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Adaptive facade systems: classification proposal and bibliometric analysis developed through systematic literature review

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ABSTRACT

Adaptive façades, developed in recent years to increase user comfort and reduce energy consumption, offer innovative solutions for optimizing daylight regulation in interior spaces. This study examines adaptive façade systems in the context of daylight performance. In this context, research adopts a systematic methodological approach that combines qualitative and bibliometric analyses of existing literature. The proposed framework synthesizes existing façade classification proposals, integrating categories such as movement typologies, control strategies, and daylight-specific performance metrics to provide a coherent classification approach. Subsequently, an extensive review of existing studies in the field was conducted, key concepts and prevailing research directions were identified, and the scope of the study was narrowed. A selected group of studies from the existing literature was then subjected to detailed evaluation and analyzed using the new classification system. The aim of this study is to map adaptive façades for daylighting using a bibliometric and systematic approach, propose a new theoretical framework based on previous classifications, and apply this framework to selected studies identify research patterns, methodological gaps, and future directions.

Introduction

Research in building technologies, particularly in recent years, has focused on sustainability, energy efficiency, and user-centered performance criteria (GhaffarianHoseini et al. 2013; Martínez-Molina et al. 2016; Franco 2020; Mandala, Sutanto, and Santoso 2021; Gholami and Jalilisadrabad 2023). Increasing demand for energy efficiency, and the guiding influence of international environmental policies (e.g., the Paris Agreement and the United Nations Sustainable Development Goals) support the consideration of solutions as systems that support environmental performance efficiency (McCollum et al. 2018; Tolliver, Keeley, and Managi 2019). In this context, building envelopes and façade systems, in particular, stand out as one of the most critical interfaces, rather than simply physical dividers between interior and exterior spaces (Aelenei et al. 2018). They have become the focus of research on multidimensional parameters such as daylight performance, user comfort and energy consumption. This trend in the literature has evolved from static façades to passive design strategies at different times, and with the advancement of technology, the role of façades has been discussed from different perspectives. Nevertheless, in recent years, there has been a growing interest in the transformation of façades from merely fixed building elements to adaptive systems that respond to environmental inputs.

A review of the literature reveals that these adaptive façade systems have been examined with different approaches, defined, and classified using different terms (Jamilu, Abdou, and Asif 2024). While classification systems share commonalities but also differ in focus, the increasing number of applied and academic studies, coupled with the multidisciplinary nature of the topic, makes it difficult to develop a comparative framework. This complicates the evaluation and categorization of proposed studies and, thus, the direction of future research. Therefore, a proposed classification system that can be used to categorize existing studies is believed to fill a significant gap in the literature.

Therefore, two main objectives were identified within the scope of this study. The first is to propose a classification that will facilitate and systematize the study of adaptive façade systems by combining them under specific categories. The second is to analyze the studies obtained through a systematic literature review. Within this scope, mapping was conducted using the Web of Science and Scopus databases, thus examining prominent publications in the field. This review not only provided a map of the existing body of knowledge but also revealed the areas where research is focused, which areas are lacking, and which research gaps need to be addressed in the future. By combining these two objectives, the knowledge in the field is brought together and a holistic perspective is presented.

Classification of adaptive façade systems and a unified classification framework

The increasing number of studies in the literature on responsive facade systems, along with the classification studies of these studies and examples implemented in practice, demonstrate that the development of classification studies and models for these systems has been inevitable. While the prominent classification studies in the literature focus on different categories from different perspectives, the criteria in each study complement and enhance each other.

In one of the first proposed classifications, Ochoa and Capeluto (2008) proposed a three-by-five matrix and grouped them. The main classes were identified as sensor input elements, control processing elements, and actuating elements. Subcategories, design variables, sub variables, and common values within these classes were examined. For sensor input elements, sensors and user interfaces with subcategories such as light and temperature were proposed. For control processing elements, encompassing subcategories such as light controls, shading controls, and thermal comfort controls, as well as additional categories such as schedules and building management systems, were proposed. Finally, under the actuating elements category, daylighting systems, fenestration systems, ventilation systems, cooling, and heating systems were proposed. In a subsequent study, Ramzy and Fayed (2011) proposed a classification system with a different perspective than the previous study.

The researchers identified six categories, adding them to the cost-factor classification system, and proposed the following headings: kinetic systems, kineticism, control technique, system configuration, and control limit. Each category has four subcategories. Kinetic systems are classified as skin units' system, retractable elements, revolving buildings, and biomechanical systems. While kineticism is classified from limited to variable, control technique is classified as direct, responsive, internal, and indirect, as well as combinations. System configuration is classified as embedded, dynamic, and combination, while control limit is defined as minor, medium, significant, and variable. Cost is categorized as small, medium, large, and huge. In the classification system proposed by Loonen et al. (2015) the goal or purpose of the system was identified as the first category.

This category includes categories as thermal comfort, indoor air quality, visual performance. Other main categories are response function, operation, technologies, response time, spatial scale, visibility, and degree of adaptability. Each response function is associated with the system's purpose. Response time ranges from seconds to decades, and spatial scale is prominent within the scope of the study. The proposed system classifies the component to which it is adapted: building material, facade element, wall, roof, or whole building. A more compact classification system has been proposed by Waseef and Nashaat (2017). They categorize façade systems into two main categories: facade configuration, and facade function. Facade configuration examines façade systems based on their geometric transformation, pattern shape, facade form, and facade material. Facade function includes energy generation, aesthetic function, and environmental control. Only environmental control has subheadings: solar thermal control, daylighting control, ventilation control, noise control, and humidity control. Another comprehensive study was proposed by Başarır and Altun (2017).

