Integration Thermal and Daylight Performance of Responsive Facades: A Comprehensive Literature Review

Mustafa Serhan ÜNLÜTÜRK
Lecturer, Balikesir University, Ayvalik Vocational School,
Department of Architecture and Urban Planning, Ayvalik, Balikesir, Turkey
serhan.unluturk@balikesir.edu.tr
https://orcid.org/0000-0001-8368-4169
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Abstract: *Technological advances in robotics have enabled us to see the concept of kinetics in architecture. Responsive Facades, an example of kinetic architecture, are multifunctional in terms of energy efficiency. The façade system improves thermal and visual performance with less energy in the interior. Various responsive facades are being developed according to changing environmental impacts and spatial conditions. This study aims to comprehensively review recent thermal and daylighting performance studies of responsive facades in the literature. The study aims to use the results of such existing studies to guide future studies by providing feedback on responsive facades. This can help to improve the technical development of such facades and make them suitable for construction or retrofitting. Therefore, in this sense, it contributes to the literature. Studies in the literature are tabulated and interpreted. The study concludes that there are indoor thermal and daylight parameters that designers should consider during building design and that the building should be designed to provide the building with physical conditions for the users to perform their actions most comfortably. It was also found that a responsive façade design can provide indoor thermal visual comfort by using the optimization method more frequently.*

Keywords: *Responsive Facades, Daylight Performance, Thermal Performance, Energy Efficiency, Building Envelope.*

Duyarlı Cephelerin Entegrasyon Termal ve Gün Işığı Performansı: Kapsamlı Bir Literatür İncelemesi

Özet: *Robotik alanındaki teknolojik gelişmeler, kinetik kavramını mimaride de görmemizi sağladı. Kinetik mimarinin bir örneği olan Duyarlı Cepheler, enerji verimliliği açısından çok işlevlidir. Cephe sistemi, iç mekanda daha az enerji ile termal ve görsel performansı artırır. Değişen çevresel etkilere ve mekânsal koşullara göre çeşitli duyarlı cepheler geliştirilmektedir. Bu çalışma, literatürdeki duyarlı cephelerin son termal ve gün ışığı performansı çalışmalarını kapsamlı bir şekilde incelemeyi amaçlamaktadır. Çalışma, bu tür mevcut çalışmaların sonuçlarının, duyarlı cepheler hakkında geri bildirim sağlayarak gelecekteki çalışmalara rehberlik etmesini hedeflemektedir. Bu, bu tür cephelerdeki teknik gelişmelerin iyileştirilmesine ve inşaat veya iyileştirmeler için uygulanabilir hale getirilmesine yardımcı olabilir. Dolayısıyla bu anlamda literatüre katkı sağlamaktadır. Literatürdeki çalışmalar tablolaştırılmış ve yorumlanmıştır. Çalışmada, tasarımcıların bina tasarımı sırasında göz önünde bulundurması gereken iç mekan termal ve gün ışığı parametreleri olduğu ve binanın kullanıcıların eylemlerini en rahat şekilde gerçekleştirebilecekleri fiziksel koşulları sağlayacak şekilde tasarlanması gerektiği sonucuna varılmıştır. Ayrıca, duyarlı bir cephe tasarımının optimizasyon yöntemini daha sık kullanarak iç mekan termal görsel konforunu sağlayabileceği bulunmuştur.*

Anahtar kelimeler: *Duyarlı Cepheler, Gün Işığı Performansı, Termal Performans, Enerji Verimliliği, Bina Kabuğu.*

1. INTRODUCTION

Architecture, which is a part of life, is changing and developing daily. As human activities change, the concept of movement has gained a place in design. The existing building stock cannot meet the developing needs. For this reason, designers have developed different design proposals to meet user needs and ensure energy efficiency. The building envelope, which plays a distinctive role, affects user comfort [1]. Designers have sought solutions to the problems by adding the concept of movement to the building facade [2]. The conventional static facades cannot adapt to changing climatic conditions. A responsive façade system has been developed as a design proposal that simultaneously solves changing conditions [3]. While this façade system adapts to changing environmental conditions, its structural integrity is not damaged. Responsive facades' geometric shapes and locations can produce instant solutions to evolving conditions. However, static facades do not have such a feature [4, 5].

In the context of energy efficiency, resources should be utilized with maximum effectiveness at every stage, beginning with the production phase. The Paris Agreement aims to achieve a climate-neutral environment by 2050. In 2009, the EU established its 20-20-20 targets, which seek to reduce energy consumption and greenhouse gas emissions while increasing the use of renewable energy. Responsive facades that maximize daylight and enhance natural ventilation can help optimize a building's energy consumption. It is well-known that the building sector consumes more energy than other sectors. Therefore, it is believed that this new facade system will reduce the overall energy demand of buildings.

Studies on sensitive facades built according to changing environmental conditions and needs have been conducted recently, and the features of this facade system have also been examined. It is valuable in terms of exploring the place of sensitive facades within the scope of energy efficiency studies in the literature. The study systematically reviewed the studies on the thermal and daylighting performance of responsive facades in the literature. The evaluation criteria, methods and tools used by previous studies to examine the thermal and daylighting performance of responsive facades are analyzed in depth. The study is essential in compiling previous studies on the building's physical conditions of sensitive facades, the methods used, the frequency of the studies, and the climatic regions covered by the study. The study constitutes a review for future studies on the building physics behavior of responsive facades.

