methods to design KSSs. Despite considerable growth, these solutions still represent only 21% of all analyzed shading system cases. This topic is extensively discussed, considering tropical and nastic plant movements towards this paper's conclusion. The PRISMA protocol was used to review, screen, select, and retrieve all cited papers. This review covers the most recent publications from 2022 to April 2024, recorded in the WoS and Scopus databases, and includes 66 papers.

Keywords: kinetic shading system; adaptive façade; responsive façade; daylight simulation

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1. Introduction

Buildings are a significant energy consumer, accounting for approximately 40% of total energy usage [1]. This consumption is closely linked to energy production methods and has a consequential impact on the carbon footprint. To align with the United Nations' 17 Sustainable Development Goals, particularly Goal 11, which focuses on sustainable cities and communities, it is essential to implement strategies that limit energy consumption and minimize carbon emissions [2].

The façade of a building serves as the principal interface between the interior environment and the external world. To mitigate the influence of diverse environmental factors, adaptive façade systems have been developed. These systems have the ability to respond and adapt to changes in environmental conditions "through their ability to change their performance and behaviour in real-time, according to indoor-outdoor parameters" [3] and may contain 'building components, with variable location or mobility' [4], optimizing transfers such as energy, air, and even information through the façade. According to Attia et al., an adaptive façade "can be defined as building envelope elements with thermal and/or solar, and/or visual properties that vary in time, either passively or owing to an active control" [5]. Fattahi Tabasi and Banihashemi define 'adaptiveness' as the "ability to change the system's state according to environmental changes, while the system remains basically static" [6]. An "adaptive façade" aims to improve energy performance or comfort under changing external conditions (climate, weather). 'Responsiveness' usually refers to the property of reacting to a specific stimulus.

A subset of these broad categories of adaptable systems is kinetic shading systems (KSSs), distinguished by their movable components. As the transparent part of the building's envelope plays a pivotal role in the energy performance of buildings, a KSS is used to address the challenge of heat gain through glazing and daylight distribution. Traditional static shading solutions offer limited efficacy due to their inability to adjust to the Sun's daily and seasonal movements. Although optimization of static systems is feasible, a dynamic approach that continuously adapts to solar positioning proves to be more effective. Such façades are designed to selectively permit the entry of essential daylight while obstructing direct sunlight that contributes to heat gain.

Since the 1970s, the concept of adaptive façades has been explored, with pioneers like Negroponte [7] leading the charge. Adaptable façade systems were the subject of interest of the COST TU 1403 Adaptive Façade Network consortium from 2015 to 2018 [8]. However, the actual implementation of such systems has been limited to selected case studies. These systems face significant design and operational challenges. Therefore, it is postulated that biomimetics, a design methodology inspired by natural systems, could address some of these challenges. Bionics involves meticulous observation of natural systems, abstraction of underlying principles, and their application in the design of adaptable and kinetic façades. By emulating systems developed through millions of years of evolution, the functionality of façade systems can be significantly enhanced.

The presented paper offers a unique perspective on the field of KSSs, focusing on biomimetics used to design façade systems from the standpoint of possible motion mechanics. The degree of KSS complexity from the perspective of motion mechanics is used to rank the presented solutions. The paper contains a comprehensive review of the latest scholarly publications, recorded in databases from 2022 to April 2024 (current), including systems purportedly inspired by natural mechanisms (21%). The second part of the presentation of the results (see Section 4.2) predominantly centers on KSSs that emulate the solar-responsive movements of plant petals, leaves, and stems. Additionally, this paper highlights the innovative application of smart materials capable of morphing in response to external stimuli, marking a significant advancement in façade technology.

The current state of the art, as presented in Section 2, highlights several advancements but also underscores a significant gap in the literature. Specifically, existing reviews have not comprehensively categorized and analyzed the mechanical principles and recent technological innovations in KSSs. Additionally, the specificity of motion and deformation has not been previously studied from the practical application perspective. Many KSSs, especially those parametrically defined, use deformed elements without providing a deep understanding of the practical consequences, which can render these systems impractical to build. This gap in the literature limits knowledge of the full range of KSS solutions and their potential applications, highlighting the need for a comprehensive analysis to advance practical knowledge in this field.

This review aims to fill this gap by providing a detailed and systematic analysis of recent advancements. This perspective is novel and critical for understanding the diverse mechanical principles underlying KSSs. To the best of the author's knowledge, this is one of the first reviews to employ such a categorization in the context of KSSs, following and further developing the approach presented by Tabasi and Banihashemi, including the most recent solutions [6]. Previous reviews have focused on individual aspects of KSSs or specific case studies without a comprehensive and systematic categorization. By doing so, this review provides a unique contribution to the literature, offering new insights into the mechanical principles and innovations driving the field.

The Rationale behind the Presented Review and Objectives

Previous reviews were either limited to specific aspects of these systems, such as “elastic kinetic envelopes” [9], or conducted over five years ago [10]. Therefore, offering a comprehensive overview of this rapidly evolving field is justified. Different types of kinetic motion are used, and new proposals are still being suggested and evaluated. Additionally, current concepts and prototypes are expected to evolve into fully operational building-scale solutions.

This review marks a significant contribution to KSSs, offering a fresh perspective by systematically grouping the most recent developments. It extends beyond the scope of previous works by focusing on specific features and providing a comprehensive overview of the discipline today. This review organizes solutions developed by other scientists, presenting them in a tabular format. It offers an overview of new ideas for simulation techniques and potential natural inspirations in the design of kinetic façades. The paper also facilitates benchmarking validation methods and can potentially influence future façade building designs.

2. Materials and Methods

The presented paper is a review article using the systematic literature review method, conducted following the PRISMA protocol rules (Preferred Reporting Items for Systematic Reviews and Meta-Analysis). The PRISMA protocol combines a systematic review with a meta-analysis [11]. The following subsections describe in detail the process of selecting the reports included in this review and discuss their quantitative aspects.

2.1. Eligibility Criteria, Data Identification

The data for this review were acquired from international scientific databases (WoS and Scopus), with the last search conducted on 1 April 2024. The field of KSSs has seen a significant surge in scholarly interest, particularly evident from 2021 onwards. An examination of the Web of Science database reveals that between 2000 and 2021, 621 entries were tagged with the “adaptive shading”, “kinetic shading”, and “responsive shading” keywords, including “kinetic shading system”. However, representing a notable increase, 243 new entries have been recorded since 2022 alone (21.3 per year). This rapid publication growth over the past three years marks a noteworthy trend that requires detailed analysis. A similar pattern is observed in the Scopus database, which lists 890 papers from 2000 to 2021 and **360** documents from 2022 onwards (32.17 per year). In the author’s view, the above-given data provide ample grounds for a systematic review of the literature on KSSs published in the past 27 months. The increase in the volume of papers reflects a growing recognition of the topic’s significance and a substantial rise in research interest. The trend is illustrated in Figure 1.

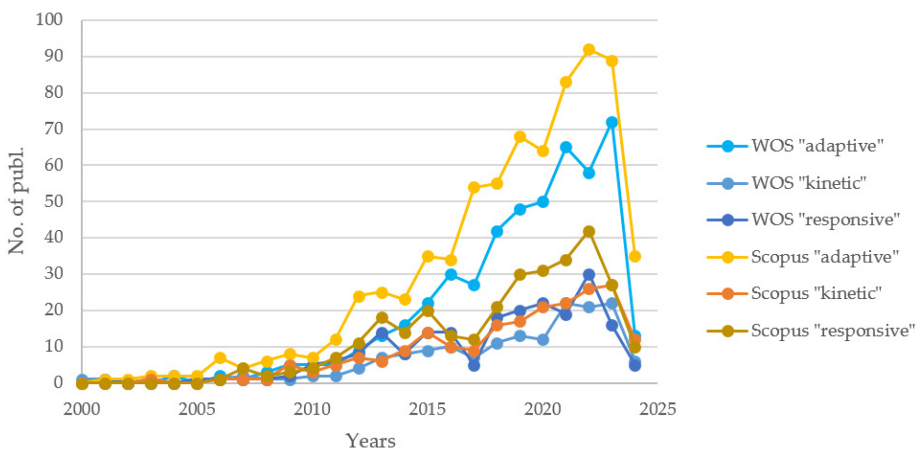


Figure 1. The number of reports indexed with the keywords “adaptive”, “kinetic”, and “responsive” façade in the Web of Science and Scopus database from 2000 to April 2024.

It should be clearly noted that the presented review takes into account a relatively short period of 27 months, from January 2022 to 1 April 2024, and the included studies are identified with "adaptive shading", "kinetic shading", and "responsive shading" keywords including "kinetic shading system".

The analyzed reports were published exclusively in English. Keywords were identified by examining the words in the titles and abstracts of studies previously reviewed, which focused on kinetic and adaptive façade systems. The selection process across all databases initially included papers indexed with the "kinetic shading" keyword. Subsequently, "adaptive shading" and "responsive shading" were also considered after the initial sorting. Following this first level of refinement, a second screening was conducted using the keyword "biomimetic". A single researcher conducted the entire review process.

The procedure to determine the inclusion of reports in this review followed three criteria:

- Mechanical Movement: The mechanical movement of KSS elements defines the system's 'kinetic' character. This criterion ensures that only systems that exhibit physical motion are included in this review. Physical motion can occur through (i) translation—linear movement of components in one or more directions; (ii) rotation—circular movement of components around an axis; or (iii) deformation—changes in the shape of components, which might include bending, stretching, or compressing. These movements are essential for a system to be considered kinetic and are fundamental to its operation and effectiveness in managing light and heat.
- Various States of the Façade: The analysis considers the different 'states' or configurations the façade can adopt. This criterion includes systems that transform between multiple states, enabling dynamic responses to changing environmental conditions. Such states might involve (i) open and closed configurations, allowing for different light penetration levels; (ii) intermediate configurations; and (iii) adaptive responses, reacting to real-time data or environmental triggers to optimize building performance. By examining these various states, this review can assess the flexibility and adaptability of the KSSs.
- Biological Inspiration: There must be a clear element of biological inspiration for the reports included in the second part of this review (Section 4.2). This criterion focuses on systems that draw design principles from nature, specifically mimicking mechanisms found in plants or other biological entities. Examples include (i) mimicking plant movements: petals, leaves, or stems opening and closing in response to sunlight (tropism) or other stimuli; (ii) biomimetic materials: using materials that change shape or properties in response to environmental conditions, similar to how natural organisms adapt; and (iii) efficiency and innovation: highlighting how these biologically inspired designs offer innovative solutions that are both efficient and sustainable. This approach advances the technological aspect of KSSs and provides insights into the potential for sustainable design.

The Web of Science and Scopus databases were initially searched within the specified timeframe (2022 to present). This search yielded 243 reports from Web of Science and 360 from Scopus. After the of removal duplicates, reports were marked for further refinement, and the titles and abstracts of all reports were meticulously reviewed. Given the manageable number of reports, each abstract underwent a double screening. In the first phase, approximately 20% of the papers were excluded because they focused on the structural behavior of the façade, including discussions on "kinetic" energy within the system, or they did not consider KSSs. Subsequently, 116 full-text documents were examined, among which 9% (11) were review papers and another 15% (18) were theoretical papers, not including the study of KSSs but referring to KSSs in general terms.

Ultimately, 66 papers were selected for inclusion in this review. Given the complexity of this investigation, an attempt was made to categorize the included reports/papers along two dimensions: simulation and experimental reports. As a result, 62% of the documents were classified as simulation papers, 10% contained experimental studies, and 28% combined experimental and simulation work. All 66 papers, each individually cited, were incorporated into this review. It must be clearly stated that this review also includes one paper authored by the review author (MB), published in February 2024. In the analyzed group, 22% of authors cited inspiration from nature in their KSS designs and further considerations. See Figure 2.

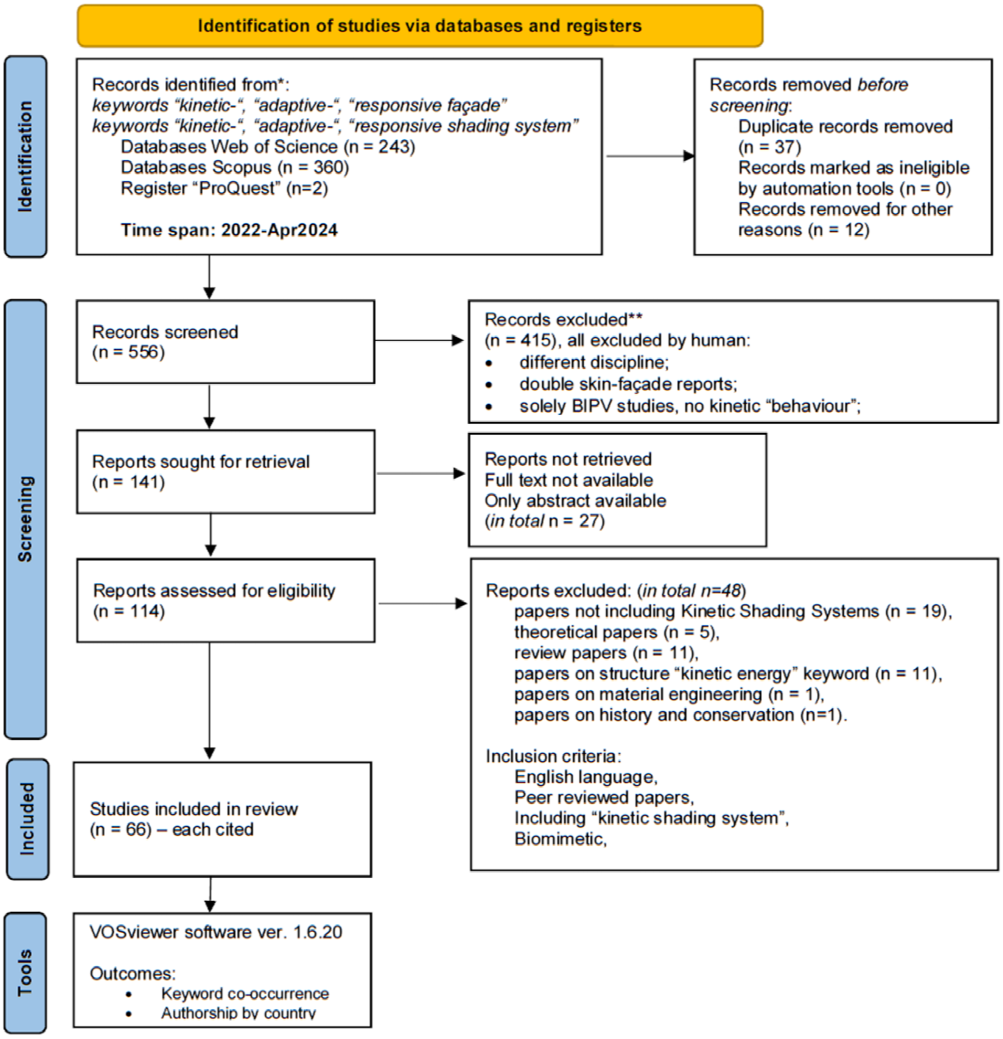


Figure 2. PRISMA flow diagram.