Classification categories include adaptation elements, type of movement, size of spatial adaptation, movement limit, and dynamic adaptation. Elements of adaptation were categorized as facade, component, element, and material, while agents of adaptation were categorized as inhabitants, objects, and environment with their own subheadings. Respond to adaptation agents were categorized as static and dynamic, and types of movement were categorized into 10 highly detailed subheadings, including folding, sliding, expanding, and shrinking. The size of spatial adaptation ranged from nm to m. The structural system for dynamic adaptation was categorized as spatial bar structures consisting of hinged bars, foldable plate structures consisting of hinged plates, scrut-cable structures, and membrane structures. Unlike previous studies, a study that includes the building type category was proposed by Attia, Lioure, and Declaude (2020). This system proposes four main categories, which are then mapped to dynamic shadings, chromogenic glazing, solar active facades, and AVF systems, each with its own subcategories.

The four main categories are defined in detail as application/purpose, control, building type, and technology/materials. Application purposes are defined in detail, with subcategories such as solar gain and daylight control, glare protection, cooling savings, and security. The building type category is categorized as residential and nonresidential buildings, namely schools, hospitals, offices, and public buildings. The technology/materials category includes details on dynamic shadings, chromogenic glazing, solar active facades, and AVF systems. Kızılörenli and Maden (2021) categorized adaptive facade systems under seven headings. First, they defined the system type as active or passive and then classified whether the movements of the elements within the system were individual movements or a total movement where all elements act together. Types of movement were classified as rotation, deforming, folding, sliding, and hybrid. System control was classified as hand-operated and central control, while system functions were categorized as daylight control, thermal control, and air flow. The final two categories are response time and visibility. Another detailed classification proposal was proposed by Voigt, Roth, and Kreimeyer (2023). This classification attempts to identify the main characteristics and set of design parameters of the façade system. The main characteristics are classified into 15 subcategories including control system, goal of adaptation, sensor input, type of adaptation, size of adaptive element, adaptation time, visibility of adaptation, position of the adaptive layer and connection to HVAC.

The system control type is classified into extrinsic and intrinsic, and the goal of adaptation is classified into 9 subcategories: thermal comfort, indoor air quality, visual comfort, acoustic quality, and energy generation. Sensor input includes categories such as light, temperature, sound, and moisture, while the type of adaptation examines whether the change is movement, texture, or color. In this classification, the adaptive element size appears and is categorized. Visibility is classified as only visible or not visible. The adaptive layer position is classified as external, in between, and internal. Another classification system examined within the scope of this study was proposed by Jamilu, Abdou, and Asif (2024), who classified adaptive systems using five main categories. These main categories, each with its own subcategories, are main function, movement and control, triggering stimulus, material properties, and facade transmittance. Facade transmittance, a prominent category, is subdivided into opaque, transparent, and semi-transparent. The system's main function is classified as bioclimatic, energy optimization, daylight harvesting, and aesthetics. Movement and control are categorized as mechanically based, with subcategories including movement control, technology used, and geometric transition, and material deformation is categorized as self-changing and external input. Triggering stimulus is categorized. Material properties are categorized into six categories: phase-changing materials, spathe-changing materials, and shape-memory materials.

The literature demonstrates that the classification of adaptive facades has been addressed by different researchers at various levels. Ochoa and Capeluto (2008) explained facades with a three-layered framework at the sensor, control, and actuator levels; Ramzy and Fayed (2011) added parameters such as system type, degree of motion, and cost. Loonen et al. (2015) expanded this approach by introducing response time and spatial scale, while Waseef and Nashaat (2017) presented a typology based on façade configuration and function. In addition, a highly detailed approach combining technical, motion-based, and morphological approaches was developed by Başarır and Altun (2017). A more material technology-focused approach was proposed by Attia, Lioure, and Declaude (2020) by grouping systems under systems such as dynamic shading and chromogenic glazing. Kızılörenli and Maden (2021), on the other hand, categorized the types of motion, focusing on whether the elements exhibiting this motion operate individually or collectively. Unlike other studies, Voigt, Roth, and Kreimeyer (2023) included extreme stimuli such as earthquakes and floods in addition to environmental effects as triggers of system motion. Jamilu, Abdou, and Asif (2024) developed a classification proposal that incorporates material properties and permeability properties of the materials in the system into categories. In summary, some models focus on technical components (Başarır and Altun 2017; Ochoa and Capeluto 2008), while others focus on morphological (Ramzy and Fayed 2011; Waseef and Nashaat 2017) or performative dimensions (Loonen et al. 2015; Voigt, Roth, and Kreimeyer 2023).

An evaluation of existing classification frameworks indicates that each provides systematic insights when viewed from its own analytical perspective. Building on these contributions, the present study adopts a filtering and integrative approach, drawing on earlier classifications while extending their applicability to more recent, predominantly simulation-based studies. This gap in the literature is addressed by a classification that simultaneously considers technical, functional, contextual, and methodological dimensions for classifying adaptable facades. The categories covered by existing classification proposals are summarized in figure 1 to serve as a basis for developing a new classification system.