2. METHODOLOGY

The definitions of daylighting performance, thermal performance, and responsive facades guide the study. Previous articles on the subject were compiled from 4 different databases using these words. The limitations of earlier studies and the methods/tools used were the evaluation criteria. Certain limitations were also imposed on the main topics identified in the study. Research on thermal performance includes i) the definition of thermal performance, ii) the thermal performance-energy relationship, and iii) thermal performance and optimization. Research on daylighting includes i) daylighting performance, ii) daylighting-energy relationship, and iii) daylighting optimization. Studies examining responsive facades include i) The definition and characteristics of a responsive facade, ii) the thermal performance of responsive facades, and iii) daylighting performance of responsive facades are analyzed in 3 groups. This study aims to investigate responsive facades' thermal and daylighting performance and provide an in-depth understanding of their energy consumption comfort relationships. Figure 1 shows the methodology used to achieve the research objective. Articles outside the scope of the study were excluded. In addition, the methods used by the articles within the scope of the study to achieve the objective were also evaluated.

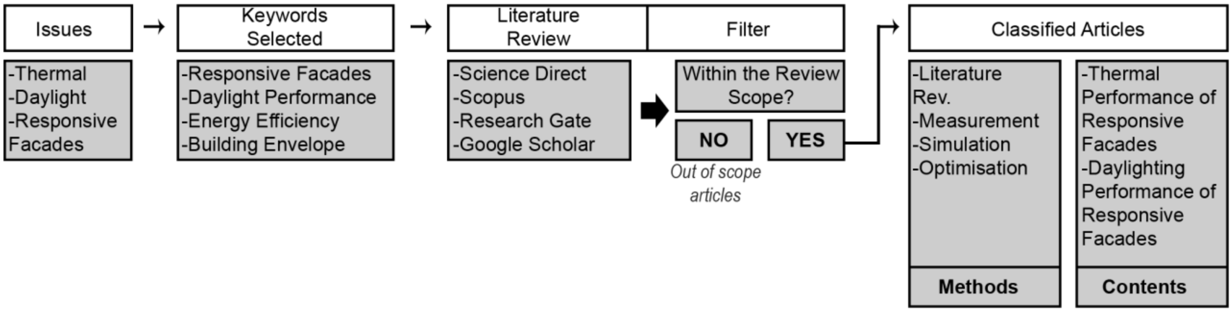

Figure 1. Workflow of the study

3. THERMAL and DAYLIGHT PERFORMANCE

People spend most of their time indoors. Users will perform different actions during the time they spend in these spaces. To perform these actions, the space must provide user comfort. If the space in which the users are located is not heated/cooled sufficiently, users may be unable to perform their actions comfortably. In such cases, the amount of energy used to provide thermal comfort indoors increases. Artificial lighting elements may be needed if daylight is not sufficiently received indoors during daylight hours. This increases the amount of energy used for lighting. When daylight is taken indoors more than necessary, glare problems may occur. This negatively affects the user's eye health.

3.1. Effect of Thermal Performance on Energy Consumption

Heating and cooling may be required to ensure user comfort in the interior of buildings. Typically, a building's heating, cooling and ventilation systems are the main energy consumers. The energy required for heating or cooling can be reduced by measures taken at the design stage of the building envelope.

A review of the literature shows that there are studies that use simulation methods to improve the thermal performance of the building. Diler used Ulu Cami as a case study in his research in Manisa. As part of the study, the researcher monitored the mosque with a data logger and created the thermal model in the DesignBuilder program. In the scenarios created, user dissatisfaction decreased from 45% to 10% [10]. In addition, a 46.9% energy saving was achieved in the designed scenario compared to the current situation. The study by Han et al. used an office building as a field study. Monitoring was carried out in the study to verify the simulation data with accurate data. PHPP and IBE perform a thermal simulation of the office building. The results of the study show that the office building is 69% more energy efficient than a standard office building [11]. Given the size of the existing building stock, the importance of improving existing buildings to increase energy efficiency must be considered. Motalebi presents a BIM-based mathematical optimisation model to improve the energy efficiency of existing buildings. The optimisation included the selection of alternative materials. The model obtained from the optimisation provided a 24% - 58.2% reduction in energy consumption [12].

Recent studies have examined the impact of various materials on energy consumption. In 2020, Li incorporated a phase change material (PCM) into the building's glass, which proved effective in enhancing thermal performance. The experimental model indicated that as the amount of PCM increases, the temperature lag also increases. However, the effect of the PCM layer thickness on transmitted solar energy varies. The total transmitted energy reaches its peak between 00:00-14:30 and 20:00-24:00, while the highest level of transmitted solar energy occurs between 05:00-11:00. In 2022, Hou integrated PCM into the walls of the building. The results of this study showed that the PCM effectively contributed to thermal management.

3.2. Effect of Daylight Performance on Energy Consumption

Using artificial lighting contributes to carbon emissions, which in turn exacerbates global warming. Sustainability involves using energy efficiently and minimizing carbon emissions. In Europe, buildings account for 40% of total energy consumption, with 19% of that energy used for lighting. Studies indicate that the electricity consumption of European buildings ranges from 20 to 50 kWh per square meter. Natural light is a crucial element in modern architecture, as it reduces the reliance on artificial lighting indoors. By effectively utilizing daylight, we can potentially save 223 million tonnes of CO2 emissions and decrease energy demand by 24,000 MW. Krarti found that the use of artificial lighting can increase a building's annual energy consumption by 40%.