2.2. Meta-Analysis

Additionally, a meta-analysis was conducted based on the data from Web of Science and Scopus extracted for 2022–April 2024. The tool for the analysis was VOSviewer software ver. 1.6.20 [12], which is open-source bibliometric software. This software was used to create two maps illustrating (i) the co-occurrence network of keywords in titles and abstracts (see Figure 3) and (ii) network visualization of co-authorship by country (see Figure 4).

In Figure 3, seven clusters can be identified, with the most prominent 3 being the following:

- Kinetics/architectural design—with the following keywords: kinetics, kinetic behavior, façade design, parametric design, parametric models;
- Façade—with the following keywords: adaptive, adaptive façade, biomimetic, biomimicry, architecture;
- Kinetic façade—with keywords such as responsive architecture and fabrication.

Data extraction from the studies was based on the data given by the authors; a small spreadsheet was designed to collect and compare extracted data. The summary of individual studies is presented in tables, comparing the different results achieved by separate teams of researchers. The risk of bias due to missing results is marginal, as the results come from numerous sources in the individual papers. Statistically, 63% of papers are based on simulation and 27.7% on both simulation and experiment, while only 9.2% have been conducted solely at the experimental level.

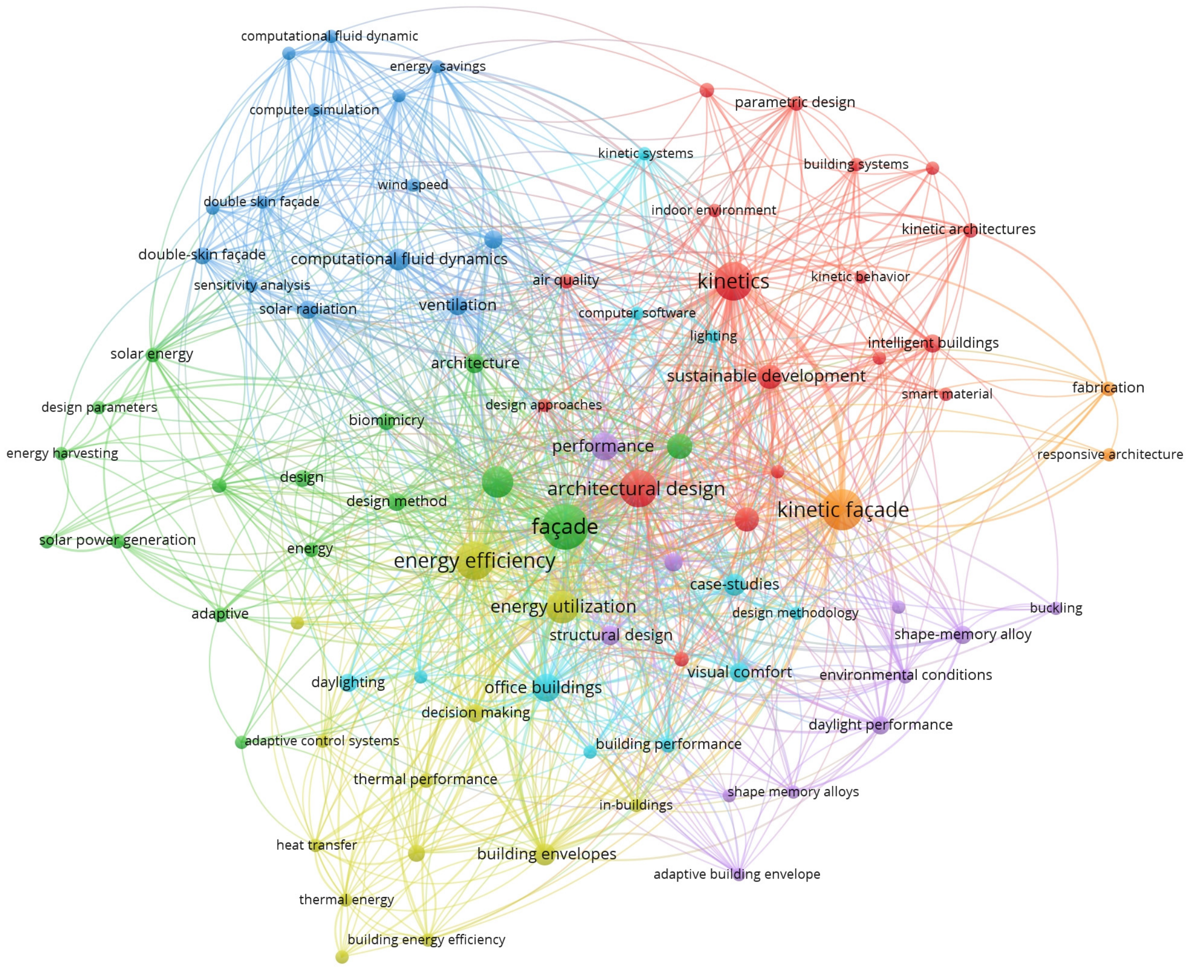


Figure 3. Network visualization of keywords and co-occurrences of data. Each circle represents a term from the titles and abstracts of analyzed papers. The size of nodes represents the frequency of occurrence, and the lines between the nodes represent the keywords' co-occurrences. Seven main clusters can be identified. Created by VOSviewer in April 2024. Different colors denote clusters.

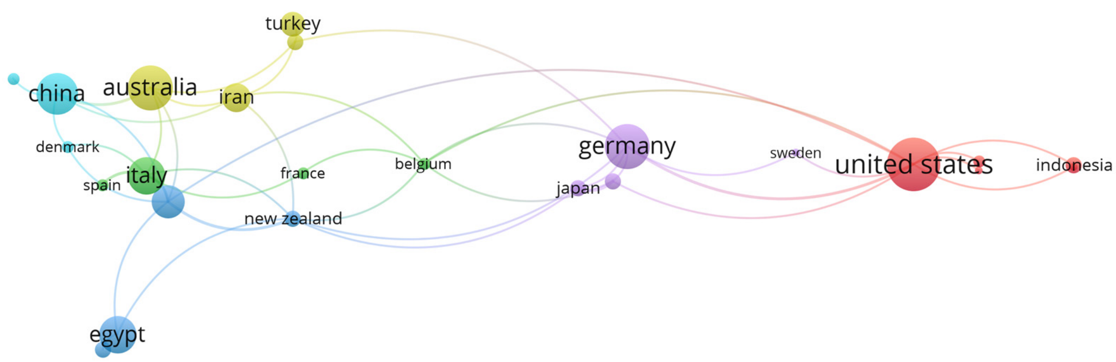


Figure 4. Network visualization of co-authorship by country. Created by VOSviewer in April 2024. Different colors denote clusters.

2.3. Used Terms and Suggested Definitions

Different authors use various terms interchangeably in the examined papers to describe identical components of KSSs. Generally, a KSS is considered an element of an "adaptive" [13,14] or "responsive" [15] façade. Based on the definitions provided above and different definitions given by the various authors, a "kinetic shading system" (KSS) is understood here to be a mechanical system designed to alter the façade's parameters in response to changes in the external environment.

2.4. Review Focus—Inspiration by Nature

A significant increase in the number of papers devoted to KSSs calls for analyzing the sources of inspiration for those systems. The papers included in this review can be divided into (i) those in which the source of inspiration is not specified (from now on referred to as "regular") and (ii) those inspired by nature (bio-inspired). The latter group is particularly interesting, as nature delivers many exciting inspirations, not only in the discipline of KSSs. The designers of KSSs analyze organisms on different levels: the morphology (the form) and physiology (the process) of living organisms according to the biomimetic methodology. Al-Obaidi et al., following Benyus [16], also differentiate a third level named "ecology", where the "form and processes of an ecosystem are duplicated." [17] in an artificial system created based on natural solutions. An exhaustive and careful consideration of biomimetics in the context of adaptive façades and KSSs is given by Faragalla et al. in the journal *Energies* [18].

A particular focus is put on the kinetics of bio-inspired KSSs. A hypothesis is formulated that bio-inspired KSSs feature much more complicated patterns of geometrical transformation.

2.5. Review Focus—Skin Motion and Deformation

KSSs use rigid or flexible elements to regulate the admission of solar radiation and, therefore, daylight and heating load. A deep understanding of the geometrical transformation is crucial in the design procedure. The mechanical principle of KSSs is usually assumed at the beginning. Further design processes (e.g., parametric optimization or multi-objective optimization) are used to determine the exact dimensions, angles, or working schedules of a KSS's elements. This is a pattern that is repeated in many analyzed papers.

The presented systematic review offers a classification of designed, tested, and most recently published KSSs (2022–April 2024) from the perspective of geometrical transformation. The geometrical transformation of KSSs includes the categories of (i) motion and (ii) deformation.

Different authors provide different definitions, but it seems all agree upon this basic differentiation. **Motion** is defined as changing the position of a rigid element in space [19]. Schumacher et al. claim it can be reduced to three basic types: "rotation, translation, or the combination of the two" [20]. Moloney provides straightforward and clear definitions: "translation describes the movement of a component in a consistent planar direction; rotation allows movement of an object around any axis" [21]. Rotation assumes a change in direction while the position remains the same, while translation is the opposite: a change in the position without a change in the orientation. Folding systems are classified as both because they feature a displacement (translation and rotation) of rigid elements. Rigid folded elements are usually hinged. In 2017, in a conference paper, Waseef and El-Mowafy, inspired by Moloney, presented an extended classification of various movements of the elements of KSSs, including sliding and folding as the subgroups of translation; one- and multi-axis rotation as a subgroup of rotation [22].

Deformation is defined as the geometrical transformation that "changes the shape of non-rigid element" [6] of a KSS. According to Schumacher et al., it includes the actions of stretching, rolling (like in a roller blind), bending/twisting, deploying [6], shearing, and fluttering of deformable elements of KSSs. This list is not exhaustive, as new types of deformation might be conceptualized, simulated, and tested. Usually, force is required to deform an object, or the object is self-deformable, like smart materials (SMA).

Moloney also includes "scaling" in the motion category, which features "expansion or contraction in size" [21], but this seems to be an oversimplification. The analysis of case studies conducted by the author shows that scaling can be achieved either by motion or by deformation. Waseef and El-Mowafy differentiate the scaling as an action based on (*i*) rotation and (*ii*) translation [22] but fail to find a precedent representing the second subgroup. In this perspective, the complicated, mechanical façade of the Institute du Monde Arabe in Paris (arch. J. Nouvel, 1989) could be categorized as featuring a motion because the change in the diameter of the KSS aperture is executed by the combination of translation and rotation of rigid elements—the aperture blades. The same result, the change in the diameter of the hexagonal aperture of a KSS, in the papers by Hosseini and Heidari [23] and Nguyen et al. [24] is executed by the deformation of flexible façade elements. The vertexes of facets surrounding the hexagonal openings are displaced in a way that necessitates these elements to be flexible rather than rigid, ensuring the system's proper functionality. Figure 5 illustrates the types of motion and deformation involved, focusing on the concept of "scaling" as depicted in Figure 6. "Scaling" refers to the adjustment of the aperture's size. It is important to note that while many authors discuss "scaling" in the context of KSSs, this term specifically refers to the transformation of the aperture itself, not the surrounding façade elements, which undergo a different type of deformation, often involving stretching to maintain the system's integrity during the scaling process. Tabasi and Banihashemi also underline this observation by noting that "a motion type like scaling (particularly in large sizes) can be only modellable via simulation since its fabrication requires a material with a very high elasticity and resistance" [6].

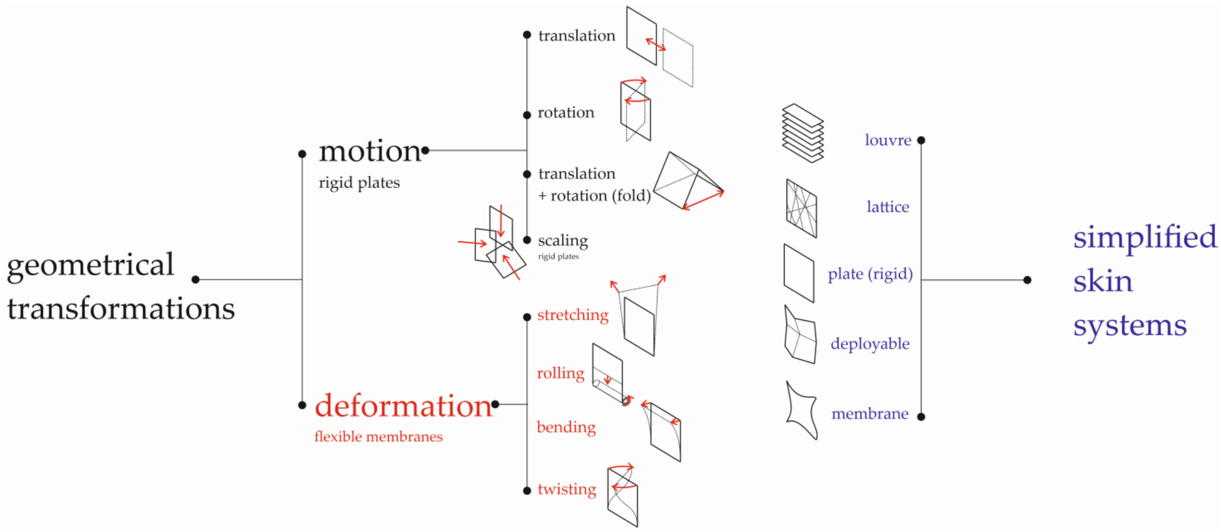


Figure 5. The simplified categorization of motion and deformation and façade skin systems. Categories of motion and deformation are pictured in colors, as well as simplified facade systems.

For the presented review, the author suggests adopting a simplified categorization of the system's skin. A more advanced categorization, including the examples and case studies, is presented in the review by Tabasi and Banihashemi [6]. The skin systems that are distinguished in the presented review are louver (slats/fins that rotate around their axis), lattice (basically a network of thin rods), plate (hinged or translated rigid panels), deployable (transformation from a compact form to stable expanded configuration), and membrane (elastic, non-rigid material undergoing deformation) systems. It might be speculated that the kirigami skin system is a subgroup of membrane systems with adequately located and sized cuts in the fabric.

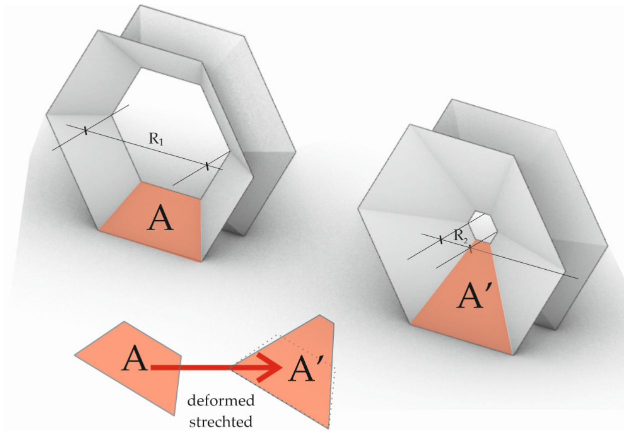


Figure 6. This figure illustrates a KSS, highlighting the distinction between the aperture's "scaling" and the deformation of surrounding façade elements. "Scaling" refers to the adjustable size of the apertures for light and air regulation—see R_1 and R_2. At the same time, the façade elements undergo deformation from A to A′, typically stretching a membrane, to accommodate the changes in aperture dimensions without compromising structural integrity. The deformed element is shown in red.