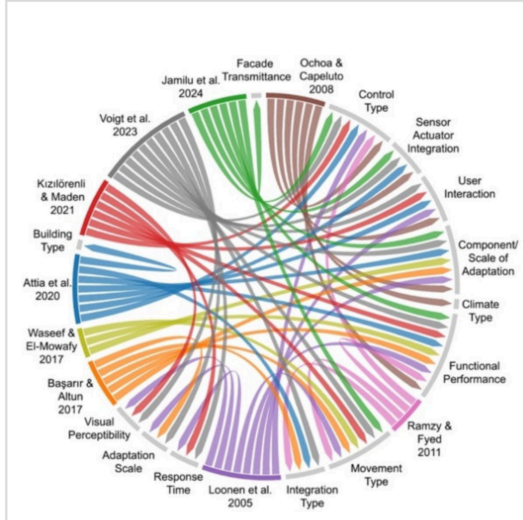

Figure 1. Scope analysis of nine studies at the subcategory level

Studies in the literature exhibit significant diversity in terms of the methods, simulation and analysis tools employed, façade systems examined, geometric configurations, and performance criteria evaluated. Some studies prioritize technical aspects such as energy efficiency and daylight performance, while others focus on factors such as user experience, aesthetic benefits, or contextual suitability. While this diversity reflects the richness of the existing literature, it also hinders the development of a comparable and holistic framework. Therefore, classifications that systematically capture the scope and methodological diversity of studies on adaptive facades are needed. In this context, particular attention was paid to the technical, functional, and contextual dimensions emphasized in previous studies, and their scope was systematically examined through specific categories.

Drawing on existing studies, the proposed classification model synthesizes these multilayered yet fragmented approaches in the literature into a new, context-aware classification system. Categories were first identified and then subcategorized (figure 2). To enable a detailed analysis of the proposed studies in the literature, the subheadings movement type, control type, facade material/transmittance, climate type, building type, functional performance, simulation/analysis tools, research method, and performance metrics were established. These subheadings were then grouped into four categories: system design features, context and application, performance assessment, and research and analytical methods.

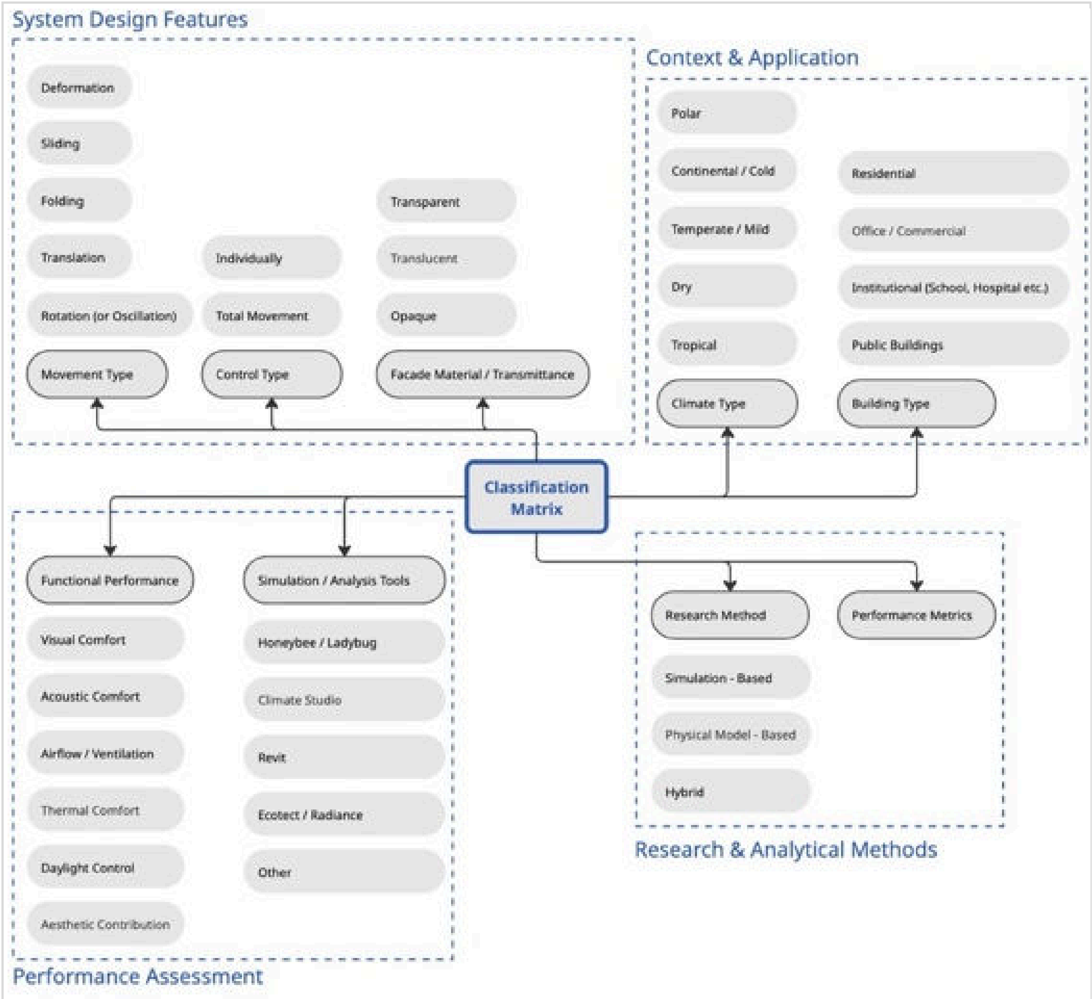

Figure 2. Multi-dimensional classification matrix developed for adaptive façade systems