IHM conducted its 2009 study in 18 different regions. The study aims to investigate the effect of building geometry, window size and glazing type on daylighting performance in other countries. The study, which focuses on office buildings, used the DOE-2 program in the simulation process. The unit of measurement used in the study is the lumen. The results of the study show that significant energy savings can be achieved through the use of daylighting control, where natural light can be appropriately introduced into the interior. Ihm found that lighting control systems can reduce the amount of energy used for artificial lighting in buildings [20]. In 2013, Alrubaih analyzed the main characteristics of daylighting and lighting control strategies, including daylight factor, illuminance and glare index. As a result of the literature review in the study, it was found that the correct design and selection of daylighting systems not only reduces the need for artificial lighting, but also the amount of energy required for cooling. In addition, the daylight factor is widely used to characterize the daylight situation in a building [21].

However, daylight alone cannot provide energy efficiency indoors. Photo sensors that regulate artificial and natural lighting indoors should be integrated [22]. Building Research Institute (BRE) and CIBSE have examined different lighting control systems and recommend using manual-automatic lighting control systems [23, 24]. Excessive daylighting indoors can also cause visual problems such as glare. To prevent these problems, shades can control daylight in designs with a high window/wall ratio [25].

Cheng's study in China aimed to reduce energy consumption by increasing the amount of daylight entering the building. To achieve this, STPV facades were integrated into the traditional facade. The study was simulated using DAYSIM. The results of the study suggested an optimal design with 50-60% transmission, 40-50% WWR range and south orientation of STPV facades in buildings located in cold climate zones to maximize the energy potential of STPV facades [26]. In 2019, Gutiérreza also investigated the relationship between the materials used in the louvre systems and daylight performance and energy consumption. DAYSIM models and daylight simulate the building under study, taking into account the DA and UDI daylight metrics. In all modelled cases, the proposed ceramic louvres outperformed the other systems, providing a more uniform distribution of light within the illuminated area. In terms of artificial lighting energy savings, aluminum louvres offered the best performance [27].

In 2019, Sun is also investigating the relationship between daylight performance and energy consumption in 5 regions of China. The study examines the energy and daylighting performance of offices in 5 different climate zones in China with PV windows and different façade designs. Radiance and EnergyPlus are used to model the analyzed building. Daylight and energy simulations are provided by the developed model. The results of the study show that the application of PV windows can lead to energy savings at a high window-to-wall ratio [28].

4. RESPONSIVE FACADES

In the late 19th century, urbanization started to develop along with industrialization and technological developments. The development of responsive facades also dates back to this period. Architects of this period aimed to design mobile responsive systems by leaving aside the static stance of the building. Movements such as Bauhaus, futurism, and constructivism considered the aesthetics of the industrial age and reflected this aesthetic in the buildings. In the 1920s, Naum Gabo's sculpture 'Standing Wawe', a kinetic artwork, pioneered architects in the movement of buildings [29].

Environmental sustainability movements and the energy crisis in the 1960s emphasized the efficient use of energy and the reduction of natural resource use. In addition, sustainability and energy efficiency started to be effective in architecture. The increasing awareness as a result of the oil crisis in the 1970s pioneered the energy-efficient design of buildings [30]. In this period, responsive facades became the most important part of environmentally friendly designs.

Ferguson defines functional responsiveness as adapting the design variables of a system to environmental conditions [31]. A responsive facade created with different calculations plays an active role in buildings [32]. Responsive components are the elements that provide adaptation according to people's needs and environmental changes [33]. High-tech responsive components can use sensor networks for environmental control. Responsive facades include elements that can move to meet the performance of the building. This facade system can provide the passage and storage of heat, light, water and air. It also offers optimal internal conditions and energy efficiency for building users. Responsive facades are essential for environmental sustainability and efficiency of resource use [34]. Figure 2 shows different responsive facade examples.

Figure 2. Some pictures of responsive façades: a) Arab World Institute, Paris (FR) [35], b) Al Bahar Towers, Abu Dhabi (AE) [36]. and Al Bahar Towers façade [37].

The working principle of a responsive facade is based on specialized subsystems, such as structural elements and sensors, that modify the building envelope according to incoming stimuli and programming [38]. A responsive building envelope includes functionalities and performance characteristics similar to those of a 'smart' building envelope, including real-time sensing, kinetic climate adaptive elements, intelligent materials, automation, and user override capability. A building with a responsive facade incorporates kinetic elements and similar functionalities and performance characteristics to a smart building envelope. The system is also capable of self-adjustment and learning using computational algorithms. In this way, it can physically manipulate the building envelope elements [39]. The development of technology facilitates the design of this facade system. In addition, building energy efficiency and comfort conditions can be increased by simulations and optimization processes before design. In 2016, Chen aimed to create a design with higher energy performance than the existing responsive facades. In this context, BIM (Building Information Modelling), parametric design, and integration of sensor devices were examined. The study conducted research on the design process of responsive facades, and criteria for compliance with green building regulations were developed. The research both simulated energy in a computer environment and calibrated the model by making accurate measurements in the physical environment. Dynamo creates a parametric model of a responsive facade. BIM-based green building control system is applied through this model. Thus, the study proposes an optimization system for responsive facade design [40].