3. State of the Art: Previous Reviews

The author analyzed previous review publications on kinetic systems. As mentioned above, international databases record limited review publications on KSSs. In 2017, Al Dakheel and Tabet Aoul published a review of active shading systems. The study reviewed smart glazing, kinetic, and renewable energy systems (e.g., algae façades). The study included folding and rotating external shading systems, describing individual applications. Special attention was dedicated to the control strategies: user-controlled or automatic using a variety of sensors and complicated control algorithms.

The study also listed challenges, limitations, and future opportunities in active shading systems [10]. In 2019, the team of Hosseini et al. provided an extensive morphological analysis of kinetic façade systems designed to improve visual and thermal comfort. The study provided an overview of 11 types of research trends and analyzed 10 existing kinetic façades. Biomimicry approaches and parametric tools were also discussed. The authors concluded by presenting a "theoretical framework for developing a morphological approach" [25]. Luo et al. extensively reviewed the active building envelope (ABE) systems. According to the definitions, an ABE requires additional "energy input to improve building performance" [26]. The authors analyzed air-, water-, and solid-based ABEs, including kinetic active building envelopes.

From the beginning of 2022 (in the review period), the number of review papers increased considerably. Matin and Eydgahi analyze technologies used in responsive façade systems based on 29 case studies [27]. Shafaghat and Keyvanfar have provided a survey that comprehensively investigated and identified dynamic façade typologies, technologies, and techniques covering opaque, transparent, and semi-transparent solutions, concluding that "research on dynamic façades has focused on automated systems, user-oriented control systems, and user-oriented system decision making" [28]. Zhang et al. review designs, performance evaluation, and control systems, concluding that two main design trends are visible in adaptive façades: "artificial technology and natural ecology" [29].

In 2022, Tabasi and Banihashemi spotted a research gap and presented a systematic literature review of responsive skins integrated with their geometric and mechanism design approaches [6]. This research directly inspired the author of the presented review. El-Dabaa and Abdelmohsen have analyzed the possibilities of utilizing shape-shifting materials, looking for the inspiration in hygroscopic properties of wood and the use of hygromorphic behavior of materials in developing adaptive architectural façades [30].

In 2023, Voigt et al. analyzed the integrated design process of adaptive façades, finding two main gaps—"the consideration of the lifecycle and the interfaces between the tasks of the stakeholders involved in the lifecycle" [31]. A framework for the integrated design process of adaptive façades on a lifecycle basis is presented and serves as a basis for further research on this topic. In a following publication, Voigt et al. announce the creation of a database of adaptive façades [32]. Alsaedi et al. present a review of adaptive façade technologies in residential buildings. The authors present a matrix table of 8033 studies on adaptive façades, concluding that most studies are dedicated to KSSs and solar shading (almost 52% of the studies are committed to energy performance) [33].

Narbust and Vanaga have provided a brief overview of construction technologies for low-emission buildings, addressing phase change materials, smart windows, and adaptable façades [34]. The team of Khraisat et al. conducted a systematic review of 24 studies on kinetic façade technologies, drawing conclusions about static and kinetic shading and identifying critical parameters for adaptive façade efficiency. The authors have also provided a PRISMA diagram [35]. A study by Sommese et al., which was released at the end of 2023, offers a bibliometric analysis and systematic review of biomimetic building envelopes and focuses on the creation of "parallels between the movements of plants in response to environmental triggers and the kinetic movements provided by smart materials" [36]. The study concentrated on material technologies featuring thermo-bimetals, shape memory alloys, responsive polymers, and photochromics. In the most recent study, Vazquez et al.'s team reviewed the taxonomy of elastic kinetic building envelopes. The authors analyze 13 case studies of elastic kinetic mechanisms, drawing the correlation pattern between elastic mechanisms and actuation type [9]. See Table 1.

Table 1. The previous review studies on kinetic façades.

No.	Ref.	Team	Year	Focus	No. of Papers
1	[10]	Dakheel and Aoul	2017	active shading systems	165
2	[25]	Hosseini et al.	2019	extensive morphological analysis of kinetic façade systems	10 case studies, 22
3	[26]	Luo et al.	2019	comprehensive review of the state-of-the-art research on ABEs for improving building energy efficiency	140
4	[27]	Matin and Eydgahi	2022	comparative study of technologies used in responsive façade systems	29 case studies
5	[28]	Shafaghat et al.	2022	dynamic façade typologies, technologies, and techniques	172
6	[20]	Zhang et al.	2022	designs, performance evaluation, and control systems	n.a.
7	[6]	Tabasi and Banihashemi	2022	design and mechanism of building responsive skins	89
8	[30]	El-Dabaa Abdelmohsen	2023	shape-shifting materials based on hygroscopic properties	41
9	[31]	Voigt et al.	2023	the integrated design process of adaptive façades	300
10	[33]	Alsaedi et al.	2023	adaptive façades for residential buildings	8033
11	[34]	Narbust and Vanaga	2023	overview of construction technologies for low-emission buildings	19
12	[35]	Khraisat et al.	2023	a systematic review of studies on kinetic façade technologies	24
13	[35]	Sommese et al.	2023	a bibliometric analysis and systematic review of biomimetic building envelopes, trends, and applications	152
14	[9]	Vazquez et al.	2024	the taxonomy of elastic kinetic building envelopes	(35)/13 case studies

Also, studies that are not directly provided as reviews are included. Koyaz et al. have given an overview of user experiences resulting from the interaction with adaptive façades. The authors have identified the factors affecting the user experience in a working environment [37]. Jalali et al. provide a theoretical framework for the design of plant-inspired adaptive façades. Data synthesis and classification were presented to support the potential integration of three photovoltaic (PV) technologies with plant-inspired building envelope design [38]. Nie et al. have employed a white-box method to analyze adaptive façades. White-box machine learning refers to an approach in which models are designed with transparency and explainability in mind and are easily accessible by architects and façade designers [39].

4. Results

Given the focus of this review on inspirations from nature in façade design, the remaining results are divided into two distinct subgroups of reports published in the analyzed timeframe. The first subgroup examines "regular" KSSs that utilize mechanical elements to modulate the building's interaction with its external environment. The second subgroup is solely dedicated to bio-inspired systems, where the authors have drawn from nature to create biomimetic systems.

The linear presentation in the presented review will progress from the most straightforward rotation-based louver systems through those employing translation (folding) and, finally, to the most intricate systems characterized by complex movement patterns and deformations. Each presented subgroup of reports will be concluded with a table describing the system parameters. The same structure is also applied to nature-inspired systems: the most straightforward solutions first, the most complicated later. This data presentation pattern is inspired by the review provided by Al Dakheel and Aoul [10] in the journal *Energies* in 2017, who present active shading systems based on the principle of increasing system complexity. This approach facilitates a structured presentation of the diverse reports. For each article reviewed, detailed information is provided, including the movement/deformation type, climate zone, building type, and the specific parameters used to assess the system's efficiency. The KSS efficiency improvement, denoted as Δ_p is calculated according to formula (1):

$$\Delta_p = \left(\frac{|m_{KSS} - m_b|}{m_b} \right) \times 100[\%] \quad (1)$$

where m_b is the metric's value in the baseline scenario and m_{KSS} is the metric's value after applying KSSs. An Excel sheet containing all the data is available in the Supplementary Materials.

Different authors use different metrics: some systems are evaluated in daylight metrics (sDA—spatial daylight autonomy, ASE— annual solar exposure, DGP—daylight glare probability), while others are assessed in the context of cooling load or energy used for artificial lighting. A baseline scenario is not always given, which makes the judgment of the system's effectiveness impossible. The diagrams of the KSSs are pictured in Figure 7.

4.1. Regular KSSs

Regular systems include KSSs that are not inspired by nature, or at least those for which the authors did not refer to inspiration from nature.

4.1.1. Motion: Rotation; Skin System: Louver

The simplest form of a KSS is a vertical or horizontal louver system based on the rotation of slats (individual or in groups). Frequently, authors analyze off-the-shelf systems [40] or use the default setting in parametric software (e.g., the "HB Louvre Shade" component in Honeybee). In 2023, Sharma and Kaushik evaluated a KSS that used vertical and horizontal louvers to improve visual comfort [41]. When the shading system was implemented, the findings indicated an enhancement in all measured daylight metrics, including DGP. Catto Luchino and Goia used a horizontal louver system to analyze double-skin façades in the context of the definition of control strategy [42]. A similar horizontal louver system with variable slat widths was analyzed in 2022 by Mangkuto et al. in tropical climates in the context of LEED v 4.1 requirements [43]. The authors have determined the optimal number and angle of shading slats. In a brief study from 2023, Hassooni and Kamoona analyzed a horizontal louver system installed in a patient's room in a hospital in Najaf, Iraq, with 50 cm deep louvers rotated at different angles, which resulted in a reduction in radiation exposure levels [44]. Shen and Han, in 2022, analyzed two types of modular KSSs. The system was divided into 45 modules of 0.7×0.7 m and was located in the front of the glazing of an office room in the city of Harbin in China. The fist type of KSS was a conventional horizontal louver shading system based on the rotation movement. The second type was named "blind" by the authors and was based on the deformation of a triangular shading element with the control point sliding on the diagonal of the module. The system was evaluated in 11 states from the perspective of daylight and glare (41% UDI improvement over the baseline scenario). The modular control strategy showed a 15% improvement over the uniform control of KSS modules [45]. De Bem et al. presented a low-cost responsive shading system prototype based on the "movable brise-solei", which is practically constructed as a KSS with horizontal slats (horizontal louver system). The KSS evaluation is provided in the context of thermal and illuminance management in a Bioclimatic Building Chamber in Curitiba, Brazil. With the responsive scenario, $UDI_{100\text{-}2000}$ is improved from 26 to 82% [46]. A louver-based study was also performed by Fikery et al., but the authors added a light shelf to increase the efficiency of the KSS. In the simulation, a tilt angle of the horizontal louver system was optimized against LEED v.4.1 requirements: "the best solutions were horizontal panels and horizontal with vertical panels combined" [47]. Chaturvedi et al. have analyzed a horizontal louver system, including external horizontal shades in a semi-arid composite climate. The optimized results reported a "six-fold Useful Daylight Illuminance (UDI) improvement, 72% cooling energy demand reduction, and 34% thermal comfort enhancement" in comparison to the baseline scenario [48].

More advanced horizontal louvers made of electrochromic modules that adjust their transmittance were analyzed by the team led by Kim et al. at Chonnam National University. The system works like a standard horizontal louver when the louvers are open, and the electrochromic elements are set to low transmittance. The study also examined configurations that mimic a double-skin façade, with the central louvers closed to facilitate a stack effect while the top and bottom louvers remained open. The findings indicated that setting the transmittance to 40–45% allowed the system to meet the LEED v4.1 daylight option criteria [49]. In the advanced study by Norouziasas et al., a new standard, ISO/DIS 52016-3, for the simulation of adaptive façades is evaluated based on the four skin systems: (S1) without any shading; (S2) with fixed horizontal shading; (S3) dynamic roller blinds and (S4) dynamic Venetian blinds, both controlled according to ISO/DIS 52016-3 algorithm (in the range of slat angles from 0 to 90°). Surprisingly, fixed shading (S2) performed better than dynamic Venetian blinds [50]. The system of horizontal louvers fixed to an existing structure covered with a PV system was analyzed by Choi for three buildings: (i) the Signal Box in Basel, designed by Herzog de Meuron in 1999; (ii) Won-Hyo Elementary School in Seoul; and (iii) Cho-Rang Elementary in Busan. Choi analyzed energy generation and concluded that the kinetic photovoltaic façade system significantly improved the energy self-sufficiency of the buildings [51,52]. Ożadowicz and Walczyk provide an experimental study of a KSS installed in Poland, protecting a three-story façade. As in the previous case, the system features horizontal louvers covered with a perovskite PV installation. The louvers are optimized to track the Sun to maximize energy production yield. The paper analyzes different control strategies for the presented KSS [40].

The team of Valitabar et al. presents the unique solution of a horizontal louver system: the proposed MLBS (Multi-Layer Blind System) consists of three separated slats, which can rotate around a horizontal axis. In addition to tilt angle changes, the "middle slat named "View slat" can move forward or backwards, independently, to control glare" [53]. This solution combines rotation and translation of rigid shading elements. The MLBS improved daylight performance and outside view by "44% and 47% respectively, while DGP and DGI remained under the desirable range" [53].

Vertical shading louvers are less frequent in the analyzed group of reports. The abovementioned vertical and horizontal louvers are used by Sharma and Kaushik [41]. Fahmy et al.'s team introduced the Integrated Kinetic Fin (IKF) system, which consists of vertical rotating louvers suitable for areas with clear skies and low solar altitudes. These fins can adjust their angles in response to the Sun's movement [54]. Marques and Boydens also used vertical rotating louvers and parametrically defined the optimal solution in a brief study in 2022 [55]. A similar geometry and motion type were used in the most recent study by Brzezicki, who studied a KSS in the form of eight rotating vertical louvers in two groups, shading a standard office room in Wroclaw, Poland (Cfb). A simulation study was followed by an experiment [56]. A prototype was built and tested in real-world conditions for three clear days in November 2023, using Testo THL 160 data loggers. The collected data were verified against the measurements in the local meteorological station [57]. The measurements showed poor performance of the system in terms of qualitative metrics, with illuminance values as high as 15–18 Klux at the level of the work plane.

4.1.2. Motion: Rotation; Skin System: Lattice

Fardous reports a KSS developed during student design workshops at Prince Sultan University in Saudi Arabia [58]. The KSS was inspired by Islamic geometry, a shape that "contains repetitive squares and circles". The system comprises solid wood and lattice diamond panels in mechanized groups rotating around vertical axes. No performance evaluation was provided in the paper.

4.1.3. Motion: Rotation; Skin System: Plate

Biloria et al. analyzed a KSS combined with BIPV, based on the individual rotation (pivoting) of 72 square panels on the horizontal and vertical axes, with a freedom of movement of 180°. The authors used the multi-objective optimization algorithm that produced results in the form of a Pareto front. The focus was on maximizing the irradiance value on the BIPV panels while minimizing internal illuminance values above 3000 lux. As a result, "an average daily of 56.94% difference in the minimum threshold level of illuminance is observed" [59]. Globa et al. analyzed a KSS in the form of a spatial hexagonal panel that was vertically rotated. The team produced a full-scale prototype and provided a Life Cycle Assessment (LCA). This paper is notable for its in-depth exploration of the kinetic façade's manufacturing stage, illustrating a sophisticated approach [60].