Subcategories within the System Design Features category examine the movement exhibited by the proposed façade system within the scope of the study, including rotation or oscillation, translation, folding, sliding, and deformation. These elements also act collectively or individually under the Control Type category. Furthermore, the material transmittance of the elements within this system, a key factor affecting the interior space, is examined within the opaque, translucent, and transparent categories. The Context and Application category categorizes the types of spaces where simulations or analyses are conducted and the climate types in which these spaces are located. Climate type categories are based on the Köppen-Geiger climate classification (Köppen 1936). Subcategories are polar, continental/cold, temperate, dry, and tropical, but combinations of these are also used in the classification based on location.

Building Type complements these climate types and focuses on the building's function. Consequently, residential, office/commercial, institutional, and public buildings are subcategories. The third main category, functional performance, is one of the most prominent categories within the classification, focusing on the proposed purpose of the façade. Subcategories such as visual and acoustic comfort, thermal regulation, daylight control, and airflow/ventilation are proposed among these objectives. In parallel, a simulation and analysis tool, which assesses whether these objectives are met, is also included in the classification. The most commonly used categories include Honeybee/Ladybug, ClimateStudio, Revit, and Ecotect/Radiance, while the "other" category is also added to the table for other programs. The final main category, research and analytical methods, addresses the study's methodological approach. Research Method focuses on the proposed system's analysis method. This method is classified by examining whether it is simulation-based, physical model-based, or a combination of both. To understand how the systems focus on daylight performance within the scope of the study, the performance metrics used are also examined. However, due to the variety of metrics used, no category was added under this heading. The metrics examined were added to the table of reviewed studies in later stages.

This approach addresses adaptive façade systems encountered in studies in the literature in technical, contextual and methodological dimensions, while also underlining the importance of daylight performance evaluations.

Literature review and overview

To systematically select systems for analysis within the classification system, adaptive façade systems aiming to improve daylight performance were searched using advanced queries in the Web of Science and Scopus databases. In both databases, the query flow was completed with the following: "façade system" AND "adaptive façade" OR "responsive façade" OR "kinetic façade" AND "daylight performance" OR "daylighting" AND "simulation" AND "daylight metrics". The publication type was restricted to article and conference paper, the publication language was English, and the years were between 2015 and 2025.

This resulted in 685 relevant publications in the Web of Science database. The search in the Scopus database yielded 290 publications. These publications were extracted from the databases and analyzed using VOSviewer software. Mapping was performed based on keywords in the studies. This attempted to highlight research trends within the studies filtered from the literature.

The keyword networks presented in figure 3 reveal the themes and relationships focused on by the existing literature, while also enabling a critical assessment of the field's limitations and weaknesses. The centrality of the concept of "daylighting" is striking; this demonstrates that daylighting research largely revolves around visual comfort, adaptive façade systems, kinetic architecture, and parametric design. However, this central concentration also suggests that conceptual diversity remains limited in the literature. For example, psychological or socio-cultural dimensions of human-building interaction, occupant behavioral preferences, long-term effects on health, or performance criteria that vary according to different climatic conditions have remained relatively minor in these networks. Similarly, despite the rise of concepts such as "thermal comfort" or "non-visual effects," the effects of daylight on biological rhythms, productivity, or social well-being have remained more marginal. The centrality of energy efficiency and performance evaluation themes reveals that daylight is increasingly being discussed in the literature within the context of building energy performance. The prominence of the concepts "energy efficiency," "visual comfort," and "energy utilization" here indicates an interdisciplinary approach, while simultaneously demonstrating a rather fragmented literature. The density of the network suggests that research has deepened in areas such as technical simulation methods, building typologies (e.g., office and residential buildings), and energy optimization, but these studies often progress in isolated subsets. This demonstrates that, despite the development of robust methodological tools, a holistic framework has not yet been established. While color clusters indicate thematic diversity, the limited connections between these clusters reveal that the field struggles to produce integrated knowledge.

Overall, these visuals clearly demonstrate the increasing prominence of daylight and energy efficiency themes in the literature, but they also highlight significant shortcomings. From this perspective, the visuals not only map the current situation but also critically illuminate the necessary directions for future research. These keywords and connections served as a guide and corroboration of the data. Thus, 38 studies representatives of the scope and density of the literature pool were selected for review and inclusion in the proposed classification model.