Since the late 19th century, the evolution of responsive facades has continued. Social-political developments and technological and environmental factors affect the development of responsive facades. Heidari, who examined the historical development and benefits of these facades, chronologically reviewed the development of responsive facades together with important events such as art movements, technological advances, and energy crises, which impacted the development of facade systems in his study in 2020. According to the results obtained in the study, energy efficiency in buildings with responsive facades is 20-60% higher than in buildings with traditional facades. The author emphasizes that the most critical factor is the adaptability of this facade system to different climatic conditions. The study emphasizes that responsive facades have high energy efficiency and low carbon emissions compared to buildings with traditional facades. It is stated that the carbon emission of a building can be reduced by up to 20% by using this facade system. The study also states that responsive facades can be applied not only at the building scale but also at the intelligent city scale. By integrating the sensors and actuators of responsive facades into urban-scale buildings, neighborhoods and urban spaces that can respond to environmental impacts can be designed. Responsive facades can reflect a society's cultural values and provide energy efficiency and user comfort. This shows that this facade is a functional building element and a cultural heritage [41].

The technologies used in responsive facades are also very significant. Heidari evaluates these systems through control, sensing, and mobilization technologies. Heidari, who wants to present the advantages and disadvantages of different systems and propose an efficient facade proposal, has examined 38 different responsive facades in this context. The study compares the control, sensing, actuator, material, and structural technologies used in these facades. The study analyzed the control technologies of these facades by analyzing how the control systems of responsive facades process signals from environmental data or user preferences. In this context, the ability of the facades to adapt to changing environmental conditions was evaluated. Sensing technologies were evaluated by assessing the performance of sensors that detect stimuli such as environmental factors such as light, temperature, and user interactions. Actuators provide the movement or physical change, one of the most important features of responsive facades. The study analyzed the material and electro-mechanical properties of the actuators. The study also analyses the material properties of the facade. It states that the adaptation of these facades to the environment increases with innovative materials such as shape-memory alloys and electroactive polymers. The study results show that responsive facades can improve energy efficiency and provide users with better thermal and visual comfort. The study's results support the results of Heidari's 2020 survey by showing that responsive facades are more energy-efficient than traditional facades. When the energy performance of responsive facades is evaluated, it is concluded that they are 40-65% more energy efficient than conventional facades [42].

4.1. Thermal Performance of Responsive Facades

The energy crisis has led people to aim for optimum conditions with minimum energy use. In addition, climate change (CC) and sustainable development require us to be careful about energy consumption. Today, it is known that energy consumption in the construction phase of the construction sector is relatively high, as well as energy consumption in the use phase of the building. When the existing building stock is analyzed in terms of thermal and energy performance, it is evident that the majority of them need to be improved. For this reason, thermal and energy performance should be taken into consideration during the design phase of buildings, and energy-efficient retrofits should be made in existing buildings. The main reason for this is the aim of providing optimum indoor user comfort and minimizing environmental problems [43]. In this context, responsive facades developed to provide energy efficiency and optimum user comfort can adapt to physical environmental conditions through the kinetics of the facade. In this way, this facade system can effectively prevent thermal discomfort in the interior. There are studies examining the thermal comfort of responsive facades in the literature. In 2013, Jang aimed to present a responsive facade design proposal using sensors and actuators in his study in Seoul. The study creates an energy model in Rhino/Grasshopper to achieve the goal. The study results emphasize that through a collaborative design system, design feasibility and decision-making processes can be accelerated [44]. A study in Italy in 2014 aimed to develop advanced integrated façades (AIF), a concept of responsive building elements, and improve thermal performance by creating a façade module. The study includes energy modeling and simulations of an actual building. As a result, in the proposed façade module, the u value is 0.08 W/m2K in the opaque part and 0.6 W/m2K in the transparent part [45].

It is known that the climatic suitability of responsive facades is high thanks to the movements and reactions in their structure. In 2018, Prieto investigated the energy performance of commercial buildings with responsive facades in hot climates. The study addressed dry and humid regions of hot temperatures. DesignBuilder and EnergyPlus have modeled and energy-simulated commercial buildings in Delft. While the average cooling demand in hot, dry climates is 22-50%, simulations show that commercial buildings with responsive facades require 26-33% energy for cooling. While the average cooling demand in hot and humid climates is between 12%-33%, simulations show that the cooling energy requirement of responsive facades is between 2-22% [46]. In Yoon's study in Seoul in 2019, he aimed to propose a responsive facade model using active and dynamic facade systems using Shape Memory Polymers (SMP) to develop temperature-sensitive facade elements. The study aims to improve energy efficiency with the use of SMP. SMPs can change shape within a specific temperature range and can optimize the energy balance in the interior space according to the temperature change in the building facade. For example, when the temperature increases, SMPs expand and provide more shade area. This prevents the indoor cooling load from increasing. Likewise, when the temperature decreases, its volume decreases, allowing more daylight to enter the interior. Yoon performed a simulation using Cubicreator, a plug-in of Grasshopper. The results of the simulation showed that the proposed SMP material reaction façade has a solar radiation level between 258.77 - 517.54 kWh/m², which is lower than the existing situation. In addition, since SMPs do not require mechanical assembly, it is stated that the maintenance cost is very low and that they can maintain energy performance in the long term [47]. In 2022, Shahrzad aimed to increase energy performance by integrating phase change materials into responsive facades. In this context, he aimed to incorporate a phase change material called MICRO-V, a temperature-sensitive material, into the responsive facade using the optimization method. In this context, the study used the COMSOL Multiphysics program in optimization. The results of the survey show that controlling the climate using phase change materials causes an average increase of 3 ◦C in air temperature during winter months and decreases the extreme temperature by 5 ◦C during extremely hot summer periods [48].