Rotation of the façade panels is also possible on a non-orthogonal axis. Sadegh et al. provide a Multi-Objective Evolutionary Algorithm (MOEA) analysis of the triangular grid-based KSS, which featured triangular panels that "can rotate from zero degrees to 90° outwards from the façade" [61]. The simulation assumed the southern exposure of the façade on the ground floor in Tehran, Iran. The authors provided the ten most efficient solutions represented by the parameters: an increase of 136.7% was simulated for UDI (21.2% to 50.2%). A very similar KSS was proposed by Golzan et al., who also use a rhomboid grid and triangular rigid panels that rotate outwards in three positions at the angles of 30, 60, and 90°. The performance of the KSS was evaluated in terms of daylight and energy consumption. A decrease of 41.32% in annual energy consumption was recorded for the angle of 30° [62]. Also, Kızılörenli and Maden tested a similar system based on a triangular grid in 2023, but the origins of the geometry originally came from tessellation patterns. The triangular rigid panels are tested at different rotation angles, resulting in a UDI increase of 51.9% with an angle of 50° [63].

In 2023, Takhmasib et al. presented the first on-site investigation of an artificial intelligence-integrated three-dimensional movable KSS. The test façade comprises replicative hexagonal transparent modules at a full scale of 1:1, installed in a mockup room of 2 × 2 × 3 m in South Korea climatic conditions. Each module has a "tripodal frame to which six pieces of triangular skin panels" are attached by a servo mechanism, allowing for the rotation of individual façade panels, ranging from 0° to 60°, to the outside. The results indicate that the proposed KF system offers desirable visual comfort, and the study demonstrated the feasibility of AI-based predictive and quickly adaptive KF control in full-scale operation [64]. Kim et al., from Sejong University, have presented three KSS panels, of which the most interesting is a "multi-direction panel, which was based on the rotation of rigid triangular plates". The dynamic multi-directional and horizontal shading systems perform much better than dynamic vertical ones in "providing beneficial daylight and reducing the percentage of under-lit and over-lit spaces" [65].

El-Mowafy et al. conducted a comprehensive daylighting study on 18 different kinetic façade types, employing a machine learning algorithm to identify the most effective designs. The selection process utilized the k-nearest neighbor (KNN) algorithm to narrow the choices. The detailed results are presented in [66]. See detailed results in Table 2.

Table 2. Kinetic systems based on the mechanical principle of motion (rotation/translation).

Ref. No.	Year	Research Type [1]	Building Type	Climate	Evaluation [2]	Metric [Unit]	m_b	m_{KSS}	Δ_p
[41]	2023	S	office	Cwa	DL	ASE [%]	25.0	21.0	16.0%
[42]	2023	S	office	Cfb	E	Q [kWh]	143.0	69.0	51.7%
[43]	2022	S	office	Aw	DL	ASE [%]	39.8	21.1	47.0%
[44]	2023	S	hospital	Bwh	E	Q [kWh]	n.a.	n.a.	75.0% *
[45]	2022	S	office	Dwa	DL	UDI [%]	50.0	71.0	42.0%
[46]	2024	S/Ex	office	Cfb	DL	UDI [%]	26.0	82.0	215.4%
[47]	2024	S	office	BWh	DL/E	UDI [%]	56.2	94.8	68.6%
[48]	2024	S/Ex	residential	BSh	DL/E	UDI [%]	11.4	81.2	610.5%
[49]	2022	S	office	Cfa	DL	VLT [%]	25.0	45.0	80.0%
[50]	2023	S/Ex	office	Cfb	E	Q [kWh]	16.3	5.9	63.7%
[51]	2023	S	office	Cfb	E	E_{gen} [kWh]	n.a.	304,566.0	n.a.
[52]	2022	S	education	Dwa	E	E_{gen} [kWh]	5.663×10^6	1.0143×10^7	79.1%
[40]	2023	Ex	office	Cfb	DL	E_v	100,370.0	1197.2	98.8%
[53]	2022	S	office	Bsk	DL	UDI [%]	n.a	n.a	44–47% *
[54]	2023	S	office	BWh	DL	C [unitless]	1000.0	780.0	22.0%
[56]	2024	S/Ex	office	Cfb	DL	UDI [%]	44.0	77.4	76.0%
[59]	2023	S	office	Cfa	DL	E_h [lux]	n.a	n.a.	56.9% *
[60]	2022	Ex	n.a.	n.a.	n.a.	GWP [kgCO_2]	119.7	91.1	23.9%
[61]	2022	S	office	Bsk	DL	UDI [%]	21.2	50.2	136.7%
[62]	2022	S	office	BWh	DL/E	Q [kWh]	195.5	115.0	41.2%
[63]	2023	S	office	Csa	DL	UDI [%]	52.9	80.4	51.9%
[64]	2023	Ex	office	DWa	DL	DGP [%]	34.0	21.0	38.2%
[65]	2024	S	office	DWa	DL	UDI [%]	55.0	95.0	72.7%
[66]	2022	S	office	BWh	DL	UDI [%]	79.0	99.0	25.3%

[1] S—simulation, Ex—experiment; [2] DL—daylight, E—energy; m_b—metric value at baseline scenario, m_{KSS}—metric value after the application of KSS, $\boldsymbol{\Delta_p}$—performance improvement, ASE—annual solar exposure, Q—thermal load, UDI—useful daylight illuminance, VLT—visible light transmittance, E_{gen}—electricity generated, E_v—vertical eye illuminance, DGP—daylight glare probability, C—contrast, E_h—horizontal illuminance, GWP—global warming potential, *—performance declared by the authors.

4.1.4. Motion: Translation; Skin System: Lattice

Böke et al. have compared the passive and adaptive strategies of two KSSs called ADAPTEX mesh and ADAPTEX wave [67]. The first is based on the translation of two rigid, dense meshes that slide in relation to each other. The SMA actuator causes the motion. The second one is based on the geometrical deformation of wave-shaped textile bands. Both proposals were tested as 1:1 scale demonstrators. No simulation or experimental results were presented.

4.1.5. Motion: Translation; Skin System: Plate

According to the previously cited references, folding is a case of combined “translation” and “rotation”. The mechanics of kinetic folding actions present a complex challenge, requiring the coordination of overlapping planes and guiding profiles. Commonly implemented solutions range from bi-folding surfaces to more complicated geometries inspired by the traditional art of origami paper folding, introducing a higher level of complexity and aesthetic appeal.

In 2023, Taleb and Moarbes conducted a simulation study on a bi-folding KSS, which was theoretically applied to existing buildings in the UAE. The study concluded that the KSS contributed to a 12% reduction in energy consumption in the East zone and suggested that the total annual cooling energy savings across three zones “could reach up to 21.3%” [68]. Salah and Kayili analyzed a KSS featuring bi-folded panels, drawing inspiration from the Kiefer showroom in Austria. They hypothesized that both Horizontal Kinetic Folded Panels (HKFPs) and Vertical Kinetic Folded Panels (VKFPs) were installed on the south-facing façade of the Karabük Governorship building in Turkey. The results show that the HKFP system reduced cooling loads by 11.52%, with the most significant reduction of 19.84% occurring on 15 June [69]. Chuan et al.’s team studied a kinetic façade that takes geometrical inspiration from Malaysian Siamese cultural, religious, and craft patterns. These intricate patterns were applied to bi-folded shades (both vertical and horizontal) on a wall with dimensions of 5.3 × 6.0 m and a window-to-wall ratio of 70%. However, while deeply influenced by tradition, the research lacked a compelling rationale for selecting these specific patterns and did not thoroughly compare their effectiveness to traditional shutters [70]. Toodekharman et al. presented a study of four kinetic bi-folding shading systems in Tehran hospital rooms. The patterns of the KSS are adopted based on the existing ones (e.g., Kiefer technical showroom). The authors claim that lowering the wall-to-window ratio is ineffective in reducing glare and conclude that “responsive façade (. . .) can also bring undesirable results. (. . .) Reflection caused by façade panels or shading may create glare and disturb the occupant’s comfort” [71]. Wu has presented an energy performance analysis of folding/sliding kinetic façades in 16 climate zones in the USA. The author has performed an analysis of two types of façades: (*i*) bi-folding (as in the Kiefer showroom) and (*ii*) sliding, in which every other panel moves towards the center of the glazing. The façades were parametrically modeled with different numbers of panels and different opening ratios. The most interesting result comes from the analysis of the closing schedules in Phoenix, which shows that “the façade is mostly closed during work hours for more than half of the year” [72], which means that occupants have to sacrifice the view for cooling energy reduction. A similar system of vertically bi-folded panels was used by Badeche and simulated in the climatic conditions of Alegria [73]. The full-height panels are made of PVC and operationally react to the Sun’s position. The evaluated period was the hottest month of the year, July, for the East façade [73]. The KSS reduced the exposure to direct radiation by 31% (from 973 to 670 kWh). Akimov et al. presented a new kinetic device based on Klemen’s Torggler Door, a type of folding element movement. The authors describe the system as follows: “the shading consists of four triangular elements: two on the top and bottom that move only in-plane (rotation) and two in the centre, connected by a spherical joint, that move out-of-plane” [74] The motion of the shading element creates gaps, through which the light can enter the room. The final dynamic façade configuration “showed an improvement of 43% following the annual daylighting analysis of 25%, 50% and 75% degrees of opening” [74].

4.1.6. Motion: Translation; Skin System: Deployable

The more complicated folding typologies include the origami folding typologies, assuming the more complicated hinged panel geometries. Kahramanoglu and Alp presented a KSS employing the Miura-ori origami technique, with a module including four pleated folding “wings” fixed in the center point. The authors state that “the average DA value increased from 51.7% to 69.73%” and “UDI increased from 61% to 80.75%” in the proposed origami KS compared to the base case [75]. A similar system composed of a smaller number of panels was presented by Meloni et al., who analyzed the origami-based Miura-ori unit as an element of a KSS. The module is a rectangular nine-vertex element, divided into four equal parts, with three mountain folds and one valley fold (plate/hinge system). The aspect is folded (deployed), and the dihedral angle β varies. The best (safe) results are achieved with the β angle = 10–40°. One of the analyzed options allows for the irradiance reduction of 56% [76]. In 2023, da Silva and Veras provided an analysis of the shading performance of the system, which is composed of folding shading quad-shape umbrellas. This Sun vector activates the kinetic device deployment by "considering the threshold angle of 30, 45 and 60°" [77]. Next, hourly Sun exposure of the building's envelope is calculated. Following this, the authors provide the results for an entire year, studying the number of activated devices (in %) in different surface orientations regarding the abovementioned thresholds.

Another geometric category of KSSs includes those designed to regulate the opening of the aperture through which daylight is transmitted into the building through scaling operations. Scaling can be achieved with rigid elements' motion and flexible elements' deformation. Both options are included below.

4.1.7. Motion: Scaling, Skin Type: Plate

Wagiri et al. conducted a simulation study on a KSS that employs a scaling principle to create apertures of varying sizes in response to environmental conditions. The hexagonal KSS module comprises two rigid frames with rigid flaps attached to each. These flaps, folded in half, slide into one another due to their precise shapes and cuts, regulating the opening of the aperture. In conclusion, the study determined a distribution percentage for modules with varying aperture ratios, with the predominant 0.7 aperture ratio covering 75.6% of the façade's surface [78].

The study of Wagiri et al. is the last regular system that used rigid element motion in the proposal of a KSS. It must be explicitly stated that the remaining part of the sub-chapter is dedicated to the systems that were parametrically defined but classified in the deformation category. The results are presented in Table 3.

Table 3. Kinetic systems are based on the mechanical principle of folding rigid elements.

Ref. No.	Year	Research Type [1]	Building Type	Climate	Evaluation [2]	Metric [unit]	m_b	m_{KSS}	Δ_p
[67]	2022	Ex	office	Bwh	DL	OF [%]	63.0	39.0	38.1%
[68]	2023	S	office	BWh	DL	$UDI_{>2000}$ [%]	n.a.	n.a.	21.3% *
[69]	2022	S	office	Bsk	E	Q_s [kWh]	17,723.0	15,681.0	11.5%
[70]	2023	S	n.a.	Aw	DL	DF [%]	2.2	48.2	2051.3%
[71]	2023	S	hospital	BSh	DL	ASE [%]	49.0	8.0	83.7%
[72]	2022	S	office	Aw-Dfb	E	Q [kWh]	n.a.	n.a.	32–56% *
[73]	2022	S	office	Csa	E	Q_s [kWh]	973.0	670.0	31.1%
[74]	2023	S	office	Csa	DL	UDI [%]	n.a.	n.a.	43.0% *
[75]	2023	S	office	Cfa	DL	UDI [%]	61.0	81.0	32.8%
[76]	2023	S	office	Cfb	E	I_e [W/m^{-2}]	n.a.	n.a.	56.0% *
[77]	2023	S/Ex	office	Aw	DL	[%]	95.0	25.0	73.7%
[78]	2024	S/Ex	office	Cfa	DL	I_e [W/m^{-2}]	n.a.	n.a.	76.0% *

[1] S—simulation, Ex—experiment; [2] DL—daylight, E—energy; m_b—metric value at baseline scenario, m_{KSS}—metric value after the application of KSS, Δ_p—performance improvement, OF—openness factor, $UDI_{>2000}$—useful daylight illuminance exceeded, Q_s—solar heat gain, DF—daylight factor, ASE—annual solar exposure, Q—thermal load, UDI—useful daylight illuminance, I_e—irradiance, SDA—proportion of shading device activated, *—performance declared by the authors.

4.1.8. Deformation: Rolling; Skin Type: Membrane

The roller blind is the simplest deformation-based shading system. It is widely used and can be easily optimized from the perspective of fabric properties and the extension (the amount of the fabric that has been unrolled to shade the façade).

Le et al. analyzed a simple KSS that features full-room-height roller blinds installed on the south façade of an office building. Five fabric types and locations were studied (CHMC, Guangzhou, Jeju, Berlin, Denver, Montreal) and parametrically optimized. In total, 7680 KSS options were generated and analyzed. As a result, optimal KSS use can reduce energy use by 36–53% [79]. Alkhatib et al.'s team also used the roller blind in an experimental study conducted in Dublin. The performance of the roller blind is compared with electrochromic glazing. Seven different control algorithms were applied to simulations of both operations of the blind and the switchable glazing. As a result, using the roller blind, depending on the control algorithm, allowed for 7% and 35% energy savings compared to a double-glazed window [80]. It also has to be mentioned here that a roller blind was also used in the comparative study by Norouziasas et al. [50] (see above Section 4.1.1).

4.1.9. Deformation: Stretching; Skin Type: Membrane

Ningsih et al. experimented with hexagonal KSSs. Each module of the façade consisted of a central body, a set of arms, forearms, and two membranes. When the shading module is activated and the arms extend, the *membranes are stretched* from the body to the arms, creating shade. From the mechanical perspective, the motion of the arms of the KSS device could be classified as rotation, but the membrane attached to the arms is stretched. The study found that when the module is in an un-deployed state, it can reduce incoming solar radiation by 60% compared to a scenario without the kinetic façade. When the module is deployed, the KSS achieves an additional 50% reduction [81]. A similar quadrangle deformation principle is used in the system suggested by Abdollahi Rizi et al., who have developed a KSS identical to the system analyzed by Hosseini et al. [23] in 2019. Following this principle, Hays et al. (2024) used the quadrangle deformation principle to create elephant skin-inspired bumps rising from the Voronoi cells in a self-shading system [82]. The KSS protecting the south façade of the office space is divided into 25 rectangular modules (5×5 matrix); each module has a pyramid-like shape with a rectangular opening. The module's depth, opening size, and horizontal and vertical movement are defined parametrically. The quadrangles constituting the walls of the KSS module are deformed (two vertexes are freely changing their position in space) and cannot maintain rigid geometry. The optimization brings a 69-percentage-point improvement in daylight performance [83].