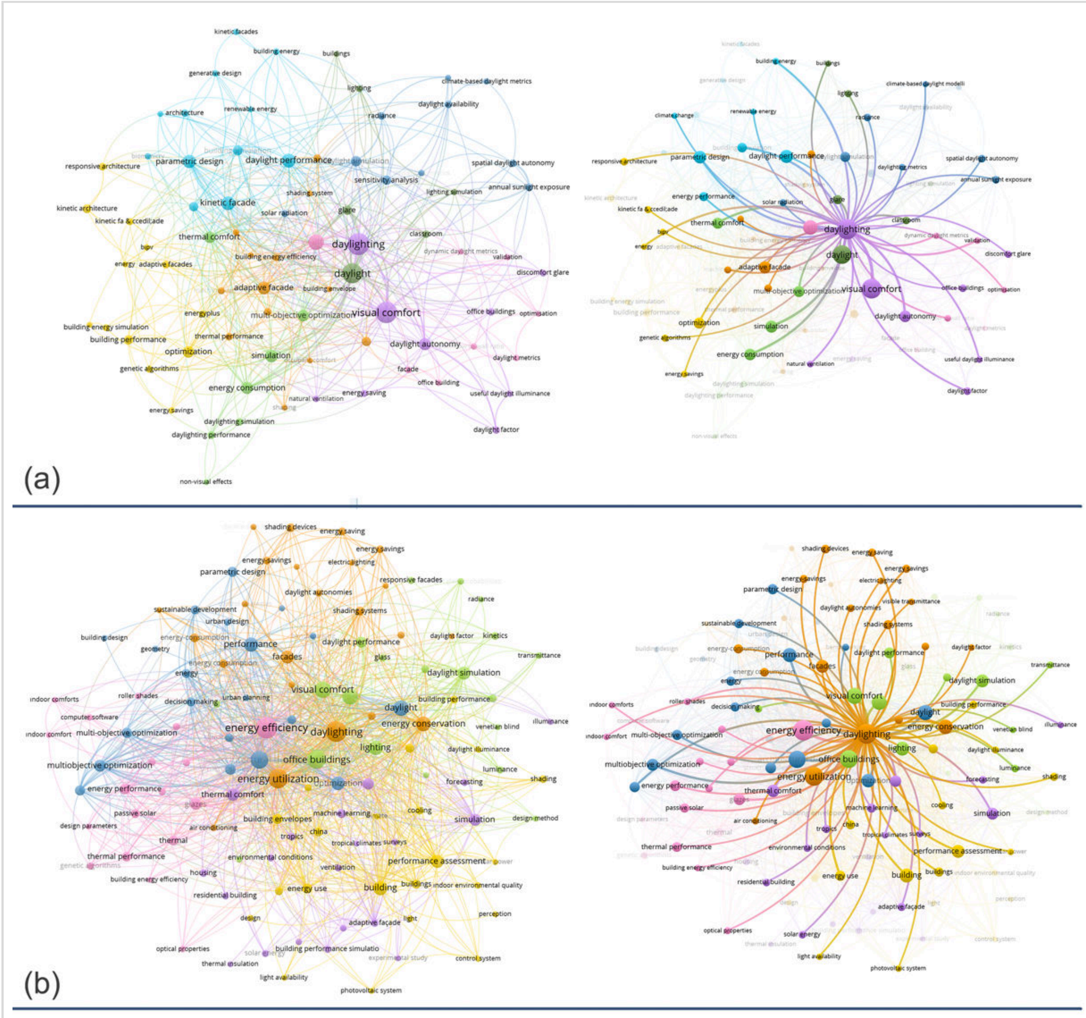

Figure 3. Vosviewer keywords co-occurrence analysis map of reviewed articles, (a) wos database, (b) scopus database

Results and discussion

Adaptive facade systems selected for examination within the scope of this study offer a wide range of design proposals, from material-based adaptive surfaces to modular systems (Fakourian and Asefi 2019; Fallahi et al. 2025; Kızılörenli and Maden 2021; Le-Thanh et al. 2021; Tabadkani et al. 2019). Although these studies address various performance dimensions such as daylight utilization, thermal comfort, energy efficiency, and user experience, they are generally examined within fragmented contexts. This fragmented approach makes it difficult to make a comprehensive comparison between different facade concepts. The selection of the 38 studies was guided by a structured qualitative screening following the bibliometric clustering. From the dominant keyword clusters identified in VOSviewer, studies were selected if they (i) explicitly proposed or tested an adaptive façade system, (ii) employed simulation-based daylight performance evaluation, and (iii) reported quantitative daylight or energy-related metrics. This ensured that the selected publications collectively represent different movement typologies (rotational, folding, sliding, deformation), material strategies, climatic contexts, and evaluation methodologies reflected in the densest regions of the literature. In this context, 38 studies selected from the literature were examined in detail using the categorization system proposed in this study (table 1).

Wanas et al. (2015) demonstrated the performance of rotating panels primarily based on illuminance. Dogan and Stec (2018) adopting a hybrid methodology that integrated physical modelling with Radiance-based simulations, compared rotating systems across multiple climates including humid subtropical and hot desert conditions reporting context-sensitive outcomes. In hot desert conditions, Mahmoud and Elghazi (2016) further highlighted the adaptability of hybrid transformations (translation–rotation–deformation) through DIVA simulations, while El-Dabaa (2016) confirmed the contribution of metallic rotating elements in enhancing illuminance control. Finally, Othman et al. (2017) reinforced a multi-criteria evaluation approach by assessing commercial-scale rotating–folding hybrid systems in a humid subtropical climate, combining daylight metrics with heating and cooling load analyses.