Responsive facades can be applied to traditional facades and different facade systems. In the literature, there is research on different facade systems where responsive facades are applied. Aruta aims to integrate a responsive facade to improve the energy performance of an office building with a DSF system in 2023. Within the scope of the study, an existing office building in Naples is considered. DesignBuilder created the energy model of the office building. EnergyPlus simulated the obtained model. The study results show that the proposed models' heating load is reduced by 17.8% to 37%, and 20% of the primary energy is saved [49]. Table 1 shows the studies on responsive facades.

4.2. Daylight Performance of Responsive Facades

The design goal of Responsive Facades is to improve the interior visual and thermal comfort. Figure 3 shows the daylight penetration into the interior of a building with a responsive facade. There are studies in the literature investigating the daylight performance of responsive facades. In 2018, Valitabar aimed to investigate the visual performance of responsive facades. In this context, it used Ladybug, the Grasshopper plugin. Ladybug simulates the daylight of the model created in Grasshopper. The results of the study show that responsive facades can provide better visual comfort conditions indoors than traditional facades [50]. In addition, another study conducted in 2018 draws attention to the shading element used in this facade system. Matin, who investigated the effect of interior visual performance on educational performance in buildings with responsive facades, created an experiment process involving students in his study. Matin parametrically designed the academic space and responsive facade in Rhino/Grasshopper and investigated the effects of design variables on visual performance. The study also aims to create optimum visual comfort conditions by considering different space occupancy rates. The study performed daylight simulations in Ladybug and Honeybee plugins of Grasshopper. The study results show that using angled shading elements in a responsive facade will increase the visual performance by 5 - 20% compared to no shading elements. With this result, the study emphasizes the importance of shading elements in providing daylight performance in responsive facades [51].

In Kim's study, he aimed to solve the geometric flexibility problem of rigid body kinetic building facades, which is disadvantageous in free-form architecture. He considered daylight and thermal criteria (UDI, DA, 0C) in his modeling. Within the scope of the study, models were produced with a 3D printer to achieve the goal. The resulting recommendations obtained the thermomechanical response of SMA activation, the stretchable fabric shell's stretchable morphology, and the maximum aperture area ratio of ~20% [52]. Chuan aimed to investigate the daylight factor (DF) of 3 different sun-sensitive façade models reflecting Siamese culture. Daylight simulation was used as a method in the study. Velux simulates daylight. According to the results obtained, the DF value varies between 1.0 and 3.5 in all models, and the religion-inspired pattern exhibits the best result among these models [53].

Studies on daylight optimization in responsive facades are also available in the literature. In 2022, Heidari aimed to optimize lighting in buildings with responsive facades. In this context, he used Rhino/Grasshopper and DIVA programs. The study states that louvers significantly increase indoor lighting in buildings with responsive facades in all possible scenarios [54]. Kahramanoglu also aimed to design a responsive facade model with origami principles to improve visual comfort in the interior space. Within the scope of the study, he used the optimization method to achieve the goal. The Kangaroo plugin carries out the simulation and optimization process. As a result of the study, it was found that the daylight performance of the proposed origami-based responsive facade is better than the current situation [55].

There are three historic squares in the city. The first is called Al-Armoutia, which still exists today and is bordered by Sibats. The inhabitants of the city continue to use it for popular events and gatherings. The second square is known as the Tanning Square, a large area surrounded by shops specializing in leather tanning. After the implementation of an organizational plan and the opening of a road at the edge of the square, most of the shops created an entrance on the road, which led to the square's neglect and the deterioration of many of its landmarks. The third square is called the Old Market Square. This square was also affected by the organizational plan; however, a corner of it remains, still surrounded by the old shops today.

Figure 3. Daylight penetration into the interior of a building with a responsive facade [56].

Toodekharman worked on visual performance in hospitals in Tehran in 2023. In his study, it is aimed to optimize visual performance in patient rooms by using a responsive facade system in hospitals. Rhino/Grasshopper created the hospital's parametric model. HoneybeePlus performed a daylight simulation of the obtained parametric model. In the study, ASE, sDA, DGI, and DGP from daylight metrics were compared. Unlike its counterparts, the study considers glare parameters (DGI and DGP). The results emphasize the importance of window/wall ratio in indoor daylight performance. It was found that the façade proposal of a hospital with a responsive facade in Tehran with a window/wall ratio of 60% showed the best result [57].

Sommese dealt with biomimicry in his study. Gazania flower develops completely when it receives sunlight. While the flower remains closed in the shade, it opens when it sees the sun. Within the scope of the study, Sommese aims to propose a light-responsive kinetic facade based on the functional principles of the Gazania flower. Rhino/Grasshopper creates the parametric model. Honeybee and Ladybug perform daylight simulations of the obtained parametric model. Since shadow areas and glare are effective in the opening and closing of the Gazania flower, the DGP metric is also considered in the study. As a result of parametric simulations, in an office building in a temperate Mediterranean climate, the biometric kinetic system can provide daylight to 87.5 to 100% of the office place [58].