Another distinguished group is that of regular KSSs in which the radius of an aperture allowing daylight into the room is regulated. This regulation could be achieved with the translation and rotation of rigid elements (e.g., aperture blades like the case of Wagiri). Still, it can also be achieved by the deformation of non-rigid elements constituting the KSS module. In this category, Alawaysheh et al. analyzed the "Dubai Frame" building and proposed an additional kinetic façade that integrates with the existing structure without altering its architectural integrity. The suggested KSS comprises various geometrically shaped shading elements that, from the perspective of geometry, could be reduced down to flat triangles, with at least one vertex changing position. As a result, no rigid plates could be used in the KSS, and the triangles constituting the KSS module are *deformed* and could be manufactured only from the flexible membrane [84]. Alawaysheh et al. have simulated the KSS and found that it could lead to a 20% energy saving and a 31% decrease in daylight illuminance levels.

Similarly, Nguyen et al. analyzed a hexagon-based KSS installed on the northeast façade of the HOB building in Ho Chi Min City in Vietnam, in which the aperture of the shading module changes according to the Sun path. With this change, six internal vertexes change their position, and the trapezoidal facets of the module are deformed (no rigid plates could be used). The final geometry of the shading system provides an ASE reduction of 10% and sDA improvement of 50% [24]. A geometrically similar KSS is used by Tabadkani et al.

The analyzed office façade has 12 modules of 1.0 × 1.0 m in a 4 × 3 matrix. Each module of the KSS is based on a hexagonal grid with six structural rings, on which "deployable shell panels can be formed of flexible materials such as natural rubber or highly flexible polyurethane" [85]. The vertexes of "shell panels" are displaced in the space along the circular paths (rings), forming the different types of apertures, allowing daylight into the building in the center of the module or at its periphery. The same geometry is used to study the various control algorithms [86]. The KSS proposal is subject to the US20180216399A1 patent "Transformable shading system" [87]. The study features four states of the KSS opening and two occupants in March, July, September, and December. In generalized results, authors claim that occupants 1 and 2 are "satisfied by 92.5% and 95.5% on average".

Also, a similar aperture regulating system was studied by Senel et al., who used a system based on the reciprocal frame principle. The rigid elements were interconnected and interlocked, and 'single freedom sliding joints' were used to change the internal aperture size. Regardless of the rigid frame of the KSS, the "shading" action could only be performed by stretching the membrane between the members of the rigid frame and the perimeter ring. The authors suggest attaching "flexible fabric", which is "stretched and relaxed", with the change in the aperture size.

The study concludes that the hexagonal module performs best, offering the most uniform daylight mitigation [88]. Liu et al. propose a novel geometrical method to shade a cylinder-shaped library using a new KSS. The system is designed as a "ring" positioned at the front of the façade. This ring is triangulated, and the triangles form a complete skin system through repeated arrays in both vertical and horizontal directions. Each triangle features a smaller triangular opening, independently regulated by the displacement of points A, B, and C [89].

The deformed membrane of a KSS is also suggested by Arauz et al., who take inspiration from the Japanese art of cutting paper: kirigami. Multiple kirigami patterns are discussed, but a basic straight-cut design is finally selected. The flexible fabric sheet is cut horizontally, with a series of short cuts that pass each other every second row. The final geometry of the KSS was achieved by the "deformation in the planar direction (stretching) perpendicular to the cut direction" [90]. The resulting geometry remained expanded metal. The system's effectiveness was evaluated in the location of Pittsburg (USA) on the 15th of April from 3 PM to 4 PM. All the results are presented in Table 4.

Table 4. Kinetic systems based on the mechanical principle of deformation (including aperture scaling).

Ref. No.	Year	Research Type [1]	Building Type	Climate	Evaluation [2]	Metric [Unit]	m_b	m_{KSS}	Δ_p
[79]	2022	S	office	Aw, Cwa, Cfa, Cfb, Bsk, Dfb	DL	Q [kWh]	n.a.	n.a.	36–53% *
[80]	2023	Ex	office	n.a.	E/DL	Q [kWh]	1623.0	1062.0	7–35% *
[81]	2023	S/Ex	residential	Am	E/DL	I_e [W/m^{-2}]	2.4	1.2	50.0%
[83]	2023	S	office	Bsk	DL	UDI [%]	28.0	91.6	227.6%
[84]	2023	S/Ex	exposition	BWh	E	E_h [lux]	n.a.	n.a.	31.0% *
[24]	2023	S	office	n.a.	DL	sDA [%]	n.a.	n.a.	92.5–95.5% *
[87]	2023	S	office	Cfb	DL	CS [%]	n.a.	n.a.	50.0% *
[88]	2022	S	office	Bsk	DL	ASE [%]	33.3	18.0	45.9%
[89]	2023	S	library	Cwa	DL	DGP [%]	32.0	22.0	31.3%
[90]	2023	S/Ex	office	Dfa	E/DL	I_e [W/m^{-2}]	440.0	510.0	15.9%

[1] S—simulation, Ex—experiment; [2] DL—daylight, E—energy; m_b—metric value at baseline scenario, m_{KSS}—metric value after the application of KSS, Δ_p—performance improvement, UDI—useful daylight illuminance, Q—thermal load, I_e—irradiance, ASE—annual solar exposure, DGP—daylight glare probability, *—performance declared by the authors.

4.2. Bio-Inspired KSSs

Twenty-two percent of recently reported KSSs come from natural inspiration within the frame of a new science discipline: biomimetics (out of 66 in total). Biomimetics is the "imitation of biological processes or models from nature aiming to solve various complex technical problems" [91]. This approach is characterized by three phases: Scoping, Research, and Implementation. The authors draw parallels between natural processes and technical systems in their research. Initially, they observe a specific phenomenon, such as room overheating or visual discomfort. Then, they study biological responses to certain stimuli, like sunlight, focusing on mechanisms that trigger movement in plant parts, including petals, leaves, and stems. This leads to an abstract representation, where they extract and articulate the underlying natural principle in technical terms. Finally, a model based on this principle is constructed and could be assessed through simulations or experimental methods. Sommesse et al. address this issue: "the third phase is about the abstraction of the biological principles and the corresponding transfer into adaptive technologies through intelligent materials that can perceive and respond to environmental stimuli" [36].

In the analyzed group of reports, KSSs inspired by nature constitute 22%. As with regular KSSs, those inspired by nature are also presented in order of increasing complexity, from those that use the simplest movement types to those with more complex spatial transformations.

4.2.1. Motion: Rotation; Skin System: Lattice/Plate

As in the case of the regular systems addressed in Section 4.1, the simplest motion and skin systems are also used, inspired by nature. Jumabekova et al. present a study of a KSS called Stegos, inspired by the morpho butterfly (emissive adaptability of wings) and chameleon skin for its color changes. The geometry of the KSS is a "rigid lattice to which are attached a multitude of orientable and thermo-responsive hexagonal flaps" [92]. The rigid flaps are rotated around the horizontal axis (closed, fully open, or half-open states) to allow daylight penetration, while the color change facilitates heat rejection/absorption. In another study published by Sadegh et al., in the *Journal of Daylighting*, a KSS inspired by the Lotus flower's geometry is analyzed [93]. This system module features a shading module in the form of a "flower" with four rigid petals, each half-petal rotating towards the outside around the vertical and horizontal axes. After the initial evaluation, the authors adopted a biomimetic approach in the next phase of their research. They draw inspiration from how biceps brachii muscles connect two bones to facilitate arm movement. This concept is applied to the shading system, which has a robust load-bearing substructure and actuators connected to the individual petals by strings. This addition influences the daylight performance and generally results in an approximately 20% decrease in "nearly all" daylight metrics due to the increased shading area.

4.2.2. Motion: Translation; Skin System: Plate

Anzaniyan et al. assessed a bionic kinetic façade element inspired by the movement mechanism of the *Lupinus Succulentus* plant. In the natural world, this plant's leaves rotate by approximately $\pm 15^\circ$ to maximize solar energy absorption. The authors developed a KSS prototype that mimics this capability. The KSS consists of inclined opaque (upper) and transparent (lower) hinged rigid panels attached to the shafts with right-handed and left-handed threads. As the shafts rotate, the panels fold up and down and change the inclination angle in the vertical plane. Besides the prototype, the authors have carried out daylight ($UDI_{300\text{-}3000}$) and energy consumption simulations. Implementing the bionic kinetic façade element led to a 7% decrease in cooling load and a 12% reduction in overall energy use during warmer months. Furthermore, the "electric lighting load" was cut by approximately 48% [94].

Folding was also used as a primary motion principle in a KSS, as presented by the Soliman and Bo teams [95]. The authors describe the natural inspiration from three biological models: *Mimosa pudica* for the folding mechanism, *Cactus* (*Echinocatus grusonii*) for the breathing unit, and *Stone Plant* (*Lithops salicola*) for the light-conducting feature. The bionic inspirations are used to create a unit that is used as a KSS that uses both (*i*) external folding fins and (*ii*) internal fins regulating the so-called "breathing unit". Rigid fins are radially located around a hexagonal opening, regulating its aperture by "push and pull springs". The system was evaluated using a simulation in Design Builder software in the climatic conditions of Cairo, Egypt. The results showed a considerable improvement in the thermal performance by 11.3% of the multi-functional biomimetic adaptive building envelope, which decreased the temperature inside by 3 °C through only natural ventilation.

4.2.3. Deformation: Bending; Skin System: Plate

Andrade et al. conducted experimental research on a kinetic shading element prototype inspired by the leaf morphology of the *Ammophila arenaria* grass. The authors chose bimetal as a material that mimics the heat-responsive curling behavior of the plant's leaves. By incorporating creases into the bimetal's active layer, they replicated the natural opening and closing reactions to temperature changes. The authors have developed a custom-made matrix for stamping bimetallic elements. A façade component was constructed using the "bimetallic biomodule". The experiments have demonstrated that it is possible to control the behavior of biomodules, which "tend to close at room temperature of around 18 °C and open at temperatures near to 32 °C" [96]. This is one of the rare studies that have carried out an experimental campaign to identify the features of the novel material. Charpentier et al.'s team provided the design process of a bio-inspired KSS based on the rapid nastic movements of plants, which are quicker than a natural phenomenon of tropisms. Initially, the authors demonstrated thermo-bimetallic (TBM) blades that emulate plant petals, opening like flowers to shield the building from excessive heat. The team designed and tested a fully functional prototype. In response to these findings, the team investigated curved line folding transformation, a technique combining folding (plastic deformation) and bending (elastic deformation) [97].

4.2.4. Deformation: Bending; Skin System: Membrane

Also, bending was used as a type of deformation in Scavée et al.'s study, presenting a KSS using Nitinol, a shape memory alloy (SMA) used as an actuator element [98]. Nitinol wires expand and contract depending on the external temperature. Mushroom grills and lotus seeds inspired the KSS. The system is made of flexible strips of fabric located perpendicularly to the surface of the glazing. The strips are bent, forming gaps of variable width, allowing daylight inside the building. The geometry of the KSS was recreated with Rhino/Grasshopper, but it only served as a model. A part of the study was performed using the prototypes. Unfortunately, the authors did not measure the amount of daylight using the constructed prototypes for poorly understood reasons. In 2022, the teams of Khosromanesh and Asefi provided a study of bio-inspired hydro-actuated building façades. The square module of the façade is diagonally divided into four parts. Each part is covered by the "valve": a triangular, grooved element made of polyurethane foam and hydrogel. The valve is bent at the range of 0–130° to the outside "under the effect of water absorption" [99]. The system is designed mainly for air exchange regulation but also works as a KSS. The idea is refined in the following publication [100], but no simulation or experimental evaluation is given (the system is not shown in Table 5).

Born et al. present an experimental study of a KSS called FlectoSol equipped with a pneumatic cushion actuator [101]. The study concentrates on the qualities and material properties of the KSS itself; no experimental or simulation validation of the system is provided. The mechanics of the KSS are based on the principle of flexible deformation of an air cushion with an unequal stiffness with the rise in pressure. The KSS module is made of a GFRP–elastomer hybrid composite and has the form of an elastic flap covered with thin-film PV, with two air chambers. As chambers are inflated, the elastic flap is bent. The study by Born et al. features a complete theory of stiffness calculation and the presentation of a four-module FlectoSol demonstrator. Still, no evaluation is given in the context of microclimatic conditions (the system is not shown in Table 5).

Table 5. Biomimetic kinetic shading systems. All types of motion and deformation.

Ref. No.	Year	Research Type [1]	Building Type	Climate	Evaluation [2]	Metric [unit]	m_b	m_{KSS}	Δ_p	Natural Inspiration
[92]	2023	S/Ex	n.a.	Cfb	E/DL	j [W/m^{-2}]	4.9	17.0	246.9%	*Morpho butterfly Chameleon*
[93]	2022	S	n.a.	n.a.	DL	ASE [%]	n.a.	n.a.	20.0% *	*Lotus flower*
[94]	2022	S/Ex	office	BSk	E	Q [kWh]	95,755.0	89,722.0	6.3%	*Lupinus Succulentus*
[95]	2023	S	office	BWh	E	CH [h]	na.	na.	11.3% *	*Echinocatus grusonii*
[96]	2024	Ex	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	*Ammophila arenaria*
[97]	2022	Ex	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	*Dionaea muscipula Aldrovanda vesiculosa*
[98]	2022	S/Ex	office	n.a	DL	DF [%]	1.6	2.1	31.3%	*Lotus flowers*
[102]	2024	S	office	Csa	DL	E_h [lux]	4879.5	557.7	110.9%	*Gazania flowers*
[103]	2023	S	office	BWh	DL	UDI [%]	39.6	83.4	66.4%	*Cerastes cerastes*
[104]	2023	Ex	n.a.	n.a.	DL	E_h [lux]	3382.6	1135.7	54.5%	*Stomata cells*
[25]	2022	S	office	BWh	DL	UDI_e [%]	22.0	10.0	461.2%	*Morpho butterfly*
[105]	2022	S/Ex	office	AW	DL	E_h [lux]	4879.5	557.7	88.6%	*DNA*

[1] S—simulation, Ex—experiment; [2] DL—daylight, E—energy; m_b—metric value at baseline scenario, m_{KSS}—metric value after the application of KSS, Δ_p—performance improvement, I_e—irradiance, ASE—annual solar exposure, Q—thermal load, CH—comfort hours, DF—daylight factor, E_h—horizontal illuminance, UDI—useful daylight illuminance; $UDI_{>2000}$—useful daylight illuminance exceeded, *—performance declared by authors.