In studies where it was recognized that both material properties and movement types vary, Kim (2018) proposed a system based on textile-based folding surfaces in a continental climate using illumination as the primary evaluation metric. Tabadkani, Banihashemi, and Hosseini (2018), in contrast, studied plastic modules exhibiting translational motion in a hot-arid climate and adopted a multi-metric approach. Hosseini, Mohammadi, and Guerra-Santin (2019) investigated the deformation of individual kinetic elements through material durability and evaluated the performance. Sheikh and Asghar (2019) focused on folding-sliding combinations and evaluated their effectiveness in regulating solar gain and heating-cooling loads along with illumination levels. Tabadkani et al. (2019) extended this trajectory by testing folding-rotating hybrid systems. Similarly, Shi, Abel, and Wang (2020) analyzed rotating-folding modules primarily through illumination-based assessments, while Fakourian and Asefi (2019) emphasized sliding-rotating configurations in terms of solar radiation performance. Collectively, compared to previous research, indicating that the field is increasingly focused on multi-criteria assessments that integrate both comfort- and energy-related dimensions.

In some other studies, methodological diversification and expansion of the tool ecosystem are remarkable. In the context of humid subtropical housing, Sabouri, Daemei, and Siyahkali (2021) optimized rotating panels with Honeybee/Ladybug; KESKİNEL (2020) simulated a façade system based on rotating panels for an educational building in a hot-summer Mediterranean climate with DIVA. In a tropical savanna climate, Le-Thanh et al. (2021) investigated the folding-deformation-rotation combinations with DIVA in an integrated manner with lighting and equipment energy consumption; Heidari Matin and Eydgahi (2022) compared rotating systems in different climates using illuminance. These studies stand out for their ability to interpret versatile solutions with energy in hot and humid climates.

Ningsih et al. (2023) examined systems consisting of rotatable panels with Honeybee/Ladybug (solar radiation); Sankaewthong et al. (2022) compared rotational panels with illuminance levels. Özdemir and Çakmak (2022) examined panels exhibiting rotational motion in the office in ClimateStudio; Hosseini and Heidari (2022) examined deformation-based individual movements with daylight metrics. In 2023, Dev and Saifudeen (2023) studied the rotating–folding system with a hybrid approach; Kızılörenli and Maden (2023) studied rotating systems with daylight metrics in ClimateStudio; Kahramanoğlu and Çakıcı Alp (2023) studied folding modules with again in ClimateStudio; Ahmed, Abdelkader, and Nessim (2023) discussed "sliding (rotational)" configurations at DIVA. These consecutive studies establish visual comfort-focused reporting using specific daylight metrics.

In more recent studies, Fatai (2024) analyzed folding systems with their energy loads (solar gain, cooling/heating load); Cılasun Kunduracı and Kızılörenli (2024) analyzed rotating panels with different daylight orientation systems; Wagiri et al. (2024) folding panels; Şenel, İlerisoy, and Soyluk (2023) the system based on panels exhibiting rotational motion; Sun et al. (2024) folding surfaces; Sommese et al. (2024) deformation based individual movements; Brzezicki (2024) rotating panels; Mehrvarz et al. (2024) folding modules; Nikookar and Sawyer (2024) reported on folding systems; Hosseini et al. (2024) reported on the deformation approach.