Table 1. Studies about responsive facades

Year of Study	Region/ Period	Latitude	Analysis /Parameter	Examined system	Aim	Method	Tool	Type of Building	Main Findings & Results
2012, [59]	Philadelphia, ABD	40^0 (N)	-	Responsive facade	Adapting the movement in cell biology to architecture.	Simulation	Rhino/ Grasshopper	Modern Buildings	Although they require high construction costs, material procurement challenges and skilled labor, complex facades have performance-based advantages.
2013, [44]	Seoul, South Korea	37^0 (N)	^{0}C	Responsive facade	To present a responsive facade design proposal with the use of sensors and actuators.	Prototyping Simulation	Facade model Rhino /Grasshopper Firefly	Modern Buildings	Through a collaborative design system, the feasibility of the design and the decision-making process can be accelerated.
2014, [45]	Torino, Italy	45^0 (N)	^{0}C	Responsive facade	To develop advanced integrated façades (AIFs), a concept of responsive building elements, and propose a façade module.	Prototyping	Model	Modern Buildings	In the proposed façade module, the u value is 0.08 W/m2K in the opaque part and 0.6 W/m2K in the transparent part.
2015, [60]	Sheffield, UK	53^0 (N)	-	Responsive facade	To compare changing environmental characteristics with responsiveness to changes in user needs and activities.	Literature Review	-	Modern Buildings	Architectural components suitable for environmental and user changes should be used in buildings. Architects should take these changes into consideration during the design phase.
2015, [61]	Torino, Italy	45^0 (N)	KWh/ m2	Responsive facade	Analyzing the orientations and thicknesses of chambers with PCM and aerogel layer-filled glass.	Simulation	Rhino/ Grasshopper DIVA	Modern Buildings	EDgl observed a reduction in energy consumption in the range of -39% to -46% compared to the Responsive Building Elements single glazing developed in the study.
2016, [62]	Cambridge, UK	52^0 (N)	W/m^2 K	Responsive facade (MFM system)	Evaluate the building performance of multifunctional façade modules with measurements.	Measurement	TWINS test cell system	Modern Buildings	As a result of the measurements, it was found that MFM systems performed very well in general.
2016, [40]	Jhongli, Taiwan	24^0 (N)	-	Responsive facade	To create a BIM based energy efficient responsive facade optimization algorithm.	Simulation	Dynamo	Modern Buildings	Digital production and sensitive sensors are required to achieve optimum performance, and this façade system can be developed with BIM-based optimization methods during the design phase.
2018, [50]	Tehran, Iran	35^0 (N)	Lx	Responsive facade	To compare sensitive facades aesthetically.	Simulation	Rhino/ Grasshopper Ladybug	Modern Buildings	Responsive facades can provide better visual comfort conditions indoors.
2018, [46]	Delft, Netherlands	52^0 (N)	kWh/ m2 year	Responsive facade	To investigate the passive cooling performance of commercial buildings located in hot climate zones.	Simulation	DesignBuilder EnergyPlus	Commercial Buildings	While the average cooling demand in hot dry climates is between 22%-50% in the current situation, these values were obtained between 26%-33% in the simulations. In hot humid climates, while the average cooling demand is between 12%-33% in the current situation, these values are between 2%-22% in simulations.
2018, [51]	Ypsilanti, USA	42^0 (N)	UDI	Responsive facade	To investigate the effect of shading elements on daylight performance in buildings with responsive facades.	Simulation	Rhino/ Grasshopper Ladybug	Educational Buildings	Responsive facades with shading elements have 5-20% better daylight performance than those without.