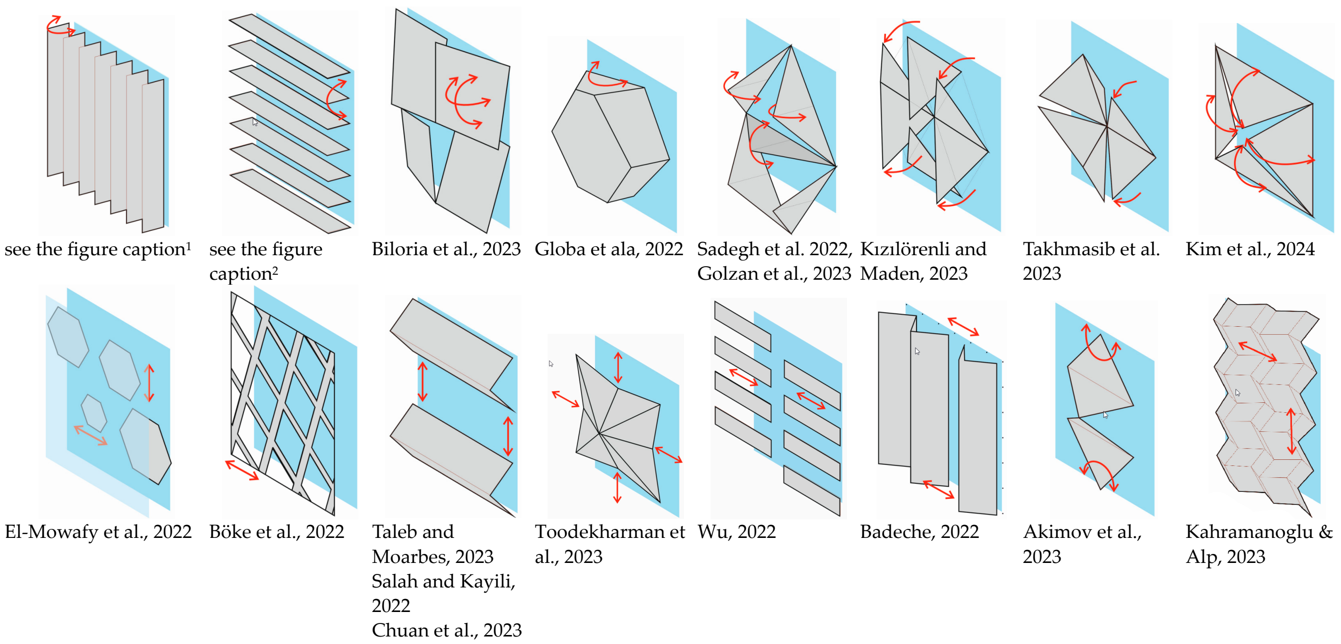


Figure 7. *Cont.*

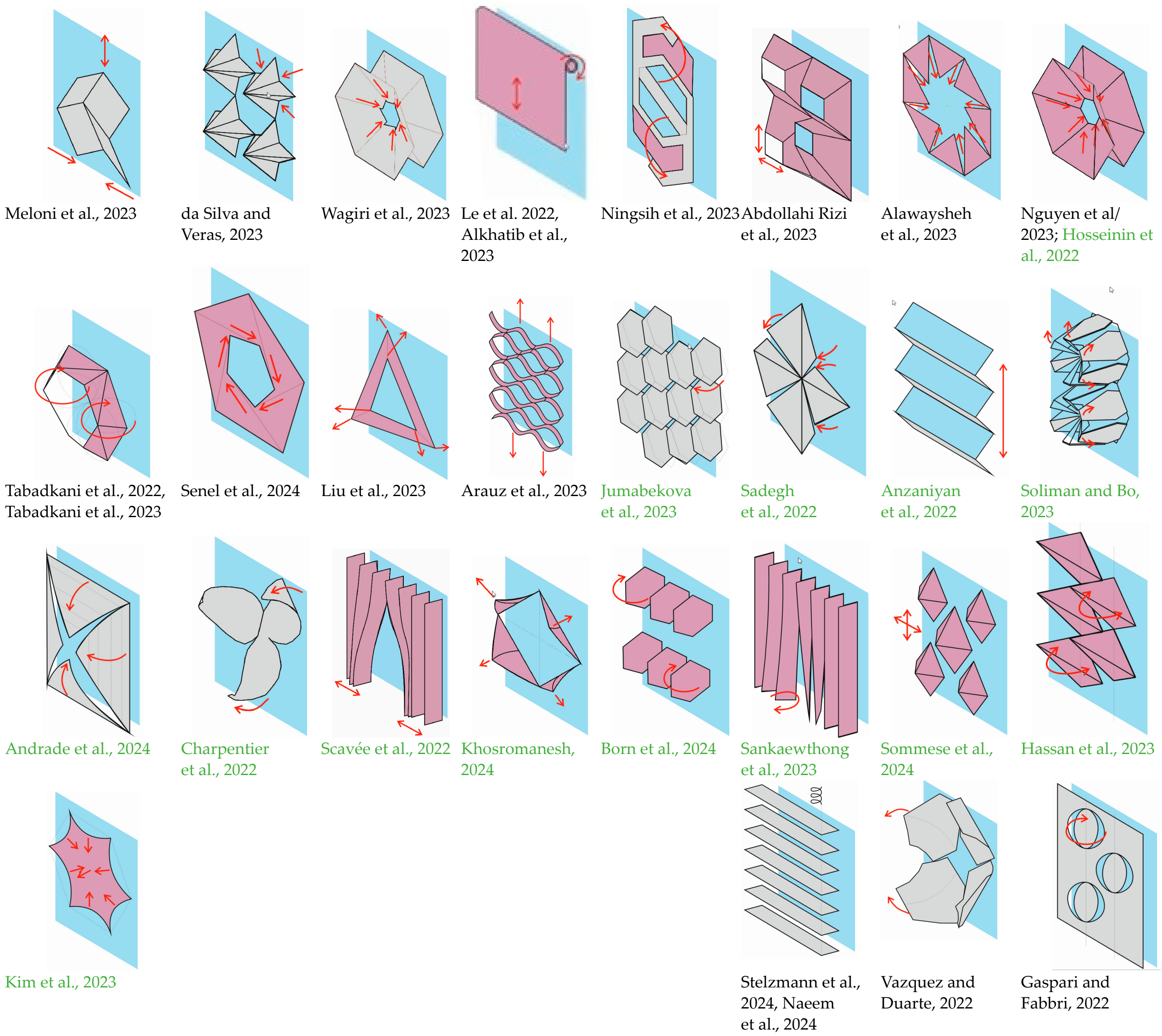


Figure 7. Schematic diagrams of KSSs with the reference numbers. Rigid plates are depicted in grey, while membranes are highlighted in red. Nature-inspired KSSs are marked with green reference. The red arrows indicate the direction of the motion/deformation. The authors of the pictured KSS's proposals: [1]—Ożadowicz & Walczyk (2023) [40], Sharma & Kaushik (2023) [41], Catto Lucchino & Goia (2023) [42], Mangkuto et al. (2022) [43], Hassooni & Kamoona (2023) [44], Shen & Han (2022) [45], de Bem et al. (2024) [46], Fikery et al. (2024) [47], Chaturvedi, Kumar & Lamba (2024) [48], Kim & Han (2022) [49], Norouziasas et al. (2023) [50], Choi (2023) [51], Choi (2022) [52], Valitabar et al. (2022) [53], [2]—Fahmy, et al. (2023) [54], Marques et al. (2022) [55], Brzezicki (2024) [56]. (also refs. [23], [59–90], [92–102], [104–110]).

4.2.5. Deformation: Twisting; Skin System: Membrane

Sankaewthong et al. presented a simulation and an experimental study of a twisted KSS. The authors refer to the morphological inspiration from nature (DNA spiral), phototropism, and natural forces twisting nanowires (Eshelby twist). The KSS consists of flexible tubes, a skeleton support affixed to the tubes, and strips of flexible fabric/membrane stretched out on the skeleton. When the flexible tube is twisted, gaps are created between the individual strips, and daylight is admitted into the test room [105]. The authors build and test a prototype in which the strips of the shading system are made of polyester. The average illuminance in the test room after the installation of the shading system decreased ten-fold (557.72 vs. 4879.45 lux), showing the very high effectiveness of the proposed system. In 2023, the same team analyzed a nature-inspired ventilation system based on the *Mimosa Pudica* mechanism, but as it is not a shading system, it is only quoted for reference [106].

4.2.6. Deformation: Stretching; Skin System: Membrane

The team of Sommese et al., in the journal *Building and Environment* have presented a study on a KSS inspired by *Gazania flowers* [102]. The authors have extensively studied the morphology of a flower. When the lateral edges of the petal curl up, the flower closes. When the edges unfold, the petal straightens and curves up, opening towards the incoming solar radiation. The bionic principle is translated into the parametric model of a modular pyramid-shaped, four-sided shading element, which could be scaled vertically and horizontally. As the vertexes of the shading module change their place in space, the base triangles are deformed and cannot be made out of rigid plates. The KSS module is subject to "periodic decentralised movements that depend on the distance of the modular element" from the point of attraction, defined as an intersection of the plane of the façade and the line connecting the Sun position and the occupant. The authors provide the results for the most optimal combinations.

Similarly, Hassan et al. have developed a KSS based on multiple natural principles. Morphological inspiration comes from the Saharan horned viper skin (*Cerastes cerastes*), behavioral from plant tropism. The KSS has the form of a diamond module that is horizontally rotated (to track the Sun) and scaled both vertically and horizontally. The horizontal diagonal of the module is "pushed" to the outside, and the triangles constituting the module are deformed (stretched). The authors have analyzed 144 cases of possible geometrical transformation of the basic module, concluding that a particular geometrical version achieved an improvement from 16.6 to 33.7% compared to the baseline scenario [103], with some cases reaching a 66.4% decrease in illuminance levels (3382.6 to 1135.7 lux).

Kim et al. have presented an innovative KSS based on plant cells' bionic mechanism, which "reduces excessive daylight and thermal loads by changing the external building shape in real time" [104], like the *tomata structure* of natural plants. The hexagonal KSS module is covered with an opaque lycra membrane stretched on the hexagonal frame and fixed to the vertexes. Six pleated fluidic elastomer actuators (PFEAs) are placed in the module's center. As the shape of the PFEAs changes, an opaque lycra membrane is pulled to the center, creating gaps on the perimeter of the module through which daylight can propagate. The authors claim that the maximum clearance of the façade is 20%, as determined by the upper-range UDI analysis.

Hosseini and Heidari [23] present a system that is, from the mechanical perspective, identical to the system analyzed by Nguyen et al. [24]. At the same time, the second team did not refer to nature-based solutions. The kinetic behavior of KSSs features the change in the size (radius) of the hexagonal aperture and the displacement of the vertexes constituting the module. In practice, no rigid elements could be used; the system has to be constructed out of a stretched flexible membrane, as the scale and the shape of quads vary. Simultaneously, *morpho butterfly wings* are the source of the bionic inspiration for the module's gazing, using "moveable composition of coloured glass regarding six different patterns of coloured glass compositions using red, green and blue colours" [23]. The colored glass compositions "remarkably decrease the heat's overloading effects" [23] near the façade with spots of more than 3000 lux of illuminance. Notably, the authors discover the role of blue-colored glass in preventing visual discomfort. See Table 5.

4.3. Smart-Material-Driven KSSs

Smart materials, particularly shape memory alloys (SMAs), are revolutionizing the design and functionality of KSSs. These innovative materials have the unique ability to remember and return to a predefined shape when exposed to a specific stimulus, such as temperature change. This characteristic makes SMAs ideal for integration into KSSs, allowing for dynamic adjustment and movement in response to environmental conditions. Using SMAs in shading systems enhances energy efficiency by adapting to sunlight and heat and adds an element of architectural beauty through their fluid motion.

Some authors of the reviewed papers do not report direct inspiration from nature; however, the systems they simulate or test utilize smart materials. Most of these materials respond to thermal stimuli and exhibit actuation, resulting in closed-loop, autoreactive behavioral patterns that resemble those in natural/biological systems.

4.3.1. Deformation: Shrinking; Skin System Louver

Stelzmann et al. present a KSS that is basically a horizontal louver system with louvers linked using stiff rods. The angular position of the louvers depends on the extension/contraction of the SMA element installed inside a glazed solar collection (to facilitate higher temperatures). The KSS is tested in a full-scale demonstrator, while no daylight or energy evaluation is provided, and this paper is not included in Table 6. Particularly on clear summer days, the system fulfilled the specifications and requirements [107]. The team of Naeem et al. presented a study on reducing cooling loads by enhancing shading efficiency in office space using KSSs with shape memory materials. The tested shape memory alloy (Nitinol) is used to manufacture springs that shrink with the temperature rise (approximately 60 °C) despite the load. The authors present a fully functional 1:1 prototype. The spring is placed at the top of the module in the focus of the parabolic mirrored concentrator and connected by a wire with a series of *shading louvers* made of dark polycarbonate. The authors state that the KSS was "able to decrease the solar radiation temperature in the internal space by an average of 8.28% to 25.62%" and reduce the cooling loads "by an average of 20.12% to 55.09% in the four months studied (July to October)" [108]. Vazquez and Duarte present an extensive experimental study on bi-stable flexible materials used for KSSs that are actuated using SMAs. The bi-stable KSS evaluated in the paper comprises a holder unit, four bistable flaps made of carbon fiber, and SMA actuators made of Nitinol springs. By contracting and expanding, the strings force the flaps to snap into the open and closed positions. The control action is exerted by heating the Nitinol springs to 55 °C [109]. See Table 6.

Table 6. Kinetic systems based on SMA and bimetallic elements.

Ref. No.	Year	Research Type [1]	Building Type	Climate	Evaluation [2]	Metric [Unit]	m_b	m_{KSS}	Δ_p
[108]	2023	Ex/S	office	BWh	E	Q [kWh]	52.2	41.5	20.12–55.09% *
[109]	2024	Ex/S	office	Dfa	DL	CH [%]	10.0	70.0	600.0%
[110]	2022	S	residential	Cfb	E	Q [kWh]	7088.0	636.0	92.0%

[1] S—simulation, Ex—experiment; [2] DL—daylight, E—energy; m_b—metric value at baseline scenario, m_{KSS}—metric value after the application of KSS, $\boldsymbol{\Delta_p}$—performance improvement, Q—thermal load, CH—comfort hours, *—performance declared by the authors.

4.3.2. Deformation: Twisting; Skin System Plate

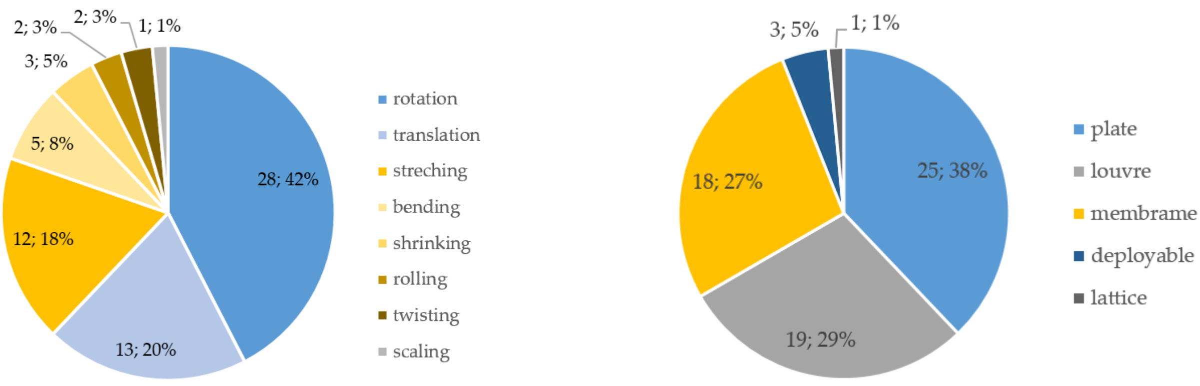
Gaspari and Fabbri analyze a KSS based on small circular rigid aluminum flaps of 0.08 m installed in a rectangular grid in a module of 3.2 × 0.8 m. They report that "each flap can rotate on its vertical or horizontal axis depending on the façade orientation" [110]. Flaps are driven by SMA springs that twist, generating the rotation of axes to which the flaps are fixed. Morphologically, the system is very similar to the system presented and tested by Jumabekova [92] (hexagonal flaps, detailed description provided above), but no bionic inspiration is quoted. The authors report a 92% reduction in cooling load for a fully closed flap and 64% for a flap rotated at 45°.