Table 1. Selected studies from literature and their classification

Authors and year	Movement type	Control type	Facade transmittance	Climate type	Building type	Functional performance	Simulation/ analysis tools	Research method	Performance metrics
Montier et al. (2013)	Sliding and Folding	Total Movement	Opaque	Humid continental climate	Office Building	Daylight Control, Thermal Comfort and Visual Comfort	IES VE	Simulation - Based	aUDI, Total Energy Consumption
Elghazi et al. (2014)	Folding	Total Movement	Opaque (metal)	Hot desert climate	Residential	Daylight Control	DIVA	Simulation - Based	Illuminance, sDA, ASE
Wanas et al. (2015)	Rotation	Total Movement	Opaque (metal)	Hot desert climate	Office Building	Daylight Control	DIVA	Simulation - Based	Illuminance
Doğan and Stec (2016)	Rotation	Total Movement	Opaque (mirror)	Varies (Humid subtropical climate, Hot desert climate, Subarctic climate)	Office Building	Daylight Control	Radiance	Hybrid	cDA, UDI
Mahmoud and Elghazi (2016)	Translation, Rotation and Deformation	Individually	Opaque (silver matte material)	Hot desert climate	Office Building	Daylight Control	DIVA	Simulation - Based	Illuminance
El-Dabaa (2016)	Rotation	Total Movement	Opaque (metal)	Hot desert climate	Office Building	Daylight Control	DIVA	Simulation - Based	Illuminance
Othman et al. (2017)	Rotation and Folding	Total Movement	Opaque	Humid Subtropical	Commercial Building	Daylight Control and Thermal Comfort	-	Simulation - Based	DF, ASE, UDI, DA, DGP, sDA, Cooling Loaad, Heating Load, Lighting Load
Kim (2018)	Folding	Individually	Opaque (fabric)	Humid continental climate	Office Building	Daylight Control	DIVA	Hybrid	Illuminance
Tabadkani et al. (2018)	Translation	Total Movement	Opaque (plastic)	hot-arid climate	Office Building	Daylight Control and Visual Comfort	DIVA	Simulation - Based	DA, UDI, sDA, ASE
Hosseini et al. (2019)	Deformation	Individually	-	Hot desert climate	Office Building	Daylight Control and Visual Comfort	DIVA	Simulation - Based	DA, UDI, EUDI, DGP
Sheikh and Asghar (2019)	Folding and Sliding	Individually	-	Hot semi-arid climate	Office Building	Daylight Control and Thermal Comfort	Autodesk Revit, Ecotect	Simulation - Based	Solar Radiation, Cooling Load, Heating Load, Illuminance
Tabadkani et al. (2019)	Folding and Rotation	Individually	Translucent	Hot-arid climate	Office Building	Daylight Control and Visual Comfort	Grasshopper + Honeybee/Ladybug	Simulation - Based	UDI, DGI, DGP
Xuepeng et al. (2019)	Rotation and Folding	Total Movement	Varies	Tropical rainforest climate	Office Building	Daylight Control	Grasshopper + Honeybee/Ladybug	Simulation - Based	Illuminance
Fakourian and Asefi (2019)	Sliding and Rotation	Individually	Varies	-	Educational Building	Thermal Comfort, Natural Ventilation and Aesthetic Contribution	Ecotect	Simulation - Based	Solar Radiation
Kenansari et al. (2020)	Rotation	Total Movement	Opaque	Humid subtropical climate	Residential	Daylight Control	Grasshopper + Honeybee/Ladybug	Simulation - Based	DA, sDA, DGP
Keskinel (2020)	Rotation	Total Movement	Opaque	Hot-summer Mediterranean climate	Educational Building	Daylight Control	DIVA	Simulation - Based	Illuminance, sDA, ASE, UDI
Hosseini et al. (2020)	Static	-	Translucent	Hot desert climate	Office Building	Daylight Control and Visual Comfort	DIVA	Simulation - Based	sDA, DA, UDI, EUDI, DGP
Shi et al. (2020)	Rotation and Folding	Total Movement	Varies	Tropical Rainforest Climate	Office Building	Daylight Control and Thermal Comfort	Grasshopper + Honeybee/Ladybug	Simulation - Based	DA, UDI, Illuminance, Total Energy Consumption
Le-Thanh et al. (2021)	Folding, Deformation and Rotation	Total Movement	Translucent	Tropical savanna climate	Office Building	Daylight Control and Thermal Comfort	DIVA	Simulation - Based	sDA, ASE, Lighting Electric Energy, Equipment Energy, Cooling Energy, Total Energy Consumption
Matin and Eydgahi (2021)	Rotation	Total Movement	-	Varies (Tropical monsoon, Hot desert climate, Humid continental climate)	Office Building	Visual Comfort	DIVA	Simulation - Based	Illuminance
Ningsih et al. (2022)	Rotation	Individually	Opaque (plywood based)	Tropical Rainforest Climate	Residential	Thermal Comfort	Grasshopper + Honeybee/Ladybug	Hybrid	Solar Radiation
Sankaewthong et al. (2022)	Rotation	Individually	Opaque (fabric)	Tropical savanna climate	Office Building	Daylight Control and Visual Comfort	ClimateStudio	Hybrid	Illuminance, DF, sDA, ASE
Özdemir and Çakmak (2022)	Rotation	Individually	Opaque (metal)	Hot-summer Mediterranean climate	Office Building	Daylight Control	ClimateStudio	Simulation - Based	DA, UDI, sDA, ASE
Hosseini and Heidari (2022)	Deformation	Individually	Transparent	Hot desert climate	Office Building	Daylight Control	Grasshopper + Honeybee/Ladybug	Simulation - Based	DA, sDA, UDI