2019, [47]	Seoul, South Korea	37^0 (N)	^{0}C	Shape memory polymer	To propose a responsive façade model suitable for the Seoul climate using active and dynamic façade systems.	Prototyping Simulation	3D printer Rhino/ Grasshopper Cubicreator	Modern Buildings	The resulting responsive façade proposal with SMP material has a solar radiation level between 258.77 and 517.54 kWh/m², which is lower than the current situation.
2019, [63]	Tabriz, Iran	38^0 (N)	^{0}C	Responsive kinetic facade	Proposing a kinetic façade using moving components.	Simulation	Ecotec	Educational Buildings	In the study, it is stated that the curtain wall system proposed for educational buildings will address the changing needs of users and will be sustainable.
2020, [41]	Ypsilanti, USA	42^0 (N)	-	Responsive facade	To examine the development of responsive facade systems chronologically.	Literature Review	-	Modern Buildings	It is concluded that art, technological developments and economic factors are influential in the development of responsive facades. The chronological chart can be used to predict the evolution of responsive façades in the future.
2021, [64]	Toronto, Canada	43^0 (N)	^{0}C	Climate responsive facades (CRFs).	Develop a preliminary design tool for creating CRFs.	Design Method	Technology screening	Modern Buildings	The responsive façade for Toronto's climate is provided by a transparent and opaque module designed on a Trombe wall containing a ventilated cavity.
2021, [65]	Naples, Italy	40^0 (N)	-	Double skin and Responsive facade	To compile studies that reduce energy losses from the building envelope with double skin and responsive façade systems.	Literature Review	-	Modern Buildings	Ecological and future-oriented designs can be made through renovations to the building stock.
2021, [66]	Lahore, Pakistan	31^0 (N)	-	Responsive facade/kineti c jali	To emphasize the importance of jali/screens by using parametric methods to obtain new facade designs.	Literature Review	-	Modern Buildings	Kinetic sensitive jali designs can be made using parametric design methods.
2022, [42]	Ypsilanti, USA	42^0 (N)	-	Responsive facade	To examine responsive facade system technology and to examine existing facade examples.	Literature Review	-	Modern Buildings	Responsive façade technologies are divided into five classes: mechanical, electromechanical, passive, information and advanced materials. The advantages and disadvantages of these technologies are discussed.
2022, [54]	Ypsilanti, USA	42^0 (N)	UDI Lx	Responsive facade	Optimising lighting in buildings with responsive facades.	Optimisation	Rhino/ Grasshopper DIVA	Modern Buildings	It was found that in buildings with responsive facades, louvers significantly increase indoor illumination in all possible scenarios.
2022, [67]	Cairo, Egypt	30^0 (N)	^{0}C	Responsive facade	To propose a responsive façade model to improve building facades in Egypt by considering the rules of building physics.	Simulation	Rhino Envi-met Climate Consultant	Garage Building	The negative effects of the built environment can be minimised with a responsive façade system designed with a good understanding of the rules of building physics.
2022, [68]	Tehran, Iran	35^0 (N)	^{0}C kWh	Microalgae bioreactive facade	To propose a model that reduces solar radiation in the building by developing a microalgae bioreactive façade and keeps the user thermal needs at an optimum level.	Experiment Simulation	EnergyPlus Rhino/ Grasshopper Honeybee	Modern Buildings	The daylight transmittance of the façade remains mostly constant, as microalgae cultures usually remain constant throughout the day. This makes it easier to control indoor thermal comfort.
2022, [48]	Toronto, Canada	43^0 (N)	^{0}C	Responsive facade	Optimisation of the multifunctional integrated climate-sensitive opaque and ventilated dynamic	Optimisation	COMSOL Multiphysics	Modern Buildings	Controlling the climate using phase change materials resulted in an average increase in air temperature of 3°C during the winter

					façade called MICRO-V.				months and a reduction in extreme temperatures of 5°C during extremely hot summer periods.
2023, [55]	Kocaeli,Turkey	41^0 (N)	UDI	Responsive facade	To increase the visual comfort of the interior, design a responsive façade model using origami principles.	Optimisation	Rhino/ Grasshopper Kangaroo	Office Buildings	The daylight performance of the proposed origami-based responsive façade is found to be better than the current situation.
2023, [52]	Gyeonggi, South Korea	37^0 (N)	UDI DA ^{0}C	Responsive facade	Solution to the problem of geometric flexibility of rigid body kinetic building facades, which is a disadvantage in free-form architecture.	Prototyping	3D printer	Modern Buildings	In the proposals, the thermomechanical response of SMA activation achieved the stretchable morphology of the stretchable fabric skin and a maximum opening area ratio of ~20%.
2023, [49]	Naples, Italy	40^0 (N)	^{0}C kWh	Responsive double skin facade	To propose a dynamic double skin façade for an existing office building in a Mediterranean climate.	Simulation	DesignBuilder EnergyPlus	Office Buildings	The heating load of the proposed models ranges from -17.8% to -37% and the cooling load from 9% to -3%. In the best proposal, savings of 20% of primary energy are achieved.
2023, [53]	Penang, Malaysia	5^0 (N)	UDI	Solar responsive facade	To investigate the daylight factor (DF) of 3 different solar responsive façade models reflecting Siamese culture.	Simulation	VELUX	Modern Buildings	According to the results obtained, the DF value varies between 1.0 and 3.5 in all models and it is seen that the religion-inspired pattern exhibits the best result among these models.
2023, [57]	Tehran, Iran	35^0 (N)	ASE sDA DGI DGP	Responsive facade	Improving visual performance in the standard patient room with a responsive facade.	Simulation	Rhino/ Grasshopper HoneybeePlus	Hospital Buildings	Window/wall ratio is very important in indoor daylight performance. In the study, the façade proposal with a window/wall ratio of 60% showed the best result.
2023, [69]	Izmir, Turkey	38^0 (N)	UDI ASE	Responsive facade	Propose responsive facade systems with semi-regular and demi-regular tessellations.	Simulation	Rhino/ Grasshopper ClimateStudio	Modern Buildings	Semi-regular and demi-regular tessellations provide optimum daylight comfort in all proposed facade models.
2023, [70]	Lisboa, Portugal	38^0 (N)	^{0}C K W/m^2	Responsive facade	Developing a climate-appropriate building envelope pre-design tool.	Auto-responsive technologies (ARTs) Simulation	Climate consultant	Modern Buildings	In cold climates, thermal adaptive strategies showed short-term suitability. In the equatorial region, thermal adaptive systems showed high suitability as air temperatures increase in the future.
2024, [58]	Naples, Italy	40^0 (N)	sDA UDI EUDI DGP	Responsive facade	To propose a light-sensitive kinetic facade based on the functional principles of the Gazania flower.	Simulation	Rhino/ Grasshopper Honeybee Ladybug	Office Buildings	As a result of parametric simulations, in an office building in a temperate Mediterranean climate, the biometric kinetic system can provide daylight to between 87.5% and 100% of the office space.
2024, [71]	Tehran, Iran	35^0 (N)	UDI ASE sDA DGP	Responsive facade	Investigation of the integration of an adaptive facade and an inclined wall for efficiency improvement.	Simulation	Rhino/ Grasshopper Ladybug	Modern Buildings	The integrated system effectively distributes daylight. It shows that the façade system reduces glare to 34% in Mogadishu and 29% in Tehran.