5. Discussion

This discussion effectively interprets the results, highlighting the strengths and weaknesses of various KSS solutions.

5.1. General Remarks on Motion/Deformation Types

In the analyzed papers, motion is the most commonly used geometrical transformation (62%), with rotation (42%) and translation (20%) being the primary types—see Figure 8. Rotating shading devices are favored for their simplicity, cost-effectiveness, fewer mechanical parts, and ease of fabrication and maintenance, as already addressed by [10]. They offer a wide range of shading angles, which are beneficial for adapting to the Sun's path and enhancing energy efficiency. While less common, translation movements provide straightforward adjustments to light and shadow patterns. Both rotating and translating systems are reliable and efficient for mechanizing KSSs, with fewer potential failure points, particularly in hinge design [111], as addressed by Sommese [36].



(**a**) (**b**)

Figure 8. (**a**) The frequency and variety of motion and deformation types observed in this study. (**b**) Prevalence of different skin systems, highlighting their occurrence within the dataset.

Deformation applies to 37.5% of the analyzed cases and is used mainly in nature-based solutions. This is less frequent, as addressed by Voigt [31].

- Complexity: deformation involves changing the shape of shading elements, which can be more complex to design and implement than simple motion mechanisms; complexity often translates into higher costs and maintenance requirements;
- Material limitations: materials that can withstand repeated deformation without failure are specialized and may be more expensive or difficult to source.

It is noteworthy that some designs incorporate element deformation in such a manner that the "deformative" aspect of the façade might not be immediately apparent, e.g., authors frequently mention "scaling" of an aperture as a motion type, while the elements "framing" this aperture are de facto deformed. This choice is often attributed to the relative ease of simulation within software environments, where the flexibility of membranes can be more readily accommodated, e.g., in parametric definitions. Using membranes instead of rigid elements may present specific challenges for real-world applications, as discussed by Voigt [31]. While membranes offer unique advantages in terms of flexibility and adaptability, they require a robust skeleton for proper tensioning and anchoring. Additionally, the material selection for membranes is critical, as it must withstand the demands of frequent deformation while maintaining its integrity over time. Such considerations are essential to ensure the longevity and functionality of KSSs. Tabasi and Banihashemi describe these solutions as 'not constructible' and 'only kinetic' in digital modeling and simulation [6].

In the analyzed papers, twisting, rolling, and shrinking occurrences are notably less frequent. However, it is important to emphasize that this trend does not necessarily reflect their prevalence in standard everyday applications. For instance, rolling is a common mechanism employed in everyday items such as roller blinds, which enjoy widespread popularity.

Voigt's statistical results show that adaptation is often achieved by moving shading elements rotationally (52%), translationally (35%), or by scaling the aperture (17%) [32]. Smart materials like shape memory alloys (SMAs) and shape memory polymers (SMPs), which deform with temperature changes, are emerging technologies. SMA elements mainly deform by bending, twisting, or shrinking and require temperatures around 60 °C for phase change, as addressed by Luo et al. [26]. Thus, in experiments, SMAs are often placed at the focal point of a solar concentrator for the necessary heat [107,108].

The matrix presented in Table 7 serves as a comprehensive visual representation that maps the relationship between various motion types and skin systems in the analyzed group of KSSs. This analytical tool effectively categorizes and contrasts the different motion mechanisms—such as rotation, translation, and deformation—with the façade systems they are integrated into.

Table 7. A matrix of comprehensive visual representation that maps the relationship between various motion types and skin systems in the analyzed group of KSSs. The nature-inspired KSSs are shown in green.

		Skin System				
		Louver	**Lattice**	**Plate**	**Deployable**	**Membrane**
Motion	rotation	[41–56]	[58]	[59–66] [92,93]		
	translation		[67]	[68–74] [94,95]	[75–77]	
	scaling			[78]		
Deformation	rolling					[79,80]
	bending	[107,108]		[96,97]		[98–101]
	twisting			[110]		[102,103]
	stretching					[24,81–90] [23,104–106]
	shrinking	[107–109]				

5.2. General Remarks on Mechanism Advancement, Responsive Functions, and Stimuli

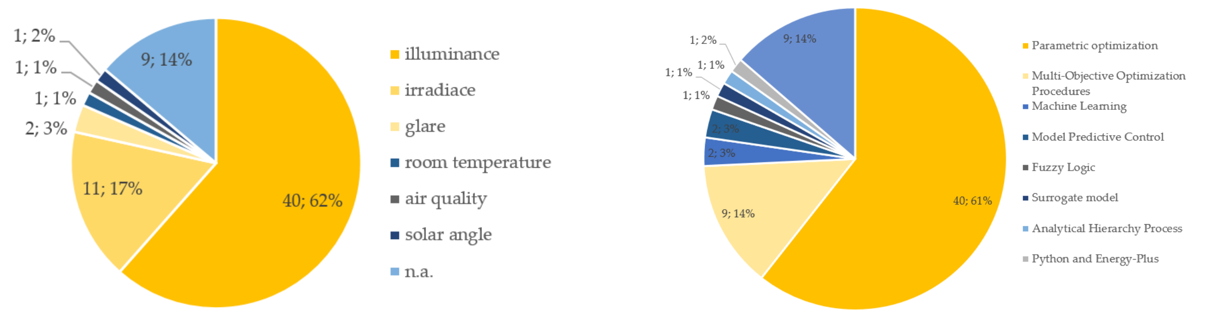
KSS mechanisms are categorized into three design approaches. Forty-one percent of solutions use mechanical components like motors, gears, and wires for transforming shading elements, termed as "practical" or "realistic." Another 57% of papers present geometric transformations conceptualized in parametric software, but these lack feasible implementation, making these methods "theoretical." The remaining 2% of studies do not propose specific designs, focusing instead on altering façade parameters like transparency or window-to-wall ratio.

KSSs are typically parametric models with adjustable parameters like rotation angle, number of louvers, and fin size. However, Ladybug/Honeybee software does not support variable geometry simulations, making scheduling difficult. Thus, about 70% of papers simulate these systems in fixed states (open, semi-closed, closed) on specific days like equinoxes and solstices. Performance is often evaluated using data averaging, as Kahramanoglu and Alp do with 'average daylight autonomy (DA)' values [75]. Of the studies considered, 18% feature kinetic systems only in computer modeling, 9% feature automatic prototypes, and 2% use sophisticated methods like Norouziasas et al.'s Energy Management System (EMS) for EnergyPlus [50]. Carlucci's dynamic shading simulation algorithm uses Python switchers based on various input variables [112].

Different environmental conditions serve as stimuli for KSSs. Of the KSSs considered, 77% respond to daylight, with 60% reacting to illuminance and 17% to irradiance. One KSS responds to glare (3%). Some studies assume illuminance as the stimulus when states are discrete. A small fraction (2%) reacts to room temperature, and another 2% to Indoor Air

Quality (IAQ). One system responds to the solar angle, while 14% have unspecified stimuli. Two case studies respond to the occupant's location [23,104].

In the analyzed group, 62% of systems undergo parametric optimization, and 13% use multi-objective optimization, including Pareto techniques. Advanced methods like machine learning, predictive control, fuzzy logic, surrogate modeling, or analytical hierarchy processes are used to find practical solutions, especially for Pareto fronts—see Figure 9.

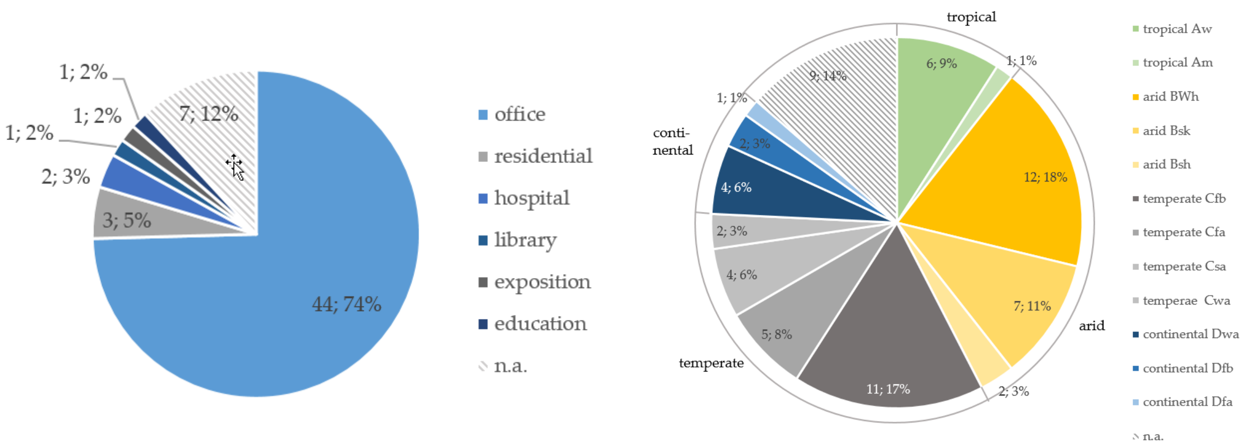


(**a**) (**b**)

Figure 9. (**a**) Distribution of stimuli types for KSSs. This graph illustrates the various environmental stimuli influencing KSS, highlighting the predominance of daylight-related responses. (**b**) Overview of optimization techniques employed in KSSs. This graph categorizes the optimization methods applied to KSSs, showcasing the balance between parametric and multi-objective optimization strategies.

5.3. General Remarks on Climate and Room Use

The analyzed case studies provide a statistical analysis of room usage and climate zones. Offices were the predominant function, accounting for 74%, followed by residential use at 5% and other functions at 8%. In 12 instances, no specific function was identified. Arid and temperate climate zones were equally represented at 34% each, totaling 68%, with tropical zones at 12% and continental zones at 10%. In 12% of cases, the climate zone was unspecified. The most frequently analyzed climate was BWh, a hot, arid desert climate, where KSSs are essential to mitigate intense solar radiation, reduce solar heat gain, and minimize air conditioning needs. Cfb and Cfa climates, indicative of temperate zones with hot or warm summers, also showed significant use of KSSs, primarily during summer, to reduce solar heat gain. Retracting KSSs in winter maximizes natural light and passive solar heating, reducing artificial heating needs. This analysis highlights the correlation between solar exposure and KSS application across different climates. See Figure 10.



(**a**) (**b**)

Figure 10. (**a**) Graph illustrating the distribution of room functions within the analyzed cases; (**b**) graph depicting the climate zones where the studied buildings are located. Arid and temperate zones are the most represented, each constituting 34% of the total cases.

5.4. The Influence of Bionic Inspiration on a System's Kinetic Complexity

Biomimetic approaches involve emulating nature's designs, processes, and behaviors to address complex challenges. The "organism level refers to an organism, such as a plant or animal, and may involve imitating the entire or part of the system" [18]. This approach creates innovations that are well adapted to their environment. By studying and applying nature's intricate forms, functions, and strategies, biomimetics provides sustainable solutions across fields like architecture and materials science, enhancing efficiency and promoting harmony with the natural world. The following points represent the summary of the problem:

- KSSs inspired by bionic principles often show higher complexity, using "deformation" types like "bending" and "stretching," achievable only by membranes.
- In biomimicry, "bending" and "stretching" mimic prevalent plant movements, capturing nature's adaptive mechanisms.
- This complexity mirrors the intricate adaptations of living organisms to their environment, with plants and animals evolving sophisticated mechanisms to respond dynamically to stimuli.
- The biomimetic design emulates these concepts; for example, nyctinastic plant movements (opening and closing petals in response to light and dark) inspire KSS devices.
- Schleicher et al. suggest that "elastic and reversible deformations" [111] are promising for hinge-less and versatile constructions.
- Nastic movements in plants, non-directional responses to stimuli like temperature, humidity, and light, occur rapidly due to changes in turgor pressure in plant cells, allowing quick, reversible movements.
- These nastic movements inspire kinetic façades, offering models for rapid and efficient adaptation to environmental changes.
- Tropic movements, directional growth responses to environmental stimuli (e.g., phototropism and gravitropism), are slower and result from differential growth rates on opposite sides of an organ.
- Tropic movements guide KSSs in orienting themselves to maximize or minimize sunlight exposure.
- By combining principles of nastic and tropic movements, designers can create shading systems that deform and move directionally, enhancing KSS functionality and efficiency.

In the discussed group of reports inspired by nature (No. = 14), both movement types, tropic and nastic, are used as inspiration.

5.4.1. Motion-Based Bionic KSSs

Despite the complex mechanisms of plant movements, these sophisticated behaviors **can be simplified into fundamental motion patterns** for biomimetic applications. Simple rotation motion has been used to design KSS panels [92] and optimize PV panel angles in folding façades inspired by plant movements that track the Sun [94]. Some designs incorporate translation and rotation motions, mimicking nastic and tropic movements [93]. For instance, systems inspired by rigid plates rotating around a perpendicular axis emulate nastic movements. The most complex rotational-based systems, such as "breathing units" composed of folding opaque and transparent panels [95], reflect high innovation but face significant practical implementation challenges.

5.4.2. Deformation-Based Bionic KSSs

Certain biological principles **require complex geometrical transformation patterns** beyond simple motions of rigid elements. For example, one proposal mimics the nastic deformation of *Ammophila arenaria* grass, bending in response to water stress [96]. This involves a rigid, ribbed bimetallic element that bends and curls based on temperature, enhancing shading effectiveness. Another complex design, inspired by the nastic movement of flower petals, uses thermo-bimetallic elements that open and close in response to solar radiation, analogous to petal growth patterns driven by phytochrome release and temperature changes [97]. Various studies use membrane bending, some conceptually [98], others employing moisture to bend multilayered membranes [99] or actuators altering PV-covered flap angles [102]. A twisted deformation is utilized in KSSs using strips of membrane. Stretched membranes, analogous to natural membranes deforming due to pressure differences, demonstrate biological adaptability. For instance, a lycra membrane façade inspired by plant *stomata* changes shape due to fluidic elastomer actuators, creating light-admitting gaps [106]. Other studies [23,104,105] transform natural analogies into technical systems with multifaceted shading elements, which are essentially deformed membranes requiring complex mechanical scaffolding for stretching. Overall, bionic systems in adaptive architecture exhibit complex geometrical transformation patterns, often relying on flexible membrane deformation to achieve adaptability.