Authors and year	Movement type	Control type	Facade transmittance	Climate type	Building type	Functional performance	Simulation/ analysis tools	Research method	Performance metrics
Dev and Saifudeen (2023)	Rotation and Folding	Total Movement	Opaque (varies)	Tropical Monsoon climate	Commercial Building	Daylight Control and Thermal Comfort	Autodesk Revit, Autodesk Insight, Velux	Hybrid	Illuminance, DF
Kızılörenli and Maden (2023)	Rotation	Total Movement	Opaque	Hot-summer Mediterranean climate	Office Building	Daylight Control	ClimateStudio	Simulation - Based	sDA, ASE, UDI, DGP
Kahramanoğlu and Çakıcı Alp (2023)	Folding	Individually	Opaque	Hot-summer Mediterranean climate	Office Building	Daylight Control	ClimateStudio	Simulation - Based	sDA, DGP, UDI, EUDI
Ahmed et al. (2023)	Sliding (Rotational)	Total Movement	-	Hot desert climate	Office Building	Daylight Control	DIVA	Simulation - Based	UDI, DGP
Fatai (2024)	Folding	Individually	-	Mediterranean climate	Office Building	Thermal Comfort	Grasshopper + Honeybee/Ladybug	Simulation - Based	Solar Gain, Cooling Load, Heating Load
Cılasun Kunduracı and Kızılörenli (2024)	Rotation	Total Movement	-	Hot-summer Mediterranean climate	Educational Building	Daylight Control	ClimateStudio	Simulation - Based	sDA, ASE
Wagiri et al. (2024)	Folding	Individually	Opaque (cardboard and metal)	Humid Subtropical	Office Building	Daylight Control and Thermal Comfort	Grasshopper + Honeybee/Ladybug	Hybrid	Illuminance, DF, solar radiation
Şenel et al. (2024)	Rotation	Total Movement	Opaque (wood and fabric)	Continental / Semi-arid climate	Office Building	Daylight Control and Visual Comfort	ClimateStudio	Simulation - Based	sDA, ASE, illuminance
Sun et al. (2024)	Folding	Total Movement	BIPV	Varies (Tropical rainforest climate, Humid subtropical climate, Temperate oceanic climate)	-	Daylight Control and Thermal Comfort	Grasshopper + Honeybee/Ladybug	Hybrid	ADF, solar radiation
Sommase et al. (2024)	Deformation	Individually	Opaque (polymer based)	-	Office Building	Daylight Control and Visual Comfort	Grasshopper + Honeybee/Ladybug	Simulation - Based	UDI, EUDI, sDA, DGP
Brzezicki (2024)	Rotation	Individually	Opaque (metal)	Varies (Oceanic climate, Cold semi-arid climate, Tropical savanna climate with dry winters)	Office Building	Daylight Control	Simulation - Based	Simulation - Based	UDI, DA, DGP
Mehrvarz et al. (2024)	Folding	Individually	-	Varies (Hot Desert Climate, Hot-Summer Mediterranean Climate, Humid Continental Climate)	Office Building	Daylight Control and Visual Comfort	Grasshopper + Honeybee/Ladybug	Simulation - Based	UDI, ASE, sDA, DGP
Nikookar and Sawyer (2024)	Folding	Total Movement	Translucent (fabric)	Humid continental climate with hot summers	-	Daylight Control and Thermal Comfort	ClimateStudio	Simulation - Based	Solar Radiation, sDA, ASE
Hosseini et al. (2024)	Deformation	Individually	-	Hot desert climate	Office Building	Daylight Control and Visual Comfort	Grasshopper + Honeybee/Ladybug	Simulation - Based	sDA, UDI, EUDI, DGP
Yaman et al. (2025)	Folding	Total Movement	Opaque (metal)	Hot-summer Mediterranean climate	Office Building	Daylight Control and Thermal Comfort	Grasshopper + Honeybee/Ladybug	Simulation - Based	sDA, ASE, TCV, EUI
Kızılörenli and Orhon (2025)	Folding	Individually	Opaque	Hot-summer Mediterranean climate	Office Building	Daylight Control	Grasshopper + Honeybee/Ladybug	Simulation - Based	sDA, ASE, GA
Yunitsyna and Sulaj (2025)	Folding	Total Movement	-	Humid Subtropical	Educational Building	Daylight Control and Visual Comfort	ClimateStudio	Simulation - Based	sDA, ASE, sDG, Illuminance
Fallahi et al. (2025)	Rotation and Folding	Total Movement	-	-	Office Building	Daylight Control and Visual Comfort	Grasshopper + Honeybee/Ladybug	Simulation - Based	DGP, UDI

In 2025, Yaman, Kızılörenli, and Tokuç (2025) evaluated folding panels with energy-visual hybrid metrics in Honeybee/Ladybug; Kızılörenli and Orhon (2025) evaluated folding systems; Yunitsyna and Sulaj (2025) evaluated proposed system in ClimateStudio; Fallahi et al. (2025) evaluated the rotating–folding hybrid. This last group reported on the widespread use of Honeybee/Ladybug and ClimateStudio; daylight metrics standardized in visual comfort analysis; It also demonstrates that integrated performance readings are established with energy indicators.

Overall, these studies reveal a clear evolution in adaptive façade research, moving from illuminance-based, single-metric evaluations toward multi-criteria performance assessments that integrate daylight, visual comfort, and energy-related indicators. Despite this methodological maturation, comparative assessment across different adaptive mechanisms remains limited, as most studies focus on a single system configuration or climatic context. Consequently, the literature is rich in isolated performance evaluations but lacks a unified framework capable of systematically relating façade behavior, environmental context, and performance outcomes. This gap directly motivates the development of the proposed classification model.

Conclusions

The systematic mapping completed within this study not only provides a clearer understanding of the current state of knowledge but also establishes a comparative basis for future research and evaluation-oriented studies. Within this framework, façade systems proposed in the literature were examined and organized using the developed classification matrix. This matrix enables different adaptive façade approaches and assessment methods to be evaluated within a shared analytical structure, allowing both common patterns and critical differences among studies to become more visible.

The results indicate that a substantial portion of existing publications concentrate on specific climatic conditions or isolated system configurations, while comparative investigations across multiple contexts remain limited. This highlights the need to broaden the scope of future research, particularly in terms of cross-climatic and cross-typological analyses. In this respect, the study goes beyond compiling existing approaches and instead exposes methodological variations, gaps, and underexplored relationships within the literature.

Looking ahead, future research may benefit from critically re-examining how annual daylight metrics are currently employed, as many studies rely on fixed usage scenarios and simplified operational assumptions when interpreting long-term performance. Rather than treating daylight, energy use, and thermal conditions as parallel outputs, there is a need to explore their interrelations within a shared evaluation logic, particularly in connection with façade control strategies. In this context, human-related parameters such as occupant presence, visual perception, and adaptive behavior remain underrepresented and are often addressed through generic assumptions rather than explicit modeling. Furthermore, the majority of existing investigations remain confined to the single-building scale, which limits the transferability of their conclusions. Addressing these methodological constraints through more context-aware and multi-scale research designs may support more robust interpretations of adaptive façade performance.

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Ecenur Kizilörenli contributed to the research concepts preparation, methodologies, investigations, data analysis, visualization, articles drafting and revisions.

Ahmet Vefa Orhon contribute to the research concepts preparation and literature reviews, data analysis, of article drafts preparation and validation.