5. DISCUSSION

The reviewed studies are divided into four groups: "Responsive Facades in Literature", "Thermal Performance of Responsive Facades", "Daylight Performance of Responsive Facades", and "Thermal and Daylight Performance of Responsive Facades" according to their main research areas (Figure 4). 8 studies are literature reviews of the research on responsive facades. While 13 studies examine the thermal performance of responsive facades, five studies examine the daylight performance of this facade system. Only 1 of the reviewed studies examines both the thermal and daylight performance of responsive facades.

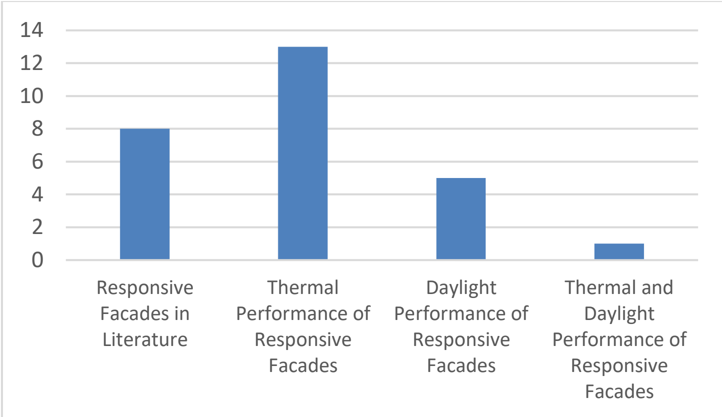

Figure 4. Classification of the analysed studies according to the subjects (Prepared by the author).

Figure 5 shows the tools used to achieve the goal in the studies analysed. The most used program in simulation and optimisation algorithms is Rhino/Grasshopper. 13 studies use the Rhino/Grasshopper program. Honeybee&Ladybug, Kangaroo plugins integrated into Rhino/Grasshopper design and energy simulations. Five studies used Honeybee&Ladybug and 1 study used the Kangaroo plugin. In 3 different studies, Climate Consultant and Climate Studio programs were used to compare thermal comfort criteria.

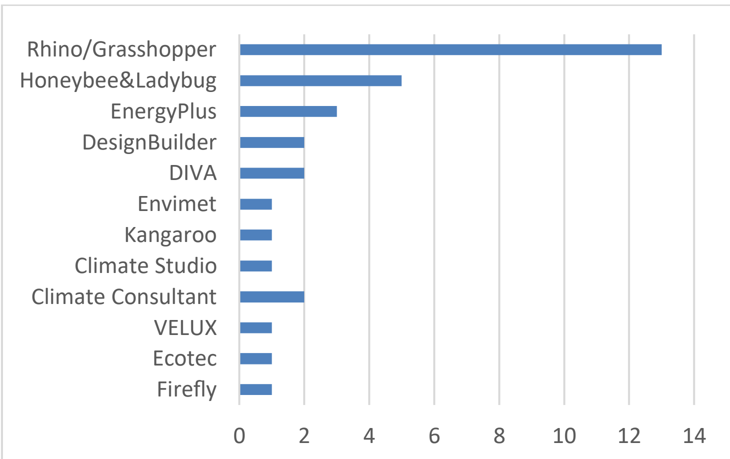

Figure 5. Tools used in the studies (Prepared by the author)

6. CONCLUSION

The effects of the building envelope on user comfort are undeniable. The design and characteristics of the façade, which forms the boundary between the interior and exterior, directly affect the thermal and daylight performance of the interior. Parameters such as window/wall ratio, properties of the materials used on the facade, and orientation have an impact on the physical conditions of the building. The main problem is to get the desired amount of daylight and heat indoors. If daylight is less than sufficient, artificial lighting elements are needed. If the daylight is more than required, it causes glare and vision problems. The transfer of heat from indoors to outdoors during the heating period increases the energy needed for heating, while the transfer of heat to indoors during the cooling period increases the energy required for cooling.

Environmental conditions and user needs are not static. Designers have developed responsive facades that allow the facade to move according to changing environmental conditions and user needs. This façade system provides optimum intake of daylight and heat into the interior and minimizes air leakage. In this way, both user comfort and energy efficiency are increased. Studies in the literature show that energy consumption in buildings with responsive facades is less than traditional facades [61].

Today, the Rhino/Grasshopper program creates parametric-based 3D models. These models allow different design proposals for responsive facades to be easily created and different simulations can be made. Optimization studies enable us to obtain models that achieve the best results of the goals set over millions of other alternatives. Considering climate change and global warming, it is thought that the energy consumption of the designs made today may increase in the coming years due to increasing air temperatures. For this reason, this study indicates that researchers working on responsive facades should consider future weather scenarios.

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MUSTAFA SERHAN UNLUTURK, Lecturer,
In 2018, he completed his undergraduate education at Balıkesir University, Faculty of Architecture, Department of Architecture. In 2020, he completed his master's degree in ‘building envelope airtightness’, one of the parameters affecting energy efficiency in buildings. Since 2020, he has been working as a Lecturer at Balıkesir University. His studies are mostly on building energy optimization, facade systems, daylighting and thermal performance.