5.5. Advantages and Disadvantages of Included Technologies

The advantages and disadvantages of the presented shading systems generally result from their level of mechanical complexity. The louver façade skin system is the simplest, based on rotation and translation, as in the case of retractable louvers. The advantages include (*i*) the ability to adjust to provide optimal shading throughout the day and (*ii*) precise control over indoor light levels and glare. The disadvantages include (*i*) increased cost of installation and maintenance due to mechanical components, (*ii*) the necessity of regular maintenance, and (*iii*) electricity consumption of motorized systems, which can offset some energy savings. When PV elements are installed on louvers, additional benefits include energy generation and sustainability, reducing the carbon footprint and enhancing building sustainability. Lattice skin systems face issues similar to those of louver façade skin systems.

Plate skin systems utilizing folding motion are mechanically more challenging, as the size of the plates is usually greater than that of the louvers. These systems require more robust mechanical components, with motors needing more energy to mechanize the plates and the railing requiring regular lubrication. Additionally, because of the size of the plates, the systems must be designed to withstand wind gusts. The advantage of the system is that the plates in the closed state can serve as mechanical protection for the glazed façade, for example, in rapid climate events. Plate systems are frequently designed to be aesthetically pleasing, which is why architects often select them.

Deployable skin systems are space-efficient due to their limited size in the folded-flat state. Still, they are mechanically challenging due to the extended hinging that must operate at an extended rotation angle (e.g., 360°, as the plates must fold flat). The mechanics of deployable structures are complex and, in building engineering, are often the subject of theoretical study only. Membrane systems that undergo deformation vary from simple mechanical operations of rolling (relatively common and failure-free) to complicated deformations that, in practical implementation, would require a transformable skeleton. Also, membrane materials are prone to defects if folded/stretched multiple times.

Advanced bionic-based shading systems offer sophisticated mechanical solutions inspired by nature's adaptive mechanisms. These systems often incorporate complex geometrical transformations and dynamic responses to environmental stimuli, making them highly innovative yet mechanically complicated. Due to their advanced nature, these systems are prone to numerous potential malfunctions. The complexity of their design involves multiple moving parts, intricate hinge mechanisms, and precise actuators that must be appropriately coordinated to achieve the desired adaptive responses. This complexity increases the likelihood of mechanical failures, such as misalignment, components' wear and tear, and synchronization issues. The realization of advanced bionic-based systems would likely require a comprehensive and iterative design process encompassing several critical stages: advanced design, testing, prototyping, and production. Scaling up production involves logistical challenges, such as sourcing specialized materials and managing production costs.

5.6. Methodology Used to Estimate Energy Savings

Kinetic shading systems are modeled parametrically with adjustable parameters (e.g., rotation angle, number of louvers, fin size). Since Ladybug/Honeybee does not support variable geometry simulations, many authors simulate these systems in specific states (open, semi-closed, closed) on critical days like equinoxes and solstices. Sharma and Kaushik use four specific days [41]; Mangkuto et al. simulate 21 June, 21 March, and 21 December. System performance is often determined by data averaging or approximation, as Kahramanoglu and Alp use "average DA value" [75] for benchmarking.

Static parametric systems are frequently optimized using genetic algorithms (GAs). An initial population of parameter values is generated stochastically, and each value is assessed with a fitness function. Poor-performing values are discarded iteratively, while the best ones proceed to the next generation until optimal values are reached. A GA can optimize single variables (e.g., Galapagos plugin, as used by Wagiri et al. [78]) or multiple variables (e.g., Octopus plugin), forming a Pareto front. Sadegh et al. use a fitness function based on mean illuminance values for three kinetic façade configurations (open, semi-open, closed) [93].

Simulating a variable system requires determining the switching schedule between states over the test period. Reinhart's method simulates discrete states of kinetic shading systems, assigning illuminance values to predefined hours by environmental conditions. Brzezicki uses this method [56], while Tabadkani et al. simulate a 12-element kinetic shading system in four states (48 simulations), optimizing a surrogate model using vertical eye illuminance (EV), task illuminance (ET), and view to outdoor (VR) metrics [85].

- In 2023, the ISO/DIS 52016-3:2023 standard was published for adaptive building envelope elements, using internal operative room temperature and illuminance to determine shading system states. Norouziasas et al. use an Energy Management System (EMS) for EnergyPlus, including ISO/DIS 52016-3:2023 requirements [50]. It should be noted that the software capable of simulating KSSs is limited and often considered "high threshold", demanding advanced coding skills addressed by an "Application guide for EMS" [113]. Only 3 out of 66 studies use BSDF to calculate daylight passage through complex façades [45,79,104].

5.7. A robust Understanding of the Reviewed KSSs

To gain a robust understanding of KSSs from multiple perspectives, several key factors should be considered:

- System performance Δ_p. The authors provide very different metrics; the baseline scenario is not always given, some metrics are custom-defined, and percentages are mistaken with percentage points. The average performance of KSS—$\overline{\Delta}$—is calculated independently for daylight-based and energy-based metrics. The distribution of the performance values indicates the presence of outliers, which heavily influence the average values. These outliers are primarily associated with non-standard metrics, such as the "percentage of comfort hours", "DF between 1–3.5%", or "openness factor". These non-standard metrics often capture extreme conditions or rare events, leading to outlier values. When outliers are removed, the average values are significantly reduced, indicating a $\overline{\Delta_d}$ =46.8% improvement for daylight-based metrics (σ = 31.5%, n = 41) and a $\overline{\Delta_e}$ =43.3% improvement for energy-based metrics (σ = 28.5%, n = 19). Outliers disproportionately impact the average values, possibly skewing the overall performance assessment; ignoring them allows one to focus on typical behavior, and a clearer picture of the typical performance could be provided. However, outliers should be considered in specific contexts to ensure these critical scenarios are not overlooked. All data associated with this estimation are in an Excel file in the Supplementary Materials.
- Material Durability: Rigid plate systems are more durable, while deformation-based systems are often unbuildable due to the lack of suitable membranes.

- Mechanical Reliability: Data are mostly unavailable since most KSSs were only subjected to simulations, and constructed systems were mainly prototypes without empirical data. Some advanced designs featuring hinges were noted [74,99], while others presented mechanically challenging prototypes [107,108].
- Cost Analysis: Only one paper provided a detailed cost analysis, including Life Cycle Costing for the Australian market, covering operational, maintenance, fabrication, engineering, and potential demolition costs [60].
- User Comfort: KSS concepts have evolved to dynamically adjust shading density based on the occupant's position relative to the Sun, enhancing comfort by reducing glare [75,104].
- Energy Consumption: A single experimental paper detailed the energy consumption of KSSs using electric step motors.
- Aesthetic Appeal: Though subjective, aesthetic appeal can be quantified through surveys using ranking or rating scales, as demonstrated in one study [98].
- Adaptability: High adaptability is crucial for KSS effectiveness, but varying depths of analysis in different studies make uniform evaluation challenging. Some studies provide comprehensive year-long analyses with detailed operational schedules [50,111], while others limit simulations to select days and hours. Some studies offer a comprehensive year-long analysis.
- Environmental Impact: One study included a detailed Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) [60].

6. Conclusions

This review comprehensively covers research papers published exclusively from 2022 to April 2024, providing a focused snapshot of recent advancements in the field with the example of 66 papers. It encompasses an analysis of both regular KSSs and those inspired by biological models, offering a comprehensive overview of the field's current trends and innovations.

The initial part of the research involved a bibliometric study conducted to pinpoint critical trends in scientific publications, focusing on keywords and countries and leading journals on the subject. This information is valuable for researchers, providing insight into existing work, gaps in the field, and opportunities for international and interdisciplinary collaborations.

In the second part of this study, a simplified classification based on geometrical transformation was introduced, distinguishing between regular KSSs and those inspired by natural forms. Motion and deformation analysis was provided.

Despite the innovative approaches, some studies lack clear natural analogies or experimental validation. Biomimetic designs offer promising avenues for energy-efficient and responsive architecture, yet they also highlight the challenges of translating complex biological mechanisms into practical applications.

6.1. General Conclusions

The conducted review allows the following conclusions to be formulated. The following statements summarize the key findings:

- KSSs are attracting significant attention as potential tools for environmental control and heat/solar gain reduction. Researchers' interest in these systems has surged, evidenced by a three-fold increase in related publications compared to the previous decade (2010–2019).
- Only 38% of the proposed solutions have progressed to the experimental phase. Within this subset, a mere 25% have been rigorously tested solely through experimental means. This statistic shows the beginning stage of practical application in the field.
- Most research utilizes parametric modeling and computer simulation, with Rhino/Grasshopper being the predominant software. KSSs are typically simulated in discrete states, and conclusions are drawn from a limited dataset of days/hours/states. Efforts

to enhance simulation accuracy are underway, with some research teams adopting schedules based on standards like ISO/DIS 52016-3:2023 [50] or custom-designed algorithms [112].

- The deployment of KSSs has been shown to improve façade performance by 46.8% or 43.3%. However, varying evaluation metrics (such as daylight or thermal comfort) used by different authors make it challenging to benchmark solutions unequivocally. One of the most essential recommendations from this review is to define a unified KSS evaluation system, enabling effective comparison between different systems. The dimensions of the test room, the size of the glass, the spacing of the sensors, the simulation/analysis method, and the metrics to be calculated should all be standardized. A potential unified metric could be the shading coefficient (SC), which measures the effectiveness of a shading device in reducing solar heat gain through a window. The SC is defined as the ratio of the solar heat gain through a window with a specific shading device to the solar heat gain through an unshaded, clear glass window.
- Individualized user comfort strategies are introduced with dynamic shading elements arrangement reflecting the location of an occupant in the room [104].
- Cutting-edge optimization techniques are increasingly applied, with a trend towards using multi-objective optimization procedures to refine KSS geometry and operational schedules. Research is expanding into the use of AI and ML algorithms to predict and optimize the behavior of KSSs, aiming to achieve real-time adaptive control. Fuzzy logic and genetic optimization are also used [85]. A surrogate model shortens the time of the calculations, as used in the paper [45]. In contrast, a brute force method is also used [104].
- The effectiveness of KSSs lies not entirely in their geometry's complexity but in the control algorithms' sophistication. These algorithms are the key that determines the system's responsiveness and efficiency, ultimately dictating the performance of KSSs in real-world applications.
- As new standards emerge, crafting a schedule for KSS operations and software implementation grows more complex. The focus tends to be on thermal comfort and daylight metrics.
- There is a growing emphasis on integrating real-world testing with simulations to validate the performance of KSSs under various environmental conditions.
- Sustainable materials and manufacturing processes are being explored to reduce the environmental impact of KSSs, aligning with the global push towards greener building practices.
- Some standardization is required in testing and reporting to make future research more comparable and to facilitate meta-analyses.
- Incorporating SMAs in KSSs represents a promising innovation due to their responsive properties. However, the limitation lies in their effective transformation, which occurs predominantly at temperatures around 60 °C. This characteristic can diminish their practicality in façade systems, where adaptability is crucial and typically dictated by a broader range of environmental temperatures, such as external air temperatures.
- The authors of the presented KSSs represent different fields: architecture, building engineering, physics, and material engineering. The importance of an interdisciplinary approach should be highlighted.

KSSs are a cutting-edge approach to building design that allows the exterior of a structure to respond dynamically to environmental conditions. These KSSs can adjust their properties to optimize for natural light, temperature control, and energy efficiency. The presented study conducts a comprehensive analysis of a shading system, beginning with a functional analysis that evaluates light control, thermal regulation, and energy savings. It then goes deep into mechanical and structural analysis, examining design principles, materials, and movement mechanics. Control systems analysis follows, focusing on automation, stimuli, and adaptability. Environmental and sustainability analysis assesses material sustainability, energy efficiency, and life cycle impact. However, this study is not frequent among analyzed papers. Economic analysis includes a cost–benefit comparison and return on investment calculation, but only a few papers analyze this. Aesthetic and architectural impact is rarely evaluated through design integration and façade impact using surveys. Case studies are benchmarked to involve comparative analysis and user feedback. Simulation and modeling use software tools for performance simulations and energy modeling.

6.2. Limitations of This Study

The limitations of a review study usually result from the insufficient number of included publications. To counteract possible bias, PRISMA protocols were used in the writing of this paper, but this potential limitation should nevertheless be explicitly mentioned. The limitations are due to *(i)* different performance metrics used by different authors, *(ii)* some values that were not explicitly stated in papers and had to be retrieved from the graphs, and *(iii)* unclear procedures regarding the definition of the schedule of variability of a KSS that prevented the system's dynamic behavior from being clearly understood.

Despite the constraints, this study and its method and results are original and valuable contributions to the review of the most recent KSS technologies.

Although it is necessary to exercise caution in interpreting these presented data because of the limited number of reviewed papers (No. = 66), these findings nonetheless appear to be mainly in line with systematic reviews by other researchers [32].

6.3. Future Study

This research has laid the groundwork for a comprehensive understanding of geometrical transformations in KSSs. However, the journey towards fully realizing the potential of these materials is ongoing. The following areas have been identified as pivotal for future investigation:

Defining a unified KSS evaluation system would facilitate effectively comparing diverse solutions, ensuring consistency and reliability in assessing their performance.

Future studies should prioritize the construction of **physical prototypes**. These prototypes will serve as benchmarks to evaluate the effectiveness of KSSs in real-world building scenarios.

A more nuanced **classification of KSSs based on geometrical deformation**, mainly focusing on nature-inspired designs, will be essential. This will help us understand how these materials adapt and respond to environmental stimuli.

There is a pressing need for **increased collaboration between disciplines**, especially biology and materials science.

Investigating the **response time and modularity** of KSSs under specific environmental conditions will be vital. This will ensure that the materials meet the design requirements and contribute to energy efficiency and environmental conservation.

The **motion/deformation matrix** that has been developed is a starting point. Future research should look to expand this matrix, incorporating a more comprehensive range of KSSs and environmental factors.

Through these focused efforts, the application of KSSs in building technology can evolve from a promising concept to a standard practice, contributing to the global goals of sustainability and resilience.

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Abbreviations

ABE	Active Building Envelope
ASE	Annual Solar Exposure
C	Contrast
CH	Contrast
DA	Daylight Autonomy
DF	Daylight Factor
DGP	Daylight Glare Probability
E_{gen}	Electricity Generated
E_h	Horizontal Illuminance, Illuminance
E_v	Vertical Eye Illuminance
GWP	Global Warming Potential
IAQ	Indoor Air Quality
I_e	Irradiance
KSS	Kinetic Shading System
LEED	Leadership in Energy and Environmental Design
m_b	metric values in the baseline scenario
m_{KSS}	metric value after the application of KSS
ML	Machine Learning
MOEA	Multi-Objective Evolutionary Algorithm
OF	Openness Factor
PFEA	Pleated Fluidic Elastomer Actuator
Q	Thermal Load
Q_s	Solar Heat Gain
SC	Shading Coefficient
sDA	Spatial Daylight Autonomy
SMA	Shape Memory Alloy
SMP	Shape Memory Polymer
TBM	Thermo-bimetallic
UDI	Useful Daylight Illuminance
$UDI_{>2000}$	Useful Daylight Illuminance Exceeded, also UDI-e
VLT	Visible Light Transmittance
Δ_p	Performance Improvement
$\overline{\Delta}$	Average Performance Improvement

Classification of climate zones according to Köppen W. [114].